MULTI-CRITERA DECISION SUPPORT FOR THE REVITALISATION OF RIVER FLOODPLAINS

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PROPOSITIONS

I.J. Zsuffa
Multi-criteria decision support for the revitalisation of river floodplains.
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1. The development of typical, rich and diverse biota of river-floodplain systems is based on the coexistence of two main biotopes: the lotic river channel system, and the lentic cell-system. This implies that ecological revitalisation projects should put equal emphasis on the development of both these systems.

   This thesis

2. The key to ecological revitalisation of river-floodplain systems is improving the water regime, since this is the most influential abiotic factor and furthermore, the water regime has undergone serious deterioration from the point of view of ecology due to the different interventions into the river system.

   This thesis

3. Vegetation models applied for impact assessment in river-floodplain revitalisation projects should preferably be physiologically-based models, since regression-based conditional models are inevitably specific to the existing water regime, which is however subject to modifications.

   This thesis

4. Genetic Algorithms based search techniques enable the application of impact assessment tools of any kind, ranging from simple equations to complex numerical models. The only constraining factor is the calculation speed of these tools, however, the rapidly increasing capacities of computers are gradually eliminating this problem.

   This thesis

5. It is time to get rid of the illusion that one day scientists will come up with a technique that locates the best compromise solution for a multi-criteria decision problem without demanding that decision makers get thoroughly acquainted with the given problem.

   This thesis

6. The river Danube consists of two-thirds water and one-third fish.

   Medieval Hungarian saying

7. The crucial question posed to human beings is as follows: are you ready to face eternity or not? This is the criterion for our life.

   C.G. Jung. Von Schein und Sein. Walter Verlag 1990.

SUMMARY

Zsuffa, I.J. 2000. *Multi-criteria decision support for the revitalisation of river floodplains.* Doctoral Dissertation, Wageningen University, The Netherlands.

Ecological revitalisation of river floodplains has become a very actual issue worldwide. It has been recognised that floodplains have the potential to become ecologically very productive areas inhabited by many valuable and rare species. Floodplains also play an important role in regional and even in continental context. Namely, beyond their own ecological values floodplains are also important as far as migration and spreading of species are concerned.

Only very few natural floodplains have been left along the major regulated rivers of Europe. Thus, revitalisation of the existing ones has a special importance. Some of the revitalisation objectives can be achieved by means of administrative measures but there are several problems, which need active engineering intervention. These problems to be remedied are the results of adverse changes in hydrological conditions, which are the most influencing abiotic factors for floodplain ecosystems. The general problem of desiccation for example has been caused by the decreasing water levels in the rivers, following widespread river training since the 19th century.

Thus, the key to ecological revitalisation of river floodplains is improving the water regime. This is proposed to be implemented by transforming the water conveyance infrastructure in an appropriate manner. Measures like enlarging and/or narrowing floodplain-channels, erecting summer dikes, installing and operating sluices are envisaged for this purpose. Because of the requirements of flood control, navigation and land uses, and also because of conflicts between the envisaged ecological objectives, floodplain revitalisation is inevitably a decision problem with conflicting multiple objectives and multiple stakeholders forming a Decision Making Group (DMG). The task of the DMG is to identify a compromise solution, with satisfactory achievements of all objectives.

This dissertation has been conceived as to develop a computer based Decision Support System (DSS) that assists the DMG in searching for compromise solutions for the ecological revitalisation of river floodplains. The search takes place in a discrete decision space where the alternative solutions are specific combinations of water control measures mentioned above.

The proposed DSS is based on the Evolutionary SEquential Multi-Objective Problem Solving (ESEMOPS) method developed by Bogardi & Sutanto [1994]. ESEMOPS actually solves a series of surrogate optimisation problems. These surrogate problems seek a minimum of the deviations between the actual aspiration levels of the DMG regarding the individual objectives and their respective achievements through optimisation. It is important to emphasise that surrogate optimisation problems are not substitutes for an explicit expression of the DMG's preference function. By comparing and analysing the solutions of these problems the DMG only gains information concerning the set of feasible solutions, and learns about the interrelationships (trade-offs) between the applied evaluation criteria. These interrelationships are estimated by alternatively treating some objectives as constraints thus enforcing their achievement. On the basis of intermediate results, the DMG modifies its preference structure (by modifying the aspiration levels) and repeats the surrogate optimisation processes. This iterative-interactive search goes on until the DMG declares a certain solution as the best compromise solution for the given problem.

Surrogate optimisation problems are solved with the help of a Genetic Algorithms (GA) based search technique. The major advantage of GA is that it relies exclusively on information already available in the input (population of alternative solutions), and output (surrogate objective values) of criteria evaluations throughout the search towards the optimum of the actual surrogate problem.

During each GA run a high number of alternative solutions has to be evaluated according to the selected criteria. Criteria evaluation is carried out with the help of a complex modelling system. The most important module of this system is a hydrodynamic model, which enables to simulate the water regime on the floodplain. The applied model is called FOK, which has been developed by the author. FOK belongs to the family of unsteady cell-type floodplain models. Its most pronounced feature is the extremely high simulation speed, which is required by the DSS in order to complete the GA searches within reasonable time limits. The high calculation speed has been achieved with the help of adaptive time step and model configuration control and with that of applying pre-calculated 'delivery functions' for flow calculations in the floodplain-channels. FOK is also enabled to cope with supercritical flow conditions, which may frequently occur in such channels.

Output of the FOK model (water level time series on the floodplain) are input for ecological models, which help to estimate the achievements of ecological criteria. Ecological models embedded into the DSS are ranging from the physiologically based MEGAPLANT model [Scheffer *et al.*, 1993] simulating the growth of water plants to habitat evaluation models for fish and for waders. These habitat models have been formulated by adopting existing habitat modelling approaches to the unsteady hydrological conditions of floodplains.

The DSS has been tested on a case study problem. The selected area is a sub-system of the Danube riparian Gemenc floodplain in Hungary. The identified ecological objectives prescribe the improvement of conditions for typical alluvial wet ecosystems. Special attention is paid on improving habitat conditions for fish and for waders like the famous black stork (*Ciconia nigra*). The set of criteria formulated for the ecological objectives have been supplemented with criteria representing cost minimisation and timber production. This latter is an important economical use of the area, which has to be taken into consideration in the future as well. After identifying the decision and criteria spaces a decision making 'game' has been played with the help of the ESEMOPS based DSS. The purpose of the game was to locate a best compromise solution according to the foreseen preferences of a potential DMG dealing with the revitalisation of the Gemenc floodplain.

It can thus be concluded that developing such a DSS is quite an interdisciplinary task involving the disciplines of ecology, fluid mechanics, numerical modelling, statistics and operations research. Accordingly, the key contribution of the present dissertation is the new, interdisciplinary concept that forms the basis of the proposed DSS. The major challenges that had to be faced during the development of the DSS were selection, adaptation and integration of techniques from the different disciplines.

SAMENVATTING

Zsuffa, I.J. 2000. *Multi-criteria decision support for the revitalisation of river floodplains.* (Multi-criterium beslissingsondersteuning voor het herstel van uiterwaarden) Proefschrift, Wageningen Universiteit, Nederland.

Het ecologische herstel van uiterwaarden is wereldwijd een zeer actueel onderwerp geworden. Inmiddels wordt erkend dat uiterwaarden potentieel waardevolle ecologische gebieden zijn, waar veel nuttige en zeldzame soorten kunnen voorkomen. Uiterwaarden spelen ook een belangrijke rol in regionaal en zelfs in continentaal verband omdat naast de ecologische waarde, uiterwaarden ook belangrijk zijn voor de migratie en verspreiding van allerlei soorten planten en dieren.

Er zijn heel weinig natuurlijke uiterwaarden langs de gereguleerde Europese rivieren overgebleven. Herstel van de bestaande uiterwaarden is dan ook van groot belang. Een gedeelte van het herstel van de uiterwaarden kan met behulp van administratieve maatregelen bereikt worden, maar er zijn verscheidene problemen waarvoor technische maatregelen nodig zijn. Deze problemen zijn het gevolg van veranderingen in het hydrologische systeem, de meest invloedrijke abiotische factor voor rivierbegeleidende ecosystemen. Het belangrijkste probleem bijvoorbeeld, verdroging, is veroorzaakt door het dalende water niveau in de rivieren, wat een direct gevolg is van regulering en kanalisering van de rivieren sinds de 19^e eeuw.

De voornaamste voorwaarde voor het ecologisch herstel van de uiterwaarden is dus de verbetering van het water regime. Deze verbetering kan bereikt worden door veranderingen van de waterleverende infrastructuur. Maatregelen die genomen moeten worden zijn onder andere de vergroting en/of versmalling van de kanalen, het bouwen van zomerdijken en de installatie en het operationeel maken van sluizen. Vanwege de vele eisen met betrekking tot scheepvaart, land gebruik en verdediging tegen overstromingen, is het herstel van uiterwaarden een beslissingsprobleem van verschillende belangengroepen met conflicterende doelen, die samen een Beslissings Groep (BG) vormen. De taak van de BG is een compromis te vinden met bevredigende oplossingen voor alle doelen.

Het doel van dit onderzoek is een computergestuurd Beslissingondersteunend Systeem (BS) te ontwikkelen, die de BG helpt bij het zoeken naar goede oplossingen voor ecologisch herstel van de uiterwaarden. Dit zoeken vindt plaats in een discrete beslissingsruimte waarbij de alternatieve oplossingen bestaan uit bepaalde combinaties van de hierboven genoemde maatregelen op het gebied van het Waterbeheer.

Het voorgestelde BS is gebaseerd op de Evolutionary SEquential Multi-Objective Problem Solving (ESEMOPS) methode van Bogardi & Sutanto [1994]. ESEMOPS lost een serie van surrogaat optimaliserings problemen op. Deze problemen zoeken het minimum van de afwijking tussen de werkelijk gewenste niveaus van de BG met betrekking tot de individuele doelen en de respectievelijk door optimalisatie verkregen resultaten. Het is belangrijk te benadrukken dat de surrogaat optimaliserings oplossingen geen vervangers zijn voor de voorkeur functie van de BG. Door vergelijking en analysering van de oplossingen van deze problemen, verkrijgt de BG slechts informatie over de set van haalbare oplossingen, en krijgt inzicht in de onderlinge relaties (trade-offs) tussen de gebruikte evaluatie criteria. Deze onderlinge relaties worden geschat door een aantal doelen te behandelen als beperkingen en zodoende hun haalbaarheid te verzekeren. Op grond van tussentijdse resultaten wijzigt de BG zijn preferentie structuur (door wijziging van de streefniveaus) en worden de surrogaat optimalisering procedures herhaald. Dit iteratief - interactief onderzoek gaat door tot de BG verklaart dat een bepaalde oplossing het beste compromis is voor een probleem.

De surrogaat optimaliserings problemen worden opgelost met behulp van een op de Genetische Algoritmen (GA) gebaseerde zoektechniek. Het belangrijkste voordeel van GA is dat tijdens het zoeken naar het optimum van het actuele surrogaat probleem slechts gewerkt wordt met beschikbare informatie uit de input (populatie van alternatieve oplossingen) en output (surrogaat waarden) van de criteria evaluatie.

Tijdens elke GA berekening worden een groot aantal alternatieve oplossingen volgens de vooraf bepaalde criteria gewaardeerd. Deze waardering wordt uitgevoerd met behulp van een complex modelleringssysteem. De belangrijkste module van dit systeem is een hydrodynamisch model dat de simulatie van het water regime in de uiterwaarden mogelijk maakt. Het toegepaste model is door de auteur ontwikkelt en heet FOK. FOK behoort tot de familie van variabele cel-type uiterwaarden modellen. Het bijzondere kenmerk van FOK is de zeer hoge simulatie snelheid, die nodig is voor het BS zodat de GA berekeningen binnen een redelijke tijd voltooid kunnen worden. De hoge berekeningssnelheid is mogelijk door de zichzelf aanpassende tijdstappen, controle van de modelconfiguratie en door toepassing van de voorberekende 'delivery' functies voor de doorstroom berekeningen in de kanalen. FOK kan ook super kritische stroming berekenen die vaak voor kunnen komen in de kanalen in de uiterwaarden.

De output van het FOK model, een waterstands meetreeks in de uiterwaarden, is input voor de ecologische modellen die gebruikt worden bij het inschatten van de waarden voor de ecologische criteria. De ecologische modellen die gebruikt zijn binnen het BS variëren tussen het fysiologische gebaseerd MEGAPLANT model [Scheffer *et al.*, 1993], dat de groei van water-planten simuleert, tot habitat waarderingsmodellen voor vissen en voor waadvogels. Deze habitat modellen zijn ontwikkeld met behulp van bestaande habitat modellen en de variabele hydrologische voorwaarden in de uiterwaarden.

Het BS is in een case studie getest. Het onderzoeksgebied is een subsysteem van het Gemenc gebied dat langs de Donau in Hongarije ligt. Het belangrijkste ecologische doel van dit onderzoek is de verbetering van de condities voor natte rivierbegeleidende ecosystemen zoals uiterwaarden. De verbetering van de habitat voor vissen en voor waadvogels (zoals de zwarte ooivaar) is daarbij extra benadrukt. De set van ecologische criteria is aangevuld met twee economische criteria: Minimalisering van de kosten en de mogelijkheid van hout-productie. Het laatstgenoemde criterium is een belangrijke economische activiteit in het gebied dat ook in de toekomst nog van belang zal zijn. Na benoemen van de beslissings- en criterium ruimten is er een beslissings 'spel' gespeeld met behulp van de op ESEMOPS gebaseerde BS. De bedoeling van dit spel was het beste compromis te vinden volgens de verwachte voorkeuren van een potentiële BG, die zich met het herstel van de Gemenc bezighoudt.

Er kan geconcludeerd worden dat de ontwikkeling van een dergelijke BS een interdisciplinaire opdracht is met disciplines zoals ecologie, hydraulica, numerieke modellering, statistiek en operatie onderzoek betrekt. De belangrijkste bijdrage van dit proefschrift is daarom het interdisciplinaire concept dat de basis vormt van het voorgestelde BS. De grootste uitdagingen tijdens de ontwikkeling van het BS waren de selectie, aanpassing en integratie van methoden uit de verschillende disciplines.

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1. INTRODUCTION

1.1 Objective of the study

Due to the global transformation and degradation of the natural environment, ecological revitalisation has become a very actual issue worldwide. It has early been recognised that revitalisation of the desired ecosystems has to be dealt with in regional, or even in continental context. Local habitat revitalisation should be embedded into these larger scale efforts. For example, migratory fauna need appropriate ecological conditions on their feeding and mating habitats, but also along their migration routes. Stand-alone, isolated revitalisation sites are also difficult to be colonised by the desired communities in a natural way, i.e. from other natural areas. These all turned the attention towards developing connected *ecological networks*. Ecological networks consist of *generator areas* connected to each other by means of *corridors* [de Bruin *et al.*, 1987; de Groot *et al.*, 1990]. Generator areas are the most valuable and productive parts of the network. These are the places where optimal conditions are provided for the desired species for growth and reproduction. Corridors are less valuable areas. Their role is to ensure the migration of fauna and the spreading of flora between generator areas. The latter process also needs the help of transport mediums such as wind and especially flowing water. River systems thus have the potential to form excellent ecological networks not just because the river channels mean proper corridors but also because the floodplains are excellent sites for generator areas due to their very high ecological potentials [de Bruin *et al.*, 1987; de Groot *et al.*, 1990]. These high potentials are the consequences of unrestricted supply of water and nutrients and also of the stimulatory effect of dynamic hydrological conditions. Ecological revitalisation of floodplains is thus of outmost importance not just on local but also on regional and continental scales.

Revitalisation of floodplains is however constrained by the needs and requirements of other functions such as flood control, navigation and different forms of land uses like agriculture, forestry and recreation. In addition, the different ecological objectives themselves are often in conflict with each other. These all mean that floodplain revitalisation is a constrained problem with conflicting multiple objectives, where the task is to find the best compromise solution.

Measures for ecological revitalisation may be of two main types: administrative measures and engineering interventions. Administrative measures are applied in those cases when restriction or elimination of certain activities automatically results in improvement of the ecological conditions, or generates better conditions for further revitalisation actions. Enforcing laws and rules, controlling different forms of pollution (noise pollution, solid and liquid waste disposals, etc.) is a typical example for administrative way of revitalisation. Administrative measures alone are however insufficient in those cases when lasting negative changes have been taking place in the abiotic environment. These problems need active, ***engineering*** interventions aiming to improve the abiotic conditions for the benefit of ecology. Engineering revitalisation of floodplains deals primarily with improvement of the hydrological conditions, as these are the most influencing abiotic factors for floodplain ecosystems. Improving hydrological conditions can be achieved by means of local and/or basin wide adjustment of the water conveyance infrastructure. Installation and operation of flow control structures, construction or elimination of channels and dikes, river training measures and reforestation are examples for such interventions.

Deriving the best compromise solution for engineering revitalisation of floodplains is quite an interdisciplinary task involving several disciplines such as:

1. *Ecology*: describes the relationships between organisms and their biotic and abiotic environment.

2. *Fluid mechanics*: describes the flow phenomena, which are the major abiotic factors for floodplain ecosystems.

3. *Numerical modelling*: computer based hydrodynamic and ecological models predict the effects of alternative revitalisation solutions.

4. *Statistics*: captures the random behaviour of hydrological and ecological processes, estimates recurrence probability of certain events.

5. *Operations research*: searching for the best compromise solution of a multi-objective problem can be supported by methods of operations research.

Because of the very high computational demands, coupling advanced single- or multi-objective search tools with sophisticated hydrodynamic and ecological models has not been attempted yet, in spite of the ever-increasing calculation speed of computers. Sophisticated hydrodynamic, groundwater, water quality and ecological models have already been applied in several floodplain revitalisation studies, even though identification of alternative solutions in these cases was implemented in a simple trial-and-error manner [Marchand, 1993; Nachtnebel, 1994; Nieuwkamer, 1995].

On the other hand advanced search tools of operations research (such as linear programming, dynamic programming, evolutionary algorithms, etc.) have been applied only for those water management problems, which do not require sophisticated hydrological and ecological modelling. For example the aforementioned search tools are widely used in the field of reservoir operation [e.g.: Loucks *et al.*, 1981; Kularathna, 1992; Milutin, 1998], since modelling the spatial and temporal distribution of water within a reservoir system requires only simple balance equations.

Having this in mind the primary objective of this study is to create a robust Decision Support System (DSS) for floodplain revitalisation that is relying on the coupling of sophisticated modelling and search techniques. The envisaged role of the DSS is to support decision makers in identifying compromise, engineering solutions for the constrained multi-objective problem of ecological revitalisation of river floodplains. The scope of the DSS is restricted to the lentic part of the river-floodplain system, which is characterised by ecosystems adapted to standing water. Lentic floodplain systems have received little attention so far, as most of the revitalisation projects have been dealing with lotic ecosystems hosted by flowing river channels.

It is important to state that this study does not attempt to explore the 'white spots' of fluid mechanics, ecology and operations research. The most important contribution of this study is to develop an interdisciplinary concept and use it as a basis for the aforementioned complex DSS. Accordingly, the major challenges are *selection*, *adaptation* and *integration* of techniques from the disciplines listed above. Finally, it is also important to state that the desired DSS is aimed to have an open design, which will make possible to improve it in the future by integrating new techniques developed within the frame of specialised disciplinary research programmes.

1.2 Outline of the study

As Figure 1.1 indicates the study starts with three introductory chapters: Chapter 2 describes the mechanism of hydrological, morphological and ecological processes on river-floodplain systems; Chapter 3 introduces the mechanism of decision making in floodplain development; finally Chapter 4 introduces the case study area, reveals its ecological problems and introduces the other functions of the area which constrain the ecological revitalisation.

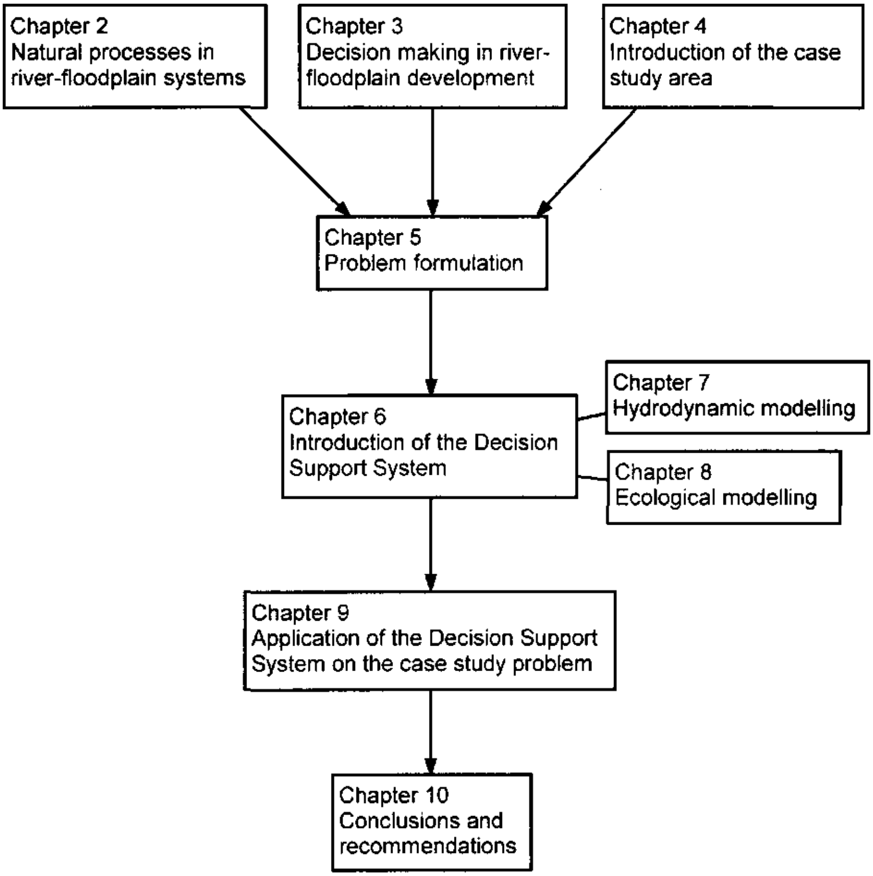

Figure 1.1 Outline of the study

Based on the theoretical background and on the revealed problems and constraints, Chapter 5 formulates the general problem of floodplain revitalisation in an engineering-mathematical way. Revitalisation measures are identified, from which the decision space is to be built up, within which the decision maker may search for the best compromise solution for the selected floodplain revitalisation problem. This search is based on evaluation criteria, which are also identified in this chapter.

Chapter 6 introduces the mathematical principles of the Decision Support System (DSS) that has been developed to support the search towards the best compromise solution. Although hydrodynamic and ecological models are integrated modules of the DSS, yet it is also possible to operate them independently from the DSS. Due to this feature, and also because of the significant differences in principles, these models are treated in chapters 7 and 8 separately (Figure 1.1).

Finally, Chapter 9 demonstrates how the developed DSS works in the practice. A decision making process is simulated with the aim to identify a potential best compromise revitalisation solution for the case study floodplain.

At the end of the thesis a glossary can be found where explanations are given about the special terms used in the text.

2. NATURAL PROCESSES IN RIVER-FLOODPLAIN SYSTEMS

The purpose of this chapter is to describe natural river floodplains from the point of view of all relevant aspects such that morphological, hydrological and ecological processes. However before going into details it is necessary to define the basic terms used.

Hydrologists define floodplain as the area, which would be inundated by the design flood of the river [Zsuffa sr., 1996, pers. com.]. The water level (or discharge) related to the design flood is specified by means of its probability of occurrence. This definition thus includes not only the temporarily inundated terrestrial areas but also the river channel(s) and the permanent standing water bodies, which submerge during such flood.

Ecological definition of Junk *et al.* [1989] reflects a more general approach, although it is spatially more restrictive: *'floodplain is the Aquatic/Terrestrial Transition Zone (ATTZ), which is periodically inundated by the lateral overflow of rivers or lakes, and/or by direct precipitation or groundwater'*. Thus, permanent water bodies (river channels and oxbow lakes) are excluded from this definition. Junk *et al.* [1989] call the union of permanent water bodies and the ATTZ as the '*river-floodplain system*', which is thus equivalent to the hydrological definition of floodplain.

For this study an intermediate definition has been constructed. Accordingly, *floodplain is the ATTZ of the river together with the permanent standing water bodies, which would submerge during the design flood of the river.* The term 'river-floodplain system' stands for the union of the floodplain and the river channel system.

Note, that according to the above definition, large areas have been detached from the ancient river-floodplain systems due to construction of flood control dikes.

2.1 Morphological and hydrological aspects

Morphological and hydrological conditions on floodplains are highly determined by that of the adjacent river. Floodplains are practically absent from the headwaters of the river. Here the river flows in narrow valleys and the fast flowing water continuously erodes its bed. Leaving the hilly headwaters, the slope and the velocity of the river drops, which results the deposition of sediment transported from upstream. This sedimentation process has been continuously filling up the wide valleys of the river throughout geo-historical times resulting wide floodplains between the river and the valley slope. The river is no longer flowing in a rocky bed but in its own alluvium. The Danube for example becomes alluvial downstream of Vienna after leaving the Alps and entering the Kisalföld flatland.

Depending on the ratio between erosion and sedimentation, alluvial rivers can either be braiding or meandering. The river is braiding if sedimentation surpasses the erosion process. It splits into branches on the top of the continuously aggrading alluvium and creates its typical river-floodplain system with many islands, reefs and branches. At the Kisalföld for example the Danube is braiding since its coarse sediment carried from the Alps, gets deposited here.

If sedimentation is in balance with erosion, the river becomes meandering. It stays in one channel, which is however continuously meandering as erosion destroys the concave banks while sedimentation builds the convex banks. Accordingly, the concave banks are usually steep while mildly sloping sandy *point bars* are built up on the convex banks (Figure 2.1). The overdeveloped meanders get sooner or later cut-off by a big flood and become dead branches. Later these dead branches become lakes as sedimentation closes their upstream and downstream mouths to the river. Such *oxbow lakes* are typical morphological structures along meandering rivers (Figure 2.1). Oxbow lakes are subjected to further aggradation due to continuous biological sedimentation [Amoros *et al.,* 1987] and to the deposition of fine suspended river sediment after floods. This *morphological succession* may lead to the complete disappearance of the lake leaving only a narrow depression on the floodplain surface (Figure 2.1).

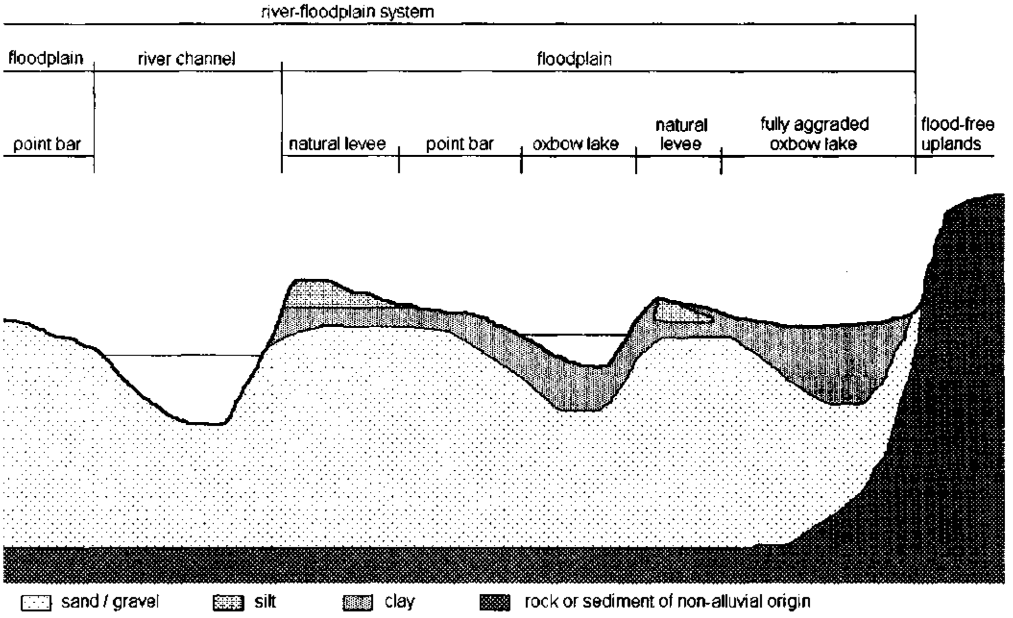

Figure 2.1 General cross-section of a natural river-floodplain system

Another way of morphological succession is when a point bar starts to emerge from the riverbed due to sand sedimentation. Later when the meander has moved away, floods continue the building process by depositing fine suspended sediment.

The concave banks of meandering rivers are usually elevated above the floodplain surface. These *natural levees* (Figure 2.1) consist of silty sediment deposited by floods right after that they overtop the steep bank and start to inundate the floodplain. Depending on the direction of the meandering process natural levees can either be built on the top aggraded oxbow lakes or on point bars of former meanders. Natural levees are of course present on the banks of oxbow lakes as well, however their relative height are decreasing due to the sedimentation of the surrounding floodplain areas.

Thus, the surface of the floodplain is continuously being elevated by the different kind of sedimentation processes. It goes on until the meandering river moves through the area and resets the morphological process. Thus, there exists a long-term balance between erosion and sedimentation.

Hydrology of floodplains is determined by that of the adjacent river. At headwaters, the river responds quickly to precipitation resulting in quick and peaky flood waves in its narrow valley. By moving downstream, flood waves are continuously spreading due to the increasing storage capacity of the bed and its adjacent floodplain, as well as to the natural flood wave diffusion process. Accordingly, big alluvial rivers are characterised by seasonal flood events with relatively slow rate of change in discharge. Above the influence of discharge regime, changes in water levels are directly influenced by the morphology of the river floodplain system. In case of a wide river channel, smaller water level increase is needed to convey the increased discharge than in case of a narrow channel. Thus, wide alluvial rivers, especially with multiple channels, promote the mitigation of rate of water level change during floods.

2.2 Ecological aspects

Three major *biotopes* can be distinguished in a river-floodplain system:

1. *Lotic* water bodies characterised by flowing water (river channels).
2. *Lentic* water bodies with stagnant water (oxbow lakes).
3. Terrestrial areas.

This section describes first the ecological processes in permanent lentic and lotic water bodies. Subsequently it describes the ecological processes taking place in the unsteady water bodies (lentic and lotic) and on the frequently inundated terrestrial areas of river-floodplain systems. It is a special feature of river-floodplain systems that the boundaries of these biotopes are not stable but recurrently traverse large areas as the inshore edge of the aquatic environment, the '*moving littoral*', traverses the ATTZ [Junk *et al.*, 1989].

2.2.1 Ecological processes in lentic water bodies

Oxbow lakes on floodplains belong to the '*shallow lake*' category. Shallow lakes are characterised by the lack of stratification. Temperature and dissolved substances are equally distributed along the water column due to diffusion and turbulence generated by the wind. The shallow depth enables the light to penetrate down to the bottom so that primary production is possible along the entire water column.

The energy source for biological life and production on the Earth's surface is the Sun. In shallow lakes algae and water-plants use solar energy and inorganic nutrients to build up organic material by means of photosynthesis (Figure 2.2}. During photosynthesis CO_2 is consumed from, while O_2 is released into the water column. At night the photosynthesis pauses and primary producers consume only O_2 for respiration. Above C, H and O, organisms also need N, P and Si, which are available for algae and water plants in the water column or in the bottom sediment in the form of inorganic nutrients such as nitrate, nitrite, phosphate and silicon. Mortality of algae and water-plants results dead organic material (detritus) which than get mineralised into inorganic nutrients by bacteria. During mineralisation, oxygen is consumed from the water column.

The nutrient cycle of a shallow lake is partly open to the atmosphere. Exchange of CO_2 and O_2 proceeds through the water surface thanks to diffusion and wind induced aeration. Nitrogen can also leave and enter the system in the form of N_2 by means of bacterial denitrification and fixation. Only the phosphorus cycle is closed to the atmosphere. Dissolved nutrients as well as suspended algae and detritus can be imported and exported by means of water exchange between the lake and its neighbouring water bodies. This process is significant in floodplain oxbow lakes being periodically leached by floods of the river. Detritus may leave the system by means of burial into the bottom sediment thus contributing to the biological sedimentation of the lake. Inorganic nutrients can also be exchanged with the groundwater system (Figure 2.2).

The quality of the lake water is determined by the concentration of dissolved and suspended materials and not by their overall masses in the lake. Above biochemical material fluxes, concentrations can also be modified by physical processes such as sedimentation, resuspension, rainfall, evaporation, seepage and inflow of waters with different concentrations.

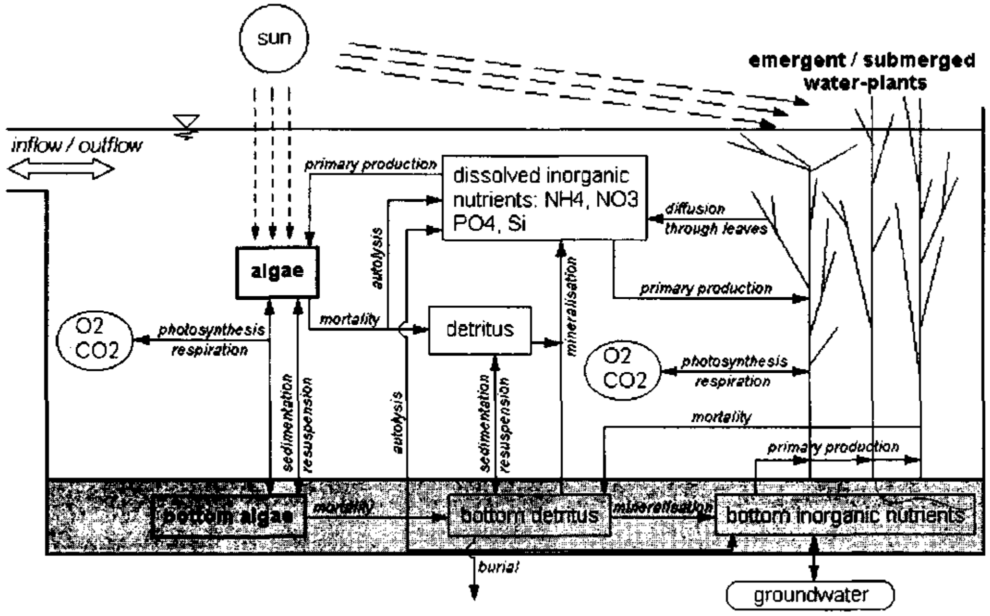

Figure 2.2 Primary production and related ecological processes in shallow lake [after Bokhorst & Groot, 1993]

The biomass produced by primary producers is the source of nutrients and energy for the fauna. Plant biomass is consumed on the second trophic level by grazers such as zooplankton, macro invertebrates and fish (Figure 2.3). The grazers are in turn food for predatory animals in the third trophic level. Mortality and metabolism of fauna contributes to the detritus pool of the lake. Some detritovore fish and macro invertebrates take nutrients and energy by consuming detritus. All animals in the water consume oxygen and produce carbon dioxide by means of respiration.

Nutrients are circulating in a shallow lake ecosystem (with some inputs and outputs) while energy flows through and leaves the system in the form of heat [Djordjević, 1993]. This principle is valid on global scale too.

Fauna of the lake can be exchanged with neighbouring water bodies by means of water in- and outflow, furthermore fish and aquatic mammals have the ability to migrate independently from the movement of water.

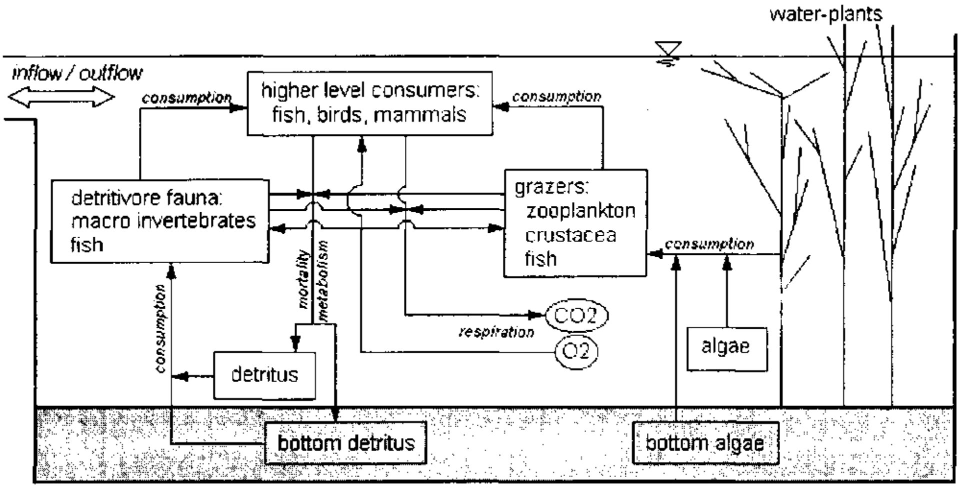

Figure 2.3 Ecological processes in shallow lake above the first trophic level

According to the quantity of nutrients available for production, lakes are classified into two main groups:

1. oligotrophic lakes: low nutrient content associated with low biomass production
2. eutrophic lakes: high nutrient content with high biomass production

Due to the sufficient nutrient supply of the river, floodplain lakes are usually eutrophic.

There are two forms of eutrophication: benthonic and planktonic [Djordjević, 1993]. In case of benthonic eutrophication, the increased quantity of nutrients boosts the growth of water plants. Growth of phytoplankton is restricted by the water plants through shading, nutrient limitation and excretion of inhibitory *allelopathic* chemicals [Hootsmans & Lubberding, 1993]. Benthonic eutrophication keeps the dissolved oxygen content within acceptable limits. The water remains transparent and suitable for fish. Anaerobe conditions develop only on the bottom due to the decomposition of dead plants. Benthonic eutrophication however may turn to planktonic eutrophication. Hootsmans & Lubberding [1993] describe a possible way of this change:

1. The increased nutrient content stimulates the growth of *epiphyte algae*, which is effected much lesser extent by allelopathic substances than phytoplankton.
2. Epiphyte algae limit the light and carbon availability for plants resulting in decreased rate of allelopathic excretion, which in turn results in the growth of phytoplankton.

3. Phytoplankton limits further the macrophyte through shading, and at the end macrophytes disappears and phytoplankton dominates the system.

Ligtvoet & Grimm [1992] describe another possible way of this change:

1. The predatory fish stock of the lake reaches its maximum density and can no longer regulate the ever-increasing prey stock.

2. The expanding planktivorous fish stock overgrazes the zooplankton resulting in an excessive growth of algae in the nutrient rich water.

Planktonic eutrophication creates an ecologically poor environment. Most fish species disappear, as they cannot stand the open turbid water. The rest of the fauna are exposed to anoxic conditions resulted by the decomposition of algal detritus. Extensive algae mortality may even cause disastrous death of the remaining fauna.

Figure 2.4 summarises the most important factors influencing algae dynamism in a water body. *Physiological factors* [Runhaar, 1991] have the most direct influence. They influence directly the physiological processes, which are photosynthesis, respiration and assimilation. Zooplankton can also be viewed as physiological factor since grazing results direct physical destruction of algae. *Conditional factors* [Runhaar, 1991] are the ones that influence the physiological factors.

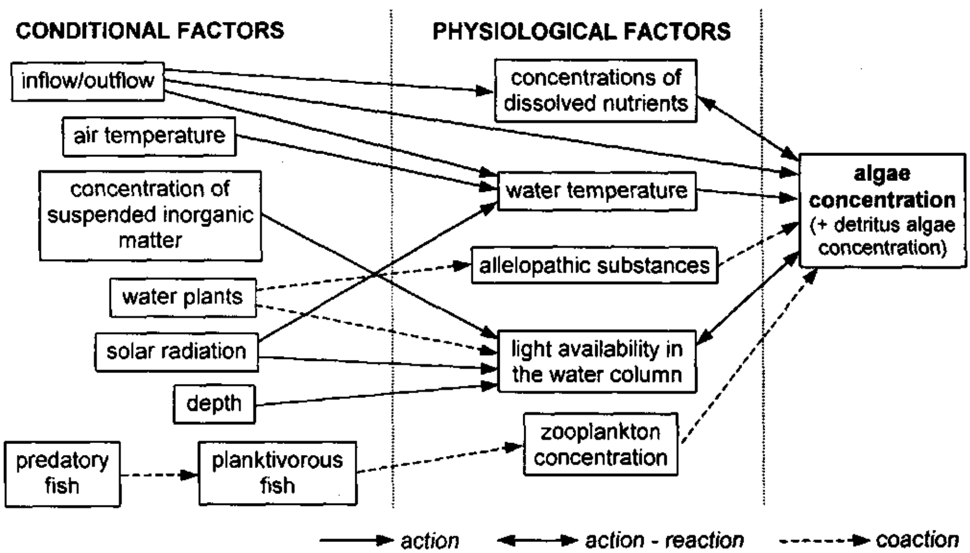

Figure 2.4 Influence chain of algae in shallow lakes

2.2.2 Ecological processes in lotic river systems

Ecological processes in permanent lotic channel systems are described by the *river continuum concept* of Vannote *et al.* [1980]. The concept states that a continuous gradient of physical conditions exist from headwater to mouth, and the structural and functional characteristics of stream communities are adapted to conform to the most probable or mean state of the system along the river. Producer and consumer communities establish themselves in harmony with the dynamic physical conditions of a given river reach, and downstream communities are fashioned to capitalise on inefficiencies of upstream processing [Vannote *et al.*, 1980].

Because of shading by riparian forests, headwaters are characterised by low rate of primary production. On the other hand the maximum interface between the forested terrain and the headwaters promotes the input of particulate organic matter (detritus) thus creating a strongly *heterotrophic* environment characterised by detritovore invertebrates. As stream size increases, the reduced importance of terrestrial organic input coincides with enhanced importance of organic transport from upstream and autochthonous primary production of algae and water-plants. Further downstream, the increased suspended sediment and fine particulate organic matter combined with increased depth limit the light availability, resulting decreased primary production, and the system becomes heterotrophic again. The fish population is characterised by few cool water species at the headwaters, while more diverse warm water communities dominate the lower courses and even planktivore species can appear in the alluvial reaches indicating the semi-lentic nature of the river [Vannote *et al.*, 1980]. This ecological continuum from the headwaters to the estuary in a natural river may be locally shifted by lateral inflow of tributaries.

2.2.3 Ecological processes in river-floodplain systems

The river continuum concept suffers from two basic limitations: it was developed on small temperate streams but has been extrapolated to rivers in general, and it was based on a concept that had been elaborated for the river basin in a geomorphological sense but was in fact restricted to habitats that are permanent and lotic [Junk *et al.*, 1989]. A river-floodplain system however is a system of connected lentic and lotic waters, which expands to the transversal dimension too, above the river's longitudinal dimension [Amoros *et al.*, 1987], and which is characterised by temporal modifications controlled by the hydrological regime of the river. This system results in adaptations of biota that are distinct from those in systems dominated by stable lotic or lentic habitats [Junk *et al.*, 1989].

Therefore, Junk *et al.* [1989] constructed the *flood pulse concept* for describing ecological processes in river-floodplain systems. This concept is based on the following principles:

1. In unaltered large river systems with floodplains, the overwhelming bulk of the riverine animal biomass derives directly or indirectly from production within the floodplain and not from downstream transport of organic matter produced elsewhere in the basin.

2. The major force controlling biota in floodplains is the pulsation (periodical rising and falling) of the water level of the river.

3. The effect of the flood pulse on biota is principally hydrological and independent of the nature of its source, so that there are many similarities between floodplains adjacent to pulsing lakes or reservoirs and pulsing rivers.

4. If no organic material except living animals were exchanged between floodplain and channel, no qualitative and, at most, limited quantitative changes would occur in the floodplain.

The channel system is viewed by the concept only as a route for fauna for gaining access to adult feeding areas, nurseries, spawning grounds, or as a refuge at low water or during winter.

Life cycles and composition of biota utilising floodplain habitats are basically determined by the flood pulses in terms of their annual timing, duration, height and the rates of rise and fall. Predictable and prolonged flood pulse typical for large alluvial rivers favours the development of anatomical, morphological, physiological and/or ethological adaptations of terrestrial and aquatic organisms to colonise the aquatic terrestrial transition zone (ATTZ) [Junk *et al.*, 1989]. Such adaptation strategies in low order streams are rather restricted due to the quick and irregular floods with short duration.

Primary production in floodplain water bodies

The hydrological state of an oxbow lake varies between two phases:

1. Isolation phase with no surface water connection to the river.
2. Contact phase with surface water connection to the river.

The duration of these phases depends on the flood regime of the river and on the morphology of the lake. Oxbows surrounded by higher levees stay most of the time isolated and only high floods make them connected to the river. On the other hand, some oxbows become connected at lower floods or even stay fully connected throughout the year thanks to their low connection thresholds. The rate of in- and outflow depends also on the sizes of the connecting morphological structure. If it is a narrow channel then only limited in- and outflows take place while in case of a wide trench, even slight increase of water level above the threshold may result the flow of huge amounts of waters.

In its isolation phase, the oxbow becomes a shallow lake where ecological processes develop as described in section 2.2.1. The trophic level of the lake is basically influenced by the quality of river water entered the lake during the flood preceding the actual isolation phase. Inflow of nutrient rich water that is followed by a long isolation period may result in sever planktonic eutrophication especially if water plants are absent. On the other hand inflow of nutrient poor water sets the lake to a lower trophic level.

Occurrence of water plants is highly influenced by fluctuation of the water level, which is a typical phenomenon in oxbow lakes. Fluctuation can impose two sorts of stresses on water plants: stranding and submergence. Brock *et al.* [1987] observed severe mortality in the water plant stands of a Rhine riparian oxbow after that it was exposed to sudden submergence caused by high floods. The primary physiological stress of submergence is light extinction. In addition, emergent water plants are also stressed by the obstruction of *stomatal* oxygen uptake from the atmosphere. Seedlings are much more sensitive to submergence stress than adult plants, due to their limited adaptation ability. Stranding of water plants by decreasing water levels causes desiccation stress, which is also detrimental especially for the seedlings.

Water level increase triggers *morphological adaptations*, namely certain water plants elongate their leaf stalks in order to allow leaf-blades to reach the surface [Brock *et al.*, 1987]. This process is carried out by spending the biomass reserves of the root tubers. Thus, elongation might significantly weaken submerged plants especially if they have limited tuber reserves. That is why all *Nymphoides peltata* of the Rhine oxbow were uprooted as a result of deep submergence; *Nuphar lutea* and *Nymphaea alba* on the other hand suffered less damage due to their bigger tuber reserves [Brock *et al.*, 1987]. *Nymphoides peltata* however, shows a better *life history adaptation* ability. It has a high turnover rate and it is able to colonise quickly a site by means of vegetative *stolons*, furthermore its seedlings can withstand exposure to a certain extent [Brock *et al.*, 1987].

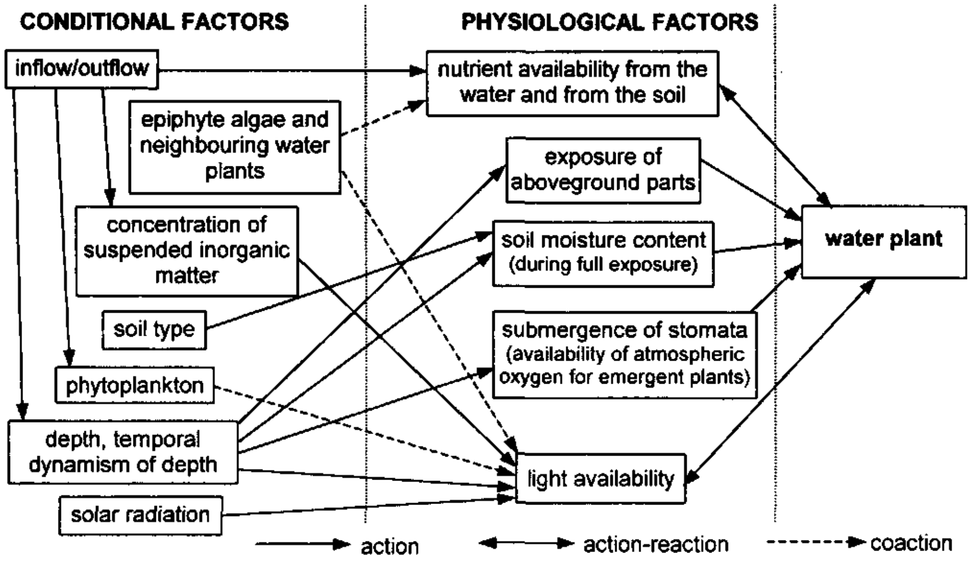

Figure 2.5 Influence chain of water plants in floodplain oxbow lakes

Slow water level increase and decrease on the other hand, allow sufficient time for in situ processes along the moving littoral [Junk *et al.*, 1989]. Accordingly, annual water plants are able to germinate and grow in the littoral zone thus maintaining a moving vegetated stripe along the inshore edge of the water. Also the submerged water plants suffer less since they have time to follow the rising water level without exhausting their resources. Primary production along the moving littoral is supported by intensive release of nutrients thanks to the accelerated decomposition of organic material on areas periodically changing between terrestrial and aquatic phases [Wood, 1951].

Fast water level fluctuation with high amplitude may lead to planktonic eutrophication due to the destruction of water plant stands. Such planktonic eutrophication proceeds much faster than those ones induced by epiphyte algae or zooplankton overgrazing (see section 2.2.1). Fast fluctuation of the Danube for example causes that the side arms of the riparian Gemenc floodplain are subjected to planktonic eutrophication [Csányi *et al.*, 1992], while the oxbows, being less exposed to the river, are in the state of benthonic eutrophication.

Terrestrial primary production on floodplains

Terrestrial vegetation of floodplains is highly dependent on the inundation conditions. This dependence is well illustrated by Andrásfalvy [1973] who stated that in natural floodplains '*the composition of vegetation indicates the elevation of the groundwater table and the durations and frequencies of inundations, almost with the accuracy of a "measuring device"*'.

Inundation has both stimulatory and stress effects on the flora. Stimulatory effects are the supply of water and nutrients needed for transpiration and growth.

Inundation imposes three types of physiological stress on plants (see also Figure 2.6):

1. Anaerobic conditions develop in the root zone as a consequence of significantly decreased gas diffusion in the saturated soil [Blom & Voesenek, 1996]. Aerobic root respiration stops, resulting decreased root growth, decreased transpiration and

decreased translocation of substances within the plant [Gill, 1970]. In addition, accumulation of toxic products takes place due to anaerobic metabolism of the plant and bacteria [Gill, 1970; Blom & Voesenek, 1996].

2. Interference with stomatal function: submergence of stomata inhibits oxygen and carbon dioxide exchange between the plant and the atmosphere. Furthermore, it also hampers the removal of toxic products of anaerobic respiration.

3. Light extinction.

This implies that the overall stress of inundation increases as mere soil saturation progresses first to partial inundation and then to complete inundation [Gill, 1970]. Obviously the duration of the different inundation stresses matters a lot. The longer the inundation the greater the physiological damage. In temperate regions however, only growing season floods impose stresses. Dormant season inundation has limited stress effect owing to the minimal oxygen demands of roots and microorganisms [Gill, 1970]. Above inundation duration and depth, the duration of flood-free periods matters also a lot because these are the periods available for the plant to recover from the injuries.

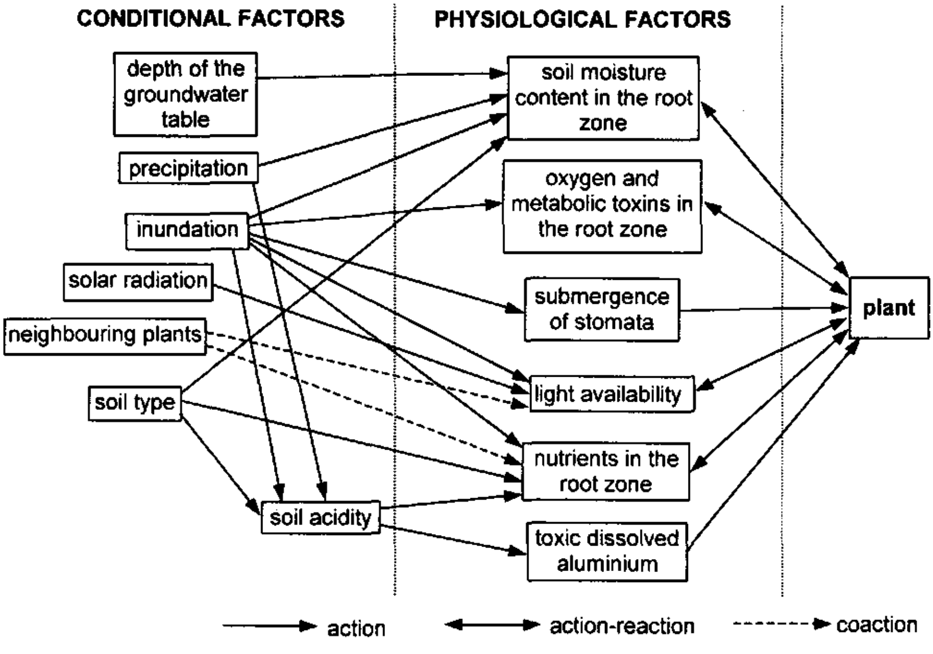

Figure 2.6 Influence chain of terrestrial plants on floodplains [after Runhaar, 1991]

The high resistance of several plants against inundation is explained by their special adaptation strategies. Inundation immediately triggers short-term physiological adaptations at most plants. The lack of oxygen forces the plant to replace aerobic respiration with anaerobic, ethanolic fermentation [Blom & Voesenek, 1996], even though it results ethanol and acetaldehyde, which are toxic for the plant [Kozlowsky, 1984, Gill 1970]. Plants with high photosynthetic rate are better adapted to light extinction, while stomatal inhibition are tolerated by those plants which are able to photosynthesise at low CO_2 level too [Blom & Voesenek, 1996].

Long-term morphological adaptation is performed by several species through developing adventitious roots on their flooded stems. These roots grow in the well-oxygenated upper layers of the water column, and they take over the oxygen and nutrient uptake role from the real roots under hypoxia [Kozlowski, 1984; Gill, 1970; Blom & Voesenek, 1996]. Many species develop a network of aerated tissue (aerenchyma) enabling the ventilation of oxygen from the unflooded leaves down to the inundated roots, and of carbon-dioxide and toxic substances on the way back (*anatomical adaptation*) [Blom & Voesenek, 1996].

Annual and biennial herbaceous species exhibit life history adaptation combined with fast turnover rates [Blom & Voesenek, 1996]. For example, *Chenopodium rubrum* completes its life cycle very quickly, during the short exposure periods, and produces seeds that will survive the next flood; the biennial *Rumex palustris* on the other hand survives flooding in a vegetative state and postpone flowering and seed production to the next year [Blom & Voesenek, 1996].

The wide scale of flood sensitivities and adaptation abilities make large differences in flooding tolerance of plant species. Also the age of plants matters a lot. In general seedlings are much less tolerant to flooding than adult plants. Depending on the extent of inundation stress, plants can be paused in growth, damaged or at worst killed. On ecosystem scale, the flooding tolerance of a species is determined not just by its chance of survival but also by the extent of damage and growth reduction, since the higher the reduction and damage it suffers, the more restricted its competitive ability against concurrent species.

Flooding stress keeps the flora of the ATTZ in a dynamic equilibrium [Junk *et al.*, 1989] by periodically shifting back the succession. The lower the terrain elevation the lower the level of this succession range. For example only pioneer species can grow at the lowest levels of the ATTZ during the short terrestrial periods because floods quickly 'reset' the terrain and the succession starts again. Succession can reach its climax stage (the hardwood forest) only on the highest grounds of the floodplain. The duration of the succession interval is influenced by the length of terrestrial periods. Exceptionally long flood-free periods promote the succession to reach higher levels so that for example bushes or even trees can establish on low-lying areas. Life cycle is an important factor too. Occurrence of annual plants is determined by annual flood regimes while bush and tree communities are influenced by hydrological events on a long time scale [Junk *et al.*, 1989].

Thus, the combined effects of timing, duration and depth of floods and the duration of flood-free periods both on annual and multi-annual time scales determine the terrestrial plant community structure of the ATTZ.

The fact that inundation conditions vary with elevation makes a rather characteristic vertical *zonation* of vegetation in natural floodplains. The upper limit of each zone is determined by the competitive ability of co-occurring species, and the lower limits by their flooding resistance [Blom & Voesenek, 1996]. Accordingly, the lowest zone of the ATTZ is grown over by pioneer species during the short terrestrial phases. The next zone above is characterised by willow bushes followed by willow trees or reedlands on higher levels. The zone above the willows is characterised by poplars while oak-ash-elm forests occupy the highest grounds of the floodplain. Seedlings of species from higher zones may temporarily settle deep in the lower zones during long flood free periods, however they soon get destroyed by the next significant flood.

Morphologically controlled successions on floodplains

In a short time scale, dynamic equilibrium characterises the vegetation structure as floods periodically shift back the succession. In a longer time scale however, the ongoing morphological processes and long-term changes in the hydrological regime trigger lasting changes in the vegetation structure. This long-term succession is thus controlled not just by autogenic successional processes like competition, vegetation dynamics, eutrophication and organic matter deposition, but also by allogenic impacts such as the morphological succession and changes of water level within the historical time scale [Amoros *et al.*, 1987].

Let's follow the course of such long-term succession at an arbitrary location in a river-floodplain system. The starting state is the open river channel. The location is now within the river channel so the ecosystem is characterised by few lotic water plants with *rheophilic* fauna. Now, the morphological succession may take two different courses: the river reach gets cut-off and becomes an oxbow lake, or the meandering process goes on and point bar starts to be built up at the subjected location. In the first case the lentic aquatic ecosystem of the oxbow is gradually replaced by pioneer terrestrial vegetation on mudflats followed by *Carex* and reed species and finally mixed rough herbage establishes as clay sedimentation gradually fills the channel bed [Schoor, 1992]. Succession on point bars takes a different course due to the different, sandy type of soil. Accordingly, pioneer vegetation and willow bushes preferring sandy soil characterise the start of the terrestrial succession, followed by willow forests and by mixed willow and poplar forests [Schoor, 1992]. In both cases natural levees of silt can be built up on the top of the sedimentation layers. Such places are usually the highest grounds of the floodplain where hard wood forests develop. It can thus be concluded that ecological succession reaches its climax state at those locations where the morphological succession results a natural levee.

If the meandering river passes through the location, it resets both the morphological and the ecological successions. This means that *two types of dynamic equilibrium* characterise the ecosystem of natural river-floodplain systems:

1. On short time scale the flood regime of the rivers maintains a dynamic equilibrium
2. On long time scale the meandering river maintains a dynamic equilibrium by periodically resetting the morphological succession.

Faunal production on floodplains

Among animal species living on floodplains, obviously aquatic species (especially fish) are influenced the most by the pulsing regime of the river.

The fish of river-floodplain systems can be classified into two distinct groups: rheophilic and *stagnophilic* species. Rheophilic fish live exclusively in the lotic channel system. They spawn in the littoral of the river channel, which also provides shelter for the juvenile fish [Schiemer & Zalewski, 1992]. Stagnophilic fish prefer lentic water bodies where they spawn, grow, feed and hide. They use the river channel system only as a migration route. In the temperate region two major abiotic factors trigger the spawning of stagnophilic fish: temperature and flooding. Each fish species has its well-defined range of temperature for spawning, however it does not necessarily means that spawning immediately starts when water temperature reaches that range. In aquatic systems exposed to regular floodings, the optimal temperature triggers only the maturation, while the spawning itself is triggered by the arrival of the flood. Rising water level stimulates mature fish to migrate towards their spawning grounds, which are the shallow inundated parts of the ATTZ. Welcomme [1985] concluded that in the majority of spawning species breeding is so timed that if floods are delayed or inadequate to trigger migration reproduction may fail in that year.

The advantage of floods on reproduction is explained as follows:

1. High primary production in the moving littoral triggers high secondary production resulting in optimal food supply for juvenile as well as for adult fish [Bayley, 1991]. Inundation immediately adds numerous fish food organisms to the water, such as insects, earthworms, and other small terrestrial animals [Keith, 1975]. Reimer [1991] describes a mass migration of cyprinide fish into flooded areas of an Austrian floodplain with the primary purpose of feeding on terrestrial food items.
2. Inundated vegetation means excellent spawning places for *phytophil* and *phytolithophil* fish and they provide shelter for the juvenile fish against predation. The eggs stay in the well-aerated water column as they are stuck onto the leaves of submerged plants.
3. Flood creates an area of water that is initially sparsely populated with fish life, a condition that stimulates the natural reproductive and growth process of the resident fishes in an attempt to fill the 'void' [Keith, 1975].

The above described 'flood pulse advantage' [Bayley, 1991] of aquatic systems exposed to floods over stagnant systems is indicated on Figure 2.7.

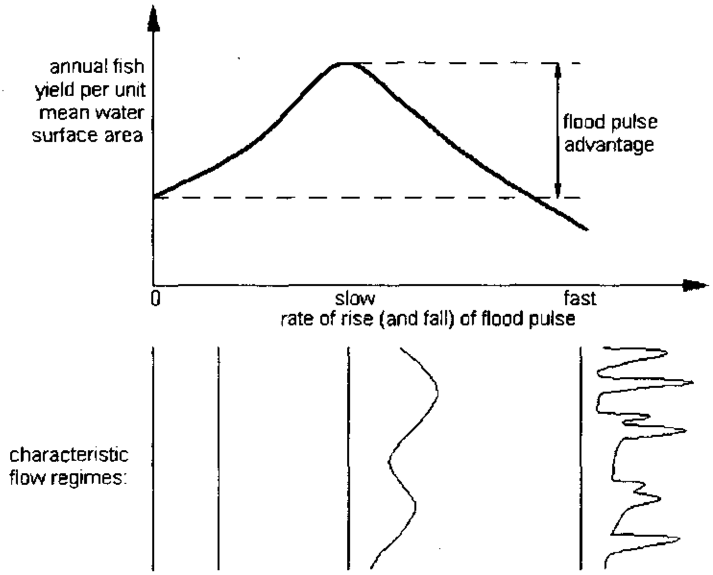

Figure 2.7 Effect of rate of rise and fall of flood pulse on fish population [after Bayley, 1991]

Figure 2.7 also indicates that fast, unpredictable fluctuation is detrimental for the fish population. Fish have got limited time for spawning and even if spawning could take place the sudden decrease of water level could result in the stranding and death of the extremely vulnerable immobile eggs and larva's especially in case of those species, like the carp and the pike, which like to spawn on very shallow inundated grasslands [Pintér, 1992; Inskip, 1982; Edwards &

Twomey, 1982]. Furthermore, sudden water level decrease may also trap fish into small ponds where they would easily die due to predation, lack of food and oxygen, or these ponds can even dry up resulting in the total annihilation of its fish stock [Welcomme, 1979].

Besides the speed of flood pulses, their heights are also of great influence on the fish population. Welcomme [1979] found that mortality increases with increasing fish density (which is, in turn, caused by decreasing water levels) on one hand, on the other hand high rates of growth and recruitment are resulted by high floods of long duration since they make accessible large areas of the very productive ATTZ for fish. Obviously, high floods provide more spawning and hiding places, and result in a bigger 'void' to be filled.

Thus, strong year-classes of fish tend to result from *gradually increasing water levels* that are accompanied by a *high amplitude flood* of long duration [Welcomme, 1979].

Keith [1975] presents evidences for the aforementioned dependence of fish on flood regime. He investigated the population dynamics of the largemouth bass (*Micropterus salmoides*) in the Bull Shoals Reservoir, Arkansas (USA). The flat bank of the reservoir (its floodplain) was exposed to regular floodings, which are of the same effects on the ecosystem as that of floodings of river floodplains (see principles of the flood pulse concept).

The observation results can be seen on figures 2.8 and 2.9. The strong year-classes of 1957, 1961, 1968 and 1973, when the water level risen above the power pool and inundated the floodplain, and the weak year classes of 1958, 1964, 1966 and 1969, when springtime water levels stayed below the power pool, prove the high positive correlation between fish biomass production and spring time flood amplitude. It is also noted that even though the water reached its highest level in 1957, the best bass spawns occurred in 1973. The reason is that the 1973 flood was just slightly lower than that of 1957, on the other hand its duration during the spawning and nursery period was significantly longer thanks to the slow rate of rise of the water level. The flood in 1957 was a fast rising one giving limited time for bass to spawn and to hatch during the spawning and nursery period.

It is important to notice that the timing of floods is also essential. Only those floods effect the reproduction, which occur during the spawning and nursery period.

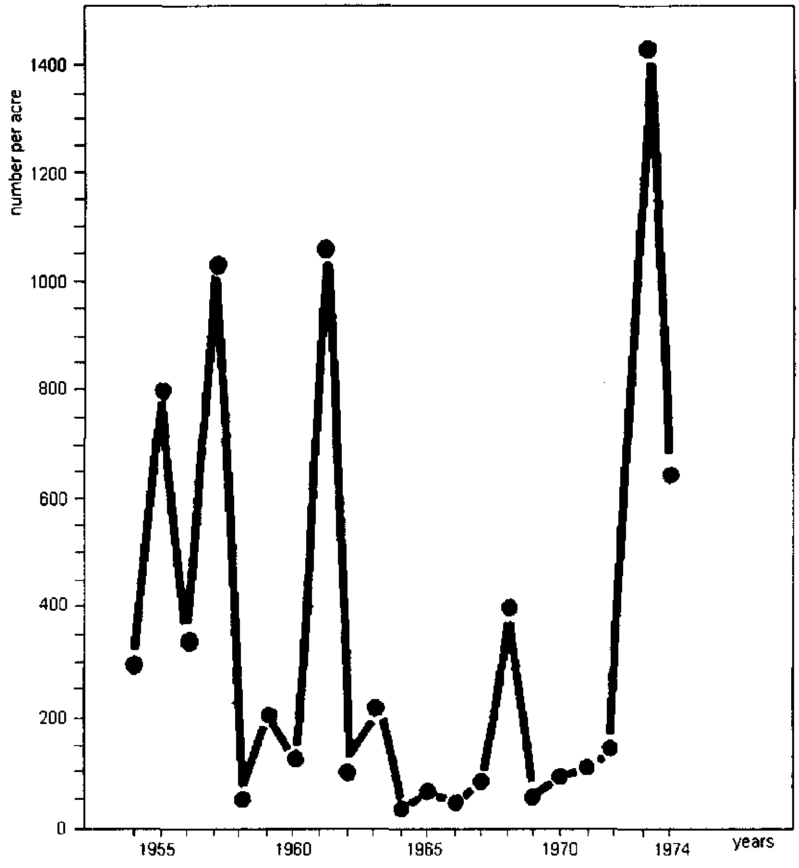

Figure 2.8 Numbers of 0-age bass in the Bull Shoals reservoir [Keith, 1975]

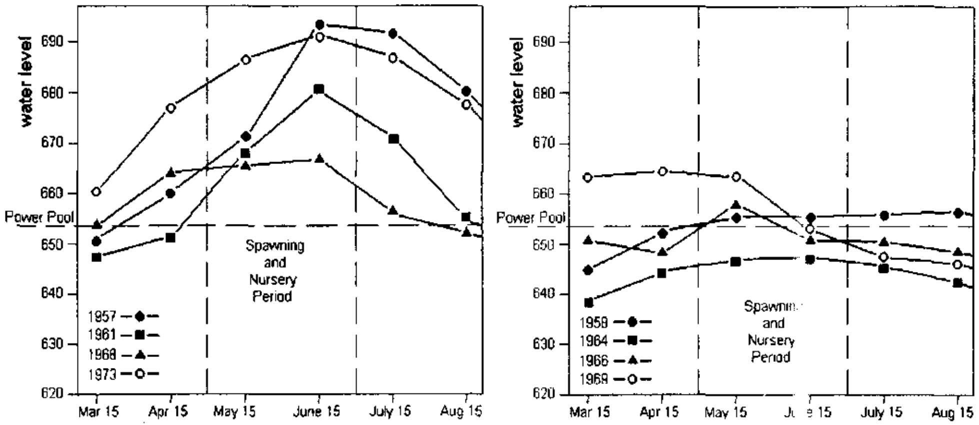

Figure 2.9 Water levels in the Bull Shoals reservoir during the spawning and nursery period [Keith, 1975]

3. DECISION MAKING IN RIVER-FLOODPLAIN DEVELOPMENT

The purpose of this chapter is to describe the process of decision-making in water resources development in general, and in river-floodplain development in particular. Case studies are also introduced with the aim to illustrate the decision making process on real-world examples. Decision support techniques applied in the case studies are also investigated, however no mathematical details of these techniques are given in this chapter.

3.1 Process of decision making in water resources development

River-floodplain systems belong to the realm of *water resources systems*. Bogardi [1994] defines, '*water resources*' as '*the occurrence of water in space and time with a certain (feasible) potential to be put into human, industrial, agricultural etc. use and for sustaining the environmental balance*'. Water resources imply the existence of a given space, the *project area*, within the available water resources and water demands should match [Bogardi, 1994]. A *water resources system* thus consists of interrelated *elements* of the project area that determine and control water resources. Elements are meant in a broad sense ranging from real physical structures through operation policies to administrative / legislative conditions. *Water resources development* means a set of co-ordinated actions aiming to modify the water resources system for the benefit of goals emerging from the socio-economic environment.

Water resources development is executed within the framework of the *decision process*. Decision process is started and terminated by the *Decision Making Group* (DMG), the authority who formulates the problem by aggregating the objectives, incentives, guidelines and constraints, coming from the socio-economic environment (Figure 3.1). It is also the DMG who makes the final decision about the project. To emphasise the overwhelming power the DMG has on the decision process, Monarchi *et al.* [1973] even placed this body into Orwellian dimensions by referring to it as the 'Big Brother' [Orwell, 1947]. Efficient decision-making does need such power indeed, nevertheless democratic principles require that all interested elements of the society have to have the right for being represented in the DMG. The ideal 'Big Brother' in the hypothetical case study of Monarchi *et al.* [1973] for example consisted of representatives of the local, state and federal governments as well as that of the interested enterprises. For more details about the principles and practice of public participation in water resources development the reader is referred to Gayer [2000].

Besides public participation it would also be desirable if members of the DMG were experts on the scientific and technical aspects of the actual water resources development project, although it is rarely the case.

The DMG is thus a composite body with members having conflicting interests. This implies that the scope of decision-making theory must also account for the mechanism of negotiation and debating and also for that of changing human attitudes, and perceptions, which all occur within the DMG when it makes decisions about preferences and constraints, and when it selects a solution for implementation. Mathematical investigation of this '*macro model*' [Bogardi & Sutanto, 1994] is a formidable task, even though it cannot be fitted into the scope of this study.

The DMG charges the *Planning Group* (PG) to identify solution(s) for the specified problem. PG should consist of professionals from all relevant fields having knowledge in planning and operations research, as well as experience in communicating with the DMG. This latter refers to skills in helping the DMG to formulate specific *criteria*[1] and *constraints* on the basis of the given problem, and to the ability of presenting the solutions to the DMG in an understandable, yet scientifically accurate manner. In case of multiple criteria, the DMG asks the PG to conduct the search towards solutions, which meet its *preferences*. In such a case the PG must have the ability to aid efficiently the DMG in *articulating* [Goicoechea *et al.*, 1982] its preferences for the applied search method.

These all implies that an *interface* (Figure 3.1) is needed between the DMG and the PG, which promotes the efficient communication and cooperation between these two groups. This interface usually takes the form of regular reporting of the PG and regular discussions between the PG and the DMG. The interface is also a forum for concerned citizens and for organisations (not being represented in the DMG) for expressing their concerns. A well functioning interface helps to derive solutions, which satisfy the needs of the DMG and the public on the one hand, and the technical / environmental constraints and preferences, the DMG and the public are not aware of (due to the lack of expertise) on the other hand.

After that the criteria and the constraint levels have been formulated and the preferences have been articulated, the PG takes over the problem and formulates it in a formal (usually mathematical) way. The general mathematical formulation of a multi-objective (multi-criteria) problem is given by Tecle & Duckstein [1994]:

$$\begin{aligned} &\text{'satisfice'}\quad \bar{z}(\bar{x}) = \left[z_1(\bar{x}), z_2(\bar{x}), \ldots z_p(\bar{x})\right] \\ &\text{subject to} \\ &\qquad g_i(\bar{x}) \le 0 \quad i = 1,2,\ldots m \end{aligned} \tag{3.1}$$

Where:

$\bar{x}\ (x_1, x_2 \ldots x_n)$ solution vector in the n-dimensional *decision space*

$x_1, x_2 \ldots x_n$ *decision variables*

$\bar{z}\ (\bar{x})$ vector of criteria functions in the p-dimensional *criteria space*

$g_1(\bar{x}), g_2(\bar{x}) \ldots g_m(\bar{x})$ constraint functions

[1] The term 'criterion' is defined in this study by adopting the definition of Tecle & Duckstein [1994]. Accordingly, a criterion '*should provide a means for evaluating the levels of an objective; as such it is defined as a measurable aspect of judgement by which alternative solutions of the given problem can be characterised*'.

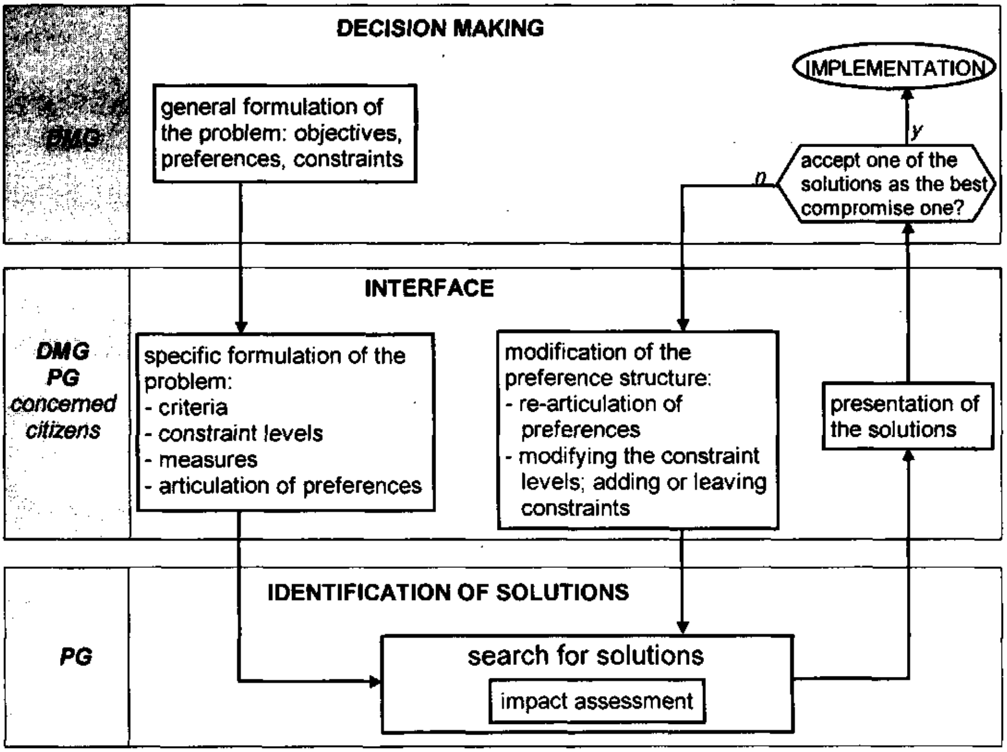

Figure 3.1 Decision process in water resources development

A special type of decision problems is when only a single objective (with a single criterion function) has been identified. In this case the task of the PG becomes optimisation, aiming to identify the *optimal solution*. Mathematical optimisation techniques are applied at this stage. In case of multiple criteria the search goes for the *best compromise* (or *best satisficing*) solution. Best compromise solution is the 'best' element of the *non-dominated* set of solutions [Tecle & Duckstein, 1994], which is identified on the basis of criteria achievements and articulated preferences of the DMG.

Definition of non-dominated solutions is given by Goicoechea *et al.* [1982]:

$$\begin{aligned} S = \{\, x : x \in X,\ & \text{ there exist no other } x' \in X \text{ such that} \\ & z_q(x') > z_q(x) \quad \text{for some } q \in \{1, 2, \ldots, p\} \\ & \text{and } z_k(x') \geq z_k(x) \quad \text{for all } k \neq q \,\} \end{aligned} \tag{3.2}$$

Where:

X *feasible region*[2] of the n-dimensional decision space

S set of non-dominated solutions within the feasible region

[2] Feasible region is the set of points in the decision space, which satisfy the given constraints.

It is possible that each feasible point in the decision space is non-dominated. To illustrate it with a simple example, let's consider a nature reserve area where only three types of vegetation cover may occur: forest, grassland and marshland. The criteria of forest, grassland and marshland areas constitute a 3-D criteria space where each feasible point is non-dominated.

Generally speaking, the search for the best compromise solution is implemented in two steps: identification (full or partial) of the non-dominated set, and selection of the best compromise solution. These steps can be aided by *mathematical multi-criteria decision support (MCDS)* techniques.

Mathematical search tools require formulating alternative solutions as certain points in a decision space. These points are associated with the corresponding points in the criteria space with the help of criteria functions. Complexity of measures and criteria however often prevents the formulation of such spaces, or even if they can be formulated their dimensionality limits the application of search techniques. In such cases *expert judgement* takes over the role of mathematical search tools in searching for *promising* (quasi non-dominated) solutions. 'Trial-and-error' search is often applied in these cases. After that a set of promising solution has been generated the (quasi) best compromise solution can be selected out with the help of MCDS techniques.

Criteria functions are in many cases complex sets of functions and models, which suggest to use the more general term of '*impact assessment*' instead. Impact assessment is embedded into the search process (Figure 3.1). Modelling is an essential part of impact assessment in water resources development. Modelling the spatial and temporal distribution of water in the system plays a central role. Depending on the type and complexity of the problem, the applied model may be a rainfall-runoff model, groundwater model, open-channel hydrodynamic model, etc., or just a set of simple continuity equations. Outputs of these *hydrological models* are inputs for the *functional models*, which derive additional information about the impacts of the project. Parameters indicating water quality, agricultural and energy production, navigation conditions, ecological conditions etc. are calculated by functional models. These outputs, along with results of subsequent cost-benefit analysis, provide data for deriving achievements for the criteria specified by the DMG and the PG (Figure 3.2).

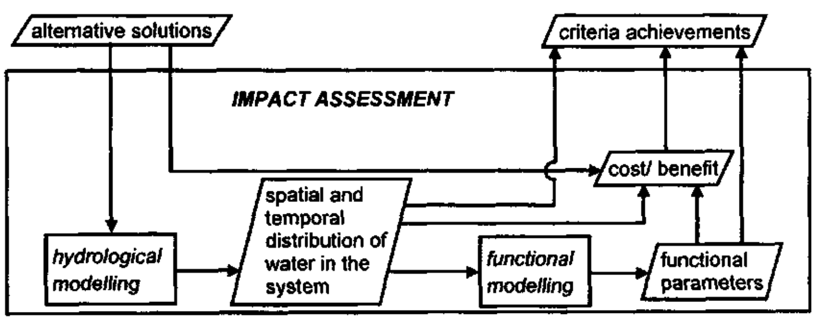

Figure 3.2 Impact assessment in water resources development

Functional modelling often precedes the search procedure by deriving 'a priori' the functional relationship between water resources and system performance. In such cases the related criteria correspond directly to water resources variables. For example, the objective of maximum agricultural production is often interpreted in terms of water quantity demands, which are the locations of maxima of yield functions derived by crop models.

Impact assessment forms an integrated, yet distinct part of the search procedure in case of 'trial-and-error' search, and in case of certain mathematical search techniques (e.g. Genetic Algorithms). In these cases, the search proceeds in an iterative way, during which the criteria achievements of the actual solution(s) direct the search towards optimal, non-dominated or promising solutions. This is however not the case with techniques like linear and dynamic programming where mathematical formulas implicitly account for the search, objectives, constraints and also for the impact assessment.

The identified solutions have to be presented to the DMG along with criteria achievements and ranks/utilities derived by MCDS techniques (Figure 3.1). In case if the DMG rejects each solution, then it charges the PG to identify new solutions on the basis of modified preferences, criteria and constraints. This *iterative* process goes on until the DMG is satisfied and accepts one of the solutions as the best compromise solution for the problem (Figure 3.1). This approach is called '*progressive articulation of preferences*' [Goicoechea *et al.*, 1982], because the DMG has the opportunity to find gradually its real preferences by learning more and more about the problem.

3.2 Examples of decision support in river-floodplain development

3.2.1 Case studies without defined decision spaces

Three river-floodplain development case studies are introduced each of which deals with generation and evaluation of a finite set of promising solutions.

River-floodplain development in Hungary

Marchand [1993] presents a study dealing with the ecological revitalisation of the Gemenc floodplain in Hungary. The identified objectives are restoration of lotic habitats, raising the groundwater levels, reduction of eutrophication and creating a diverse vegetation structure. Several promising restoration alternatives were formulated by the PG using expert judgements. These alternatives are based on measures like reopening side channels, creating new side channels and diverting water from a tributary into the floodplain lakes. The impacts of the alternatives were assessed by a set of models (1-D hydrodynamic, channel morphological, water quality and vegetation models), cost benefit analysis and ordinal estimations of impact on recreation and fisheries. The final result was a *pay-off matrix* showing the criteria achievements (*cardinal* or *ordinal*) of the promising alternatives. This matrix is to be presented to the DMG.

This study illustrates how a proper interface between the PG and the DMG should look like. This interface has two basic components:

1. Reporting on the major parts of the PG's work.
2. Regular meetings between the PG, DMG and the stakeholders, where they discuss the results written down in the reports and agree upon the further course of the project.

Creek-floodplain development in urban environment

Goicoechea *et al.* [1982] presents a creek floodplain development problem in an urban environment. The main objective was to improve flood protection as floods of the creek endangered the rapidly growing riparian districts of the city of Dallas. The City Council (the DMG) together with a consulting firm (the PG) and with the South-East Dallas Neighbourhood Club (concerned citizens) formed the interface for this decision problem and formulated the set of criteria. Ordinal and cardinal criteria have been identified expressing level of flood protection, neighbourhood improvement, number of family relocations, investment and maintenance costs, and management problems. The consulting firm than formulated eight alternative plans ranging from 'doing nothing', through creating open parkways and recreation areas, to building a bypass conduit. Impact assessment of the alternatives resulted in the pay-off matrix. Unlike in the previous case study, the decision process went further by applying the *Weighted Average* (WA) [Goicoechea *et al.*, 1982] MCDS technique to derive the relative worth of each alternative. The alternative with the highest worth was then offered to the DMG as the best compromise solution.

WA is a utility-based technique where the overall utility (the worth) of an alternative is calculated as the weighted sum of its criteria achievements. The preference of the DMG is thus articulated by assigning *weight* to each criterion. Before calculating their weighted sum, the achievements have to be scaled in order to transform ordinal achievements to numbers and also to make achievements of different criteria commensurate. In the urban floodplain development example, achievements of each criterion have been scaled down to the range of 1 to 8, where 1 stood for the worst while 8 stood for the best achievement. Scales different from this may also be applied. In fact scaling is also a way of articulating the DMG's preference structure.

River-floodplain development in Austria

Nachtnebel [1994] presented a project dealing with the development of the Austrian Danube reach downstream of Vienna. The identified objectives were, increasing hydropower generation, improvement of navigation conditions, preservation of floodplain ecosystems, improvement of recreation conditions and preservation of drinking water resources. These objectives were broken down to several specific criteria such as annual power output, duration of restricted navigation, area of floodplain forests etc.. The objectives of hydropower generation and navigation improvement implied that the solutions have to be based on barrage construction. Supplementary measures like armouring the riverbed were also identified. Because of the complexity of these measures, identification of a decision space was not possible. Thus, it was the PG's task to identify a finite set of promising hydropower alternatives. The impacts of the identified alternatives were assessed by a set of hydrodynamic, groundwater and ecological models and the achievements were aggregated into a pay-off matrix. Selection of the best compromise solution was carried out with the help of the *ELECTRE* [Benayoun *et al.*, 1966; Roy & Bertier, 1971] MCDS technique.

ELECTRE *ranks* (partially or completely) discrete solutions on the basis of criteria achievements and preferences articulated in terms of criteria weights. Similar to the WA technique ELECTRE is also able to handle criteria on any kind of cardinal / ordinal scales. However being a non-utility but outranking based technique ELECTRE is much less constrained by assumptions than WA.

3.2.2 Case studies with defined decision spaces

River-floodplain development in the Netherlands

Nieuwkamer [1995] worked out a computer based *Decision Support System* (DSS) for the development of the Rhine river-system in the Netherlands. The large spatial scale of the study justified the adaptation of a simplified representation of the river-floodplain system (Figure 3.3).

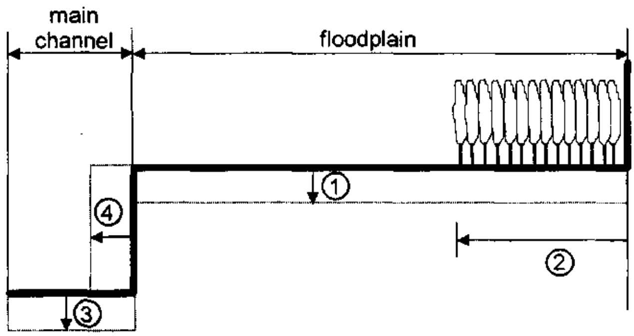

Figure 3.3 Nieuwkamer's [1995] representation of river-floodplain system

Figure 3.3 also shows the decision variables defined for the problem:

1. Depth of excavation on the floodplain
2. Width of floodplain forest (that can be controlled by means of vegetation management)
3. Depth of dredging in the main channel
4. Width of the main channel that can be adjusted by lengthening or shortening the groins

Each measure may vary along the length of the river, which means that the decision variables are function of location along the river course. The user can thus create river management alternatives by defining these functions with the help of the appropriate menu of the DSS software (Table 3.1).

Once an alternative is defined, its impact is assessed by a 1-D river-flow model and by functional models. The resulted criteria achievements, indicating flood control, nature, landscape, recreation and navigation conditions, along with investment and maintenance cost estimations are than aggregated into a pay-off matrix which is to be presented to the DMG.

In spite that the decision and criteria spaces had been identified, Nieuwkamer [1995] did not employ any mathematical tool to support the search for the best compromise solution, probably because of dimensionality reasons. The integrated and user friendly DSS software however facilitates the quick and easy generation and evaluation of alternatives, thus supporting the iterative way of solution seeking, during which the DMG is enabled to get acquainted with behaviour of the system and to find the best compromise solution (progressive articulation of preferences).

Table 3.1 Example of a river management solution as suggested by Nieuwkamer [1995]

Number of decision variable (see the list above)	Branch of the Rhine	Begin coordinate (km)	End coordinate (km)	Value
4.	Waal	0	86	- 40 m
2.	Ijssel	0	10	+ 25 %
2.	Ijssel	25	35	+ 30 %
1.	Ijssel	0	10	- 0.75 m
1.	Ijssel	25	32	- 1.50 m

The final goal of the works of Nieuwkamer [1995] and Marchand [1993] was to derive pay-off matrices with promising solutions. Selection of the best compromise solution is left completely to the DMG. Nevertheless, MCDS techniques like WA or ELECTRE would be applicable in both cases.

River-floodplain development in a hypothetical river basin

Monarchi *et al.* [1973] introduced a case study that deals with a pollution problem in a hypothetical river-floodplain system. The general objective was to reduce the wastewater load of the river at an acceptable price. Wastewater comes from two riparian municipalities and from a cannery factory. Six conflicting criteria have been identified, which are dissolved oxygen (DO) levels at three characteristic sections of the river (a nature reserve area on the floodplain and two riparian towns), percentage return on equity at the cannery and additions to tax rates at the municipalities due to improving wastewater treatment. Decision variables are the proportional reductions of waste loads (expressed in Biological Oxygen Demand (BOD)) at the three pollutant sources. Also a constraint is imposed on the problem, which is the minimum DO level at the downstream end of the considered river reach. The related objective and constraint functions were formulated by using simple mathematical models of decomposition of organic wastes in rivers, as well as equations expressing the relation between waste reduction and the costs of purification. To find a best compromise solution for this non-linear multi-criteria problem, Monarchi *et al.* [1973] applied the *SEMOPS* (SEquential Multi-Objective Problem Solving Method) technique developed by Monarchi [1972].

SEMOPS is conceived to facilitate progressive articulation of preferences. It is not restricted to assist a certain step of the decision process like WA and ELECTRE, but it rather works as an *algorithm*, which guides through the entire decision making process (see Figure 3.1) in an iterative-interactive way. In SEMOPS each objective function is associated with one or two *aspiration levels* that are levels of criteria achievements the DMG desires to exceed, stay below, stay within or stay outside. Thus, aspiration levels express the preference structure of the DMG. Based on the aspiration levels, objectives and constraints, a certain number of mathematical optimisation problems are constructed at each iteration cycle. By solving these optimisation problems with an appropriate mathematical technique, the DMG gains information concerning the set of feasible solutions, and learns about the interrelationships (trade-offs) between the objectives [Monarchi *et al.*, 1973]. On the basis of the lessons learned, the DMG modifies its preference structure by adjusting the aspiration levels, and goes for the next iteration cycle. The iteration stops when the DMG accepts a certain solution as the best compromise solution for the problem.[3]

In the hypothetical case study, presented by Monarchi *et al.* [1973] five rounds of iteration were needed to reach a solution the DMG ('Big Brother') would be satisfied with.

[3] Detailed description of SEMOPS is given in Chapter 6.

4. INTRODUCTION OF THE CASE STUDY AREA

One of the principal factor of establishment and development of human civilisation on Earth was the utilisation of river-floodplain systems. It was not by chance that the very first civilisations were formed along big rivers in Egypt, Mesopotamia, India and China. Man found advantageous living conditions in river-floodplain systems like nowhere else on Earth. Extremely high agricultural production with multiple annual harvesting was achieved on the floodplains of the Nile, Euphrates and Indus thanks to the unrestricted amounts of water and nutrient provided by these rivers. Because of the excellent riverine traffic conditions, the river-system itself meant a natural frame on which stable and highly centralised states could be established.

Three main forms of river-floodplain management have been developed during the history of mankind: *passive*, *preventive* and *active* [Zsuffa sr., 1997, pers. comm.]. Passive management meant full adaptation to the regime of the river: utilising its positive effects while avoiding the negative effects of its extremities. Ancient riverine cultures in Egypt and Mesopotamia were essentially based on passive river management, since next to agricultural utilisation of inundations, people also tried to avoid damages of floods by settling on the high grounds outside the floodplain. Passive management however proved to be inadequate in those regions where the damages of floods surpassed their advantages. In such places preventive water management developed, aiming to prevent the damages of the river regime while utilising its advantages. The basic tool of preventive management was the flood control dike system. The ancient China was the first country where extensive dike systems were erected to defend lands against river floods. The irrigation of the so-defended lands was ensured by systems of artificial channels branching-off the rivers [Czaya, 1981].

In the temperate zone preventive river-floodplain management proved to be the only way to satisfy the food demand of the increasing population of riverine countries. Due to sufficient rainfall and to the freedom from inundation damages, production on flood-free areas proved to be much more efficient than in the floodplain. This necessitated the construction of flood control dike systems. In the Netherlands as early as in the 15^{th} Century the dike system was closed along the river Rhine [de Bruin *et al.*, 1987], while in other European countries dikes were built mostly in the 18^{th} and 19^{th} centuries.

Nevertheless early dikes were often ruptured by floods (especially by ice-jam generated floods) resulting in huge damages. Thus, besides the continuous strengthening of the dikes, people started to take steps towards preventing the formation of catastrophic floods. This led to river training works, in the course of which the big meanders where cut short, the side branches were closed and a uniform riverbed was created and fixed by means of stone structures like groins and bank protections. The primary objective was eliminating the fords and reefs in the riverbed, which hampered navigation and supported the formation of ice-jams. Straightening and unifying the river channel also enabled to defend larger areas by dikes.

River training also aimed to accelerate the run-off process in the river channel in order to prevent reef formation and also to prevent the superposition of flood waves, thus increasing the flood control safety [Zsuffa sr., 1999]. This aspect of river training indicates the influence of the active river management approach. Active river management aims both the full use of the river's potential and the maximum protection against its extremities, which are to be achieved by *controlling* its regime instead of accommodating to it, which is essentially done by passive and preventive management. In practice, full water regime control can be achieved on small rivers by means of reservoirs that were already used by ancient civilisations too. Such full control is however not possible on most of the big rivers since that would require enormous large reservoirs. The river Nile with the Aswan dam and reservoir is an exceptional example. At most big rivers control has been achieved locally, by means of barrages. The aim of a barrage is to rise the water level upstream in order to improve navigation conditions, to ensure gravitational irrigation water intake and/or to gain potential energy for hydropower production.

4.1 History of river-floodplain management along the Hungarian Danube

The river Danube, after leaving its alpine headwaters, deposits its coarse sediment and forms the braiding river system of the Szigetköz on the North-West part of Hungary {Figure 4.1). Further downstream the river becomes mountainous again as it breaks through the Visegrád Mountains upstream of Budapest. By leaving this mountainous reach, it enters the Hungarian Big Plain where after some braiding reaches upstream and downstream of Budapest it becomes meandering in a wide valley, which is bordered by low plateaus from both sides.

Figure 4.1 The Hungarian Danube reach

The wide floodplains of the Hungarian Danube reach were inhabited already in the middle age and an essentially passive floodplain management practice had been introduced, where human activities were fully adapted to the flood regime of the river. Extensive cultivation was practised by taking into account the optimal positions of plant species along the flooding gradient. Accordingly, the high natural levees and point bars were reserved for the valuable hardwood forests and orchards; on lower areas, pastures were used for grazing the cattle, while reed and bulrush harvesting took place on the wet, often-inundated marshy lowlands. The highest cores of the natural levees were occupied by permanent or temporal settlements [Andrásfalvy, 1973]. To reduce further the chance of flooding, people even erected small hills on these places and built their houses on the top of them. Intensive cultivation with arable lands was not possible on the floodplains due to inundation. The floodplain oxbow lakes and the river channels were used for fishery purposes.

It was soon realised that relatively small and local morphological modifications may result significantly higher gains from floods while their harms could be reduced. This led to the construction of *'fok'-systems* and to the introduction of the related *'fok'-management*, which meant the basis for life on the Danube riparian floodplains from the middle age until the last century. The basic components of such a system were small artificial channels (in Hungarian 'fok'-s), which cut through the natural levees on the riverbanks and connected the floodplain lakes and depressions with the river (Figure 4.2). The system of these *primary fok* channels were supplemented with *secondary foks* connecting the floodplain lakes and depressions to each other, thus forming an interconnected system, which could supply even quite remote areas with water [Andrásfalvy, 1973].

The functions of fok-systems were as follows:

1. Primary foks prevented sudden, destructive inundations by gradually filling the entire floodplain during rising floods.

2. These channel systems made it possible to convey the water back to the river after floods, thus preventing long inundation of vegetation which would have resulted in the death of fish, trees, bushes and grasses.

3. Fok-channels provided access for river-fish to the shallow, easily warming-up waters of the floodplain, which were optimal spawning and feeding places. After spawning the juvenile fish could move back to the river through these channels so that the very rich fish population of the river could be sustained. These very productive water bodies also supplied plankton, worms, insects and prey fish for fish living in the river.

4. Inundation supplied water and nutrients to the forests, orchards and pastures.

5. Fok-channels served as boating routes.

Thus, the often-mentioned legendary abundance in fish of Hungary in the middle ages (as it was reported by a French monk in 1308 and regarded comparable only with that of Norway) was not merely the gift of nature. It was the result of human intervention and co-operation with nature [Andrásfalvy, 1973].

Figure 4.2 Explanatory figure from the 18th Century about Danube riparian 'fok'-systems [Marsigli, 1726]

Fisheries benefited a lot from fok-systems not just because of the extremely rich fish stock but also because of the very efficient fishing method enabled by these systems. The method relied on the fact that fish, on one hand, tend to move to the floodplain with the rising flood for spawning and feeding, on the other hand the falling floods stimulate them to move back to the river. Accordingly, local people simply closed their ways in the fok-channels by special wooden grates and caught the fish accumulating in the front of these grates before they could return to the river [Andrásfalvy, 1973]. People also put a great emphasize on sustaining the large fish stock of the river-floodplain system. Therefore, the mesh size of the grates was set so that the juvenile fish could go through and reach the river. Special gates were installed onto the grate, which were kept open during the rising flood in order to let fish move into the floodplain for spawning [Andrásfalvy, 1973].

It can thus be concluded that fok-management was essentially a passive method since men fully adapted to the unrestricted flood regime of the river, however some aspects such as mitigating the destructive power of floods and preventing long stagnation of inundations indicate an implicit preventive nature.

As the population increased and people from other regions and even from other countries settled into the area, the pressure to replace fok-management with intensive agriculture increased. This resulted a gradual change to fully preventive river management. Already in the 18th Century, large areas of the floodplain were defended by dikes, although these dikes were usually ruptured by big floods resulting serious deterioration in life conditions. The new arable lands were frequently destroyed while the traditional fok-management could not be practised either, because the channels had been closed by the dikes [Andrásfalvy, 1973]. This transitional situation lasted for almost hundred years. Sufficient flood protection was achieved only at the turn of the 19th and 20th centuries when the huge meanders of the Danube were cut-short and a strong dike system was closed along the regulated river (Figure 4.3). The full regulation of the river channel has been completed in the sixties of the 20th Century.

In general, dikes were built close to the straightened river channel in order to gain as much area as possible. There was however a landlord having huge domains on the floodplain, who did not join the Water Management Association (the board financing and managing the works), so his lands were not defended by the dikes [PMMF *et al.*, 1993]. This is the reason why an about 5-6 km wide and 40 km long floodplain remained between the new dike and the left bank of the Danube which is now the *Gemenc floodplain* (see Figure 4.1 and Figure 4.3).

River training and dike construction marked the end of floodplain management, and people definitely moved out of the remaining floodplains. The abandoned floodplain soon became habitat for typical, rich alluvial ecosystems and today the Gemenc is one of the few valuable nature reserve areas along the Danube.

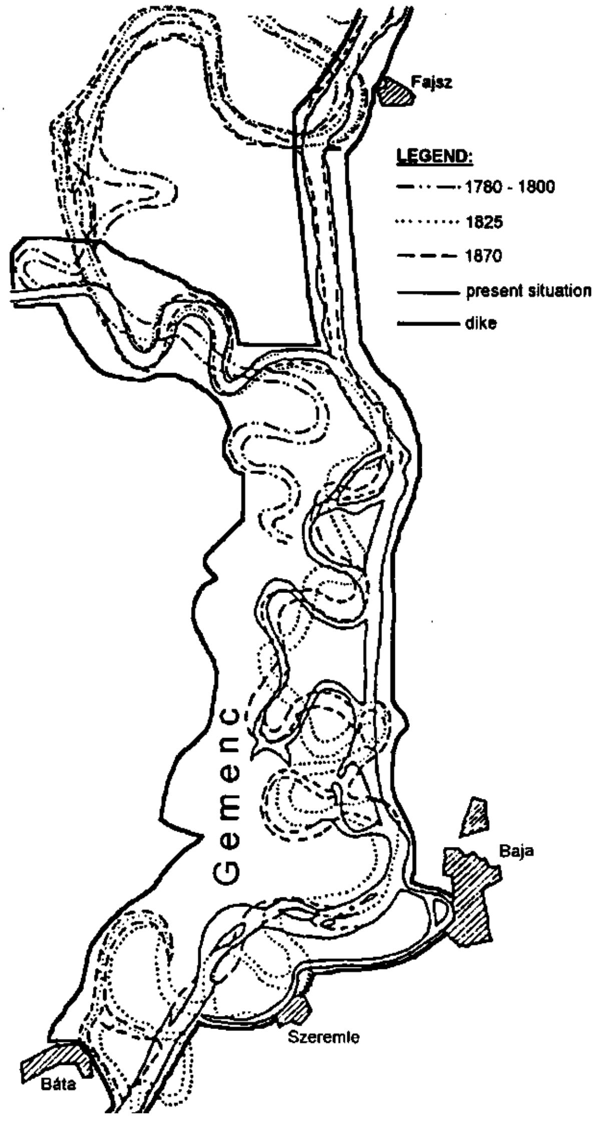

Figure 4.3 Historical changes in the course of the Danube in the southern part of Hungary due to meandering and river training (see also Figure 4.1)

4.2 Consequences of river regulation and flood protection measures

The importance of flood control and river training works can only be compared with that of the great geographical discoveries. In both cases huge unpopulated or scarcely populated territories became available for the intensive development of human civilisation. Countries like Hungary or the Netherlands practically would not exist if dikes had not defended their waste riverine floodplains, where most of their agricultural production now takes place.

Increasing the areas of cultivated lands however, could only be carried out at the expense of floodplain ecosystems.

Human interactions resulted that the ancient wide floodplains have been reduced into narrow 0-500 m wide stripes along the river. Such small, disconnected areas cannot fulfil the habitat requirements of many characteristic birds and mammals. For example the famous black stork (*Ciconia nigra*) prefers to build its nest deep in alluvial forests where the distance from the nearest human disturbance is at least 1000 m [Kalocsa, 1999, pers. com.]. Helmer *et al.* [1990] found that a population of 20 pairs of black stork requires at least 7000 ha continuous natural area with forests where they can breed, and with water bodies where they can forage. Large floodplains, which satisfy such requirements, could only survive at few locations along regulated rivers. There are only three such large floodplains along the Danube: the Szigetköz along the Slovakian-Hungarian border (see Figure 4.1), the Gemenc and the Danube Delta.

River training has shortened and narrowed the river channel resulting in significant increase of water velocities. Higher velocity resulted in increased erosion force, which finally led to the degradation of the riverbed. Because of degradation, the annual minimum, mean and maximum water levels of the Danube at the Gemenc have decreased with 1.30, 1.60 and 0.80 meters respectively, during the period 1901-1996 (Figure 4.4).

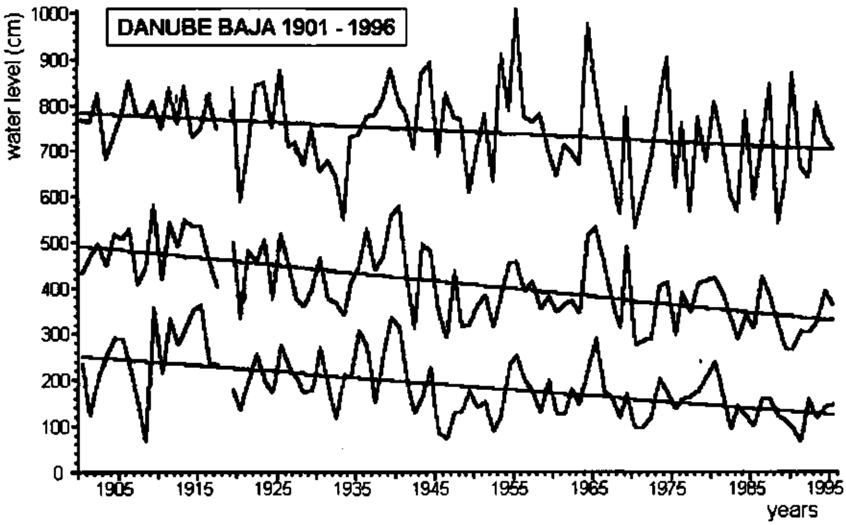

Figure 4.4 Linear trends of annual maximum, mean and minimum water levels of the Danube at Gemenc[1]

In contrast to water levels, the discharges time series of the Danube are practically trend-free as Figure 4.5 indicates. It can thus be concluded that the reason of decreasing water levels is bed degradation indeed, and not any kind of climate change.

[1] Recorded water levels are available also from the second half of the 19th Century, although those data cannot be appended to the data series of the 20th Century because the gauge was changed. However the time series of differences between water levels of consecutive days can be analysed together, as these data are independent from the level of the 0 point of the gauge. Thus a 122 year-long data series of daily water level increases (or decreases) can be applied for trend analysis as shown later in this chapter.

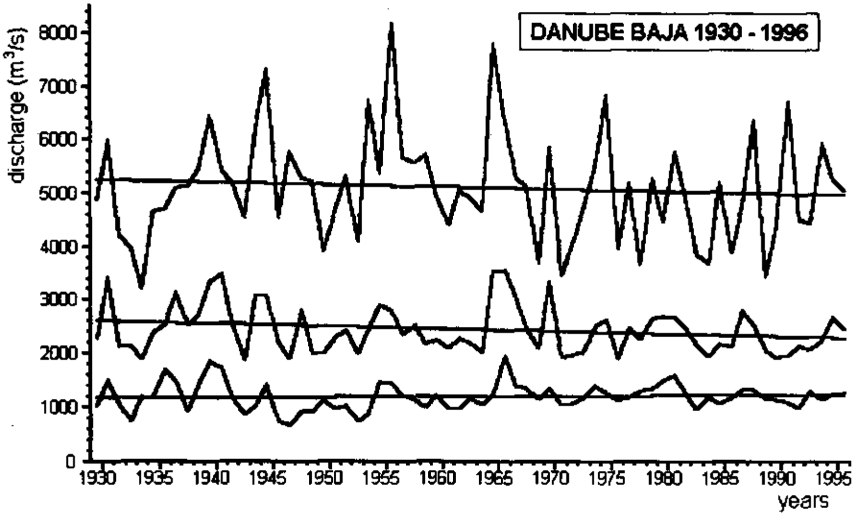

Figure 4.5 Linear trends of annual maximum, mean and minimum discharges of the Danube at Gemenc

The process of water level decrease is general for regulated alluvial rivers. For example, trend analysis demonstrated that the decreases of annual minimum, mean and maximum water levels of the Rhine at the Dutch-German border were 1.50, 1.30, and 0.50 m respectively, during the period of 1900-1990, meanwhile no significant trends in discharges were detected [Keve, 1992].

Ecological consequences of the falling water levels are serious. Shorter inundation durations and decreased groundwater levels triggered a desiccation process, in the course of which the typical, alluvial wet flora has gradually been replaced by dry vegetation [PMMF *et al.*, 1993]. In the Gemenc floodplain foresters noticed this process first after observing signs of desiccation on old willow trees. Decreased river levels also caused the shrinking of floodplain water bodies, which resulted in significant loss of habitat for aquatic flora and fauna [PMMF *et al.*, 1993]. Furthermore, the duration of connection between the river and the floodplain lakes has also been reduced which has worsened the conditions of lateral fish migration.

The decreased depth and reduced connectivity of water bodies, as well as the increased nutrient content of the river water (which still enters the floodplain water bodies during high floods) are responsible for the problem of eutrophication. In the Gemenc floodplain serious planktonic eutrophication was observed in the side arms and occasionally in the oxbow lakes too [Csányi *et al.*, 1992].

River training has caused changes in the flood wave propagation process too. Nowadays, individual flood waves are shorter; their amplitude and the rate of water level increase and decrease are higher than before. These parameters are determined by the slope, length, bed roughness and the storage capacity of the river. A regulated river with a shortened and uniformed river channel and without meanders, branches and large floodplains cannot mitigate the peaky flood waves coming from the headwaters as effectively as before river training. The canalisation of the German and Austrian Danube reach enhanced further this problem since the reservoirs behind the barrages are kept full, thus decreasing further the river's storage capacity.

Thus, the slow seasonal floods of alluvial rivers have been replaced by a flashy flood regime leading to the serious deterioration of the fish population as it is also indicated by Figure 2.7 in Chapter 2. After detailed analysis Pintér [1992] has come to the conclusion that the natural reproduction of the Danubian carp is successful in certain years only, because the quick decrease of water levels often result the death of deposited eggs and hatched larvae on the stranded spawning grounds of the floodplain.

Figure 4.6 shows the evidence of these hydrological changes by displaying the trend of the maximum daily water level decreases of the Danube during the main spawning season (April – June). Time series of daily water level decreases has been generated by calculating the differences between water levels of consecutive days:

$$dz_i = z_{i-1} - z_i \tag{4.1}$$

Where:

dz_i water level decrease on the i-th day of the main spawning season

z_i water level on the i-th day of the main spawning season

The trend function fitted on the 122 year-long time series of max. daily water level decreases is a 3rd degree polynomial function (see Figure 4.6), which proved to fit the best among a wide range of functions. The steep start of the trend indicates the immediate effects of the major river training actions that took place in the second half of the 19th century and at the beginning of the 20th century. The gently sloping mid section reflects the limited influence of minor bed regulation works that have been taking place after World War I.. At the end, the trend becomes steep again indicating the effects of the increasing number of river barrages, which have been started to be constructed from the late fifties in Austria, Germany and Slovakia.

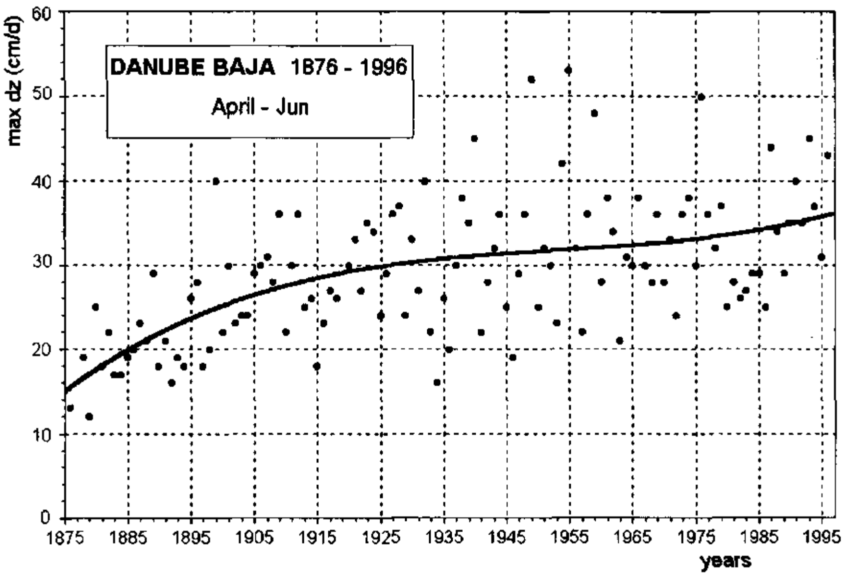

Figure 4.6 3rd degree polynomial trend of the maximum daily water level decreases during the main spawning season, Danube at Gemenc

According to this trend, the maximum daily water level decreases during the main spawning season has been increased with more than 130% during the last 122 years. Similar increasing trend can be observed in case of the maximum daily water level increases too. The total changes are probably even higher, since river training works had been started before 1876 (see Figure 4.3). Unfortunately, no recorded water level data are available from that period. In addition, new barrages will likely to be constructed in the future as well, thus the rates of water level increases and decreases are expected to augment in the future.

The aforementioned acceleration of water level changes is also indicated by the hydrographs presented on Figure 4.7.

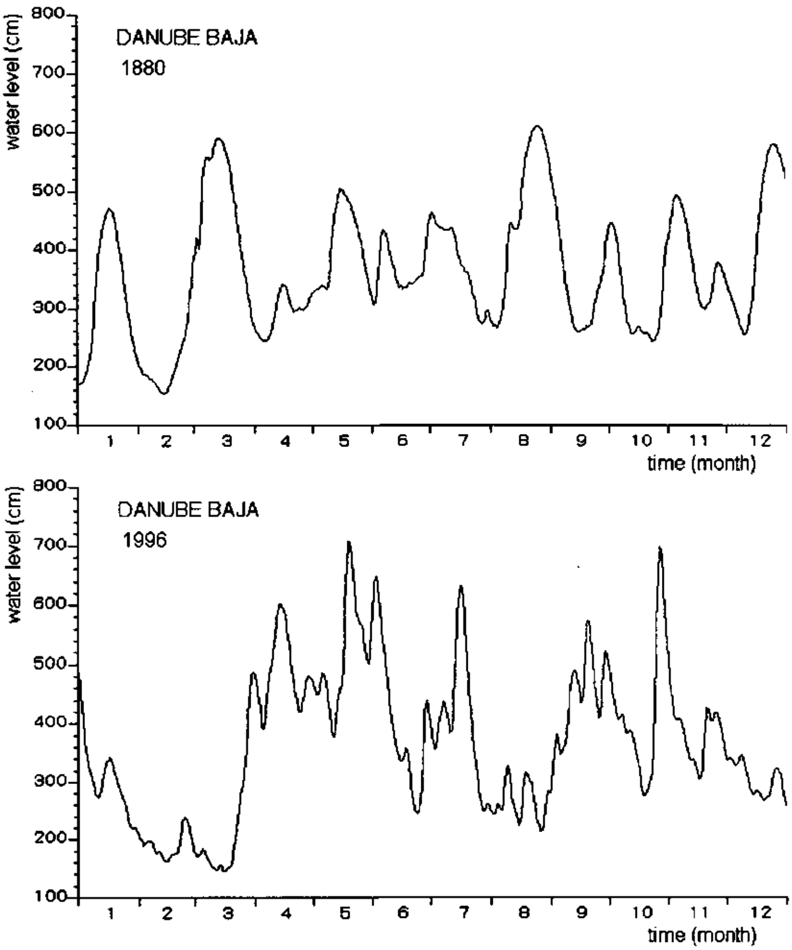

Figure 4.7 Typical annual hydrographs of the Danube from the end of the 19th and 20th centuries

4.3 The present state of the case study system

4.3.1 Geographical, morphological, hydrological and ecological conditions

The case study area of this thesis is situated on the southern part of the Gemenc floodplain (Figure 4.8). This part of the river-floodplain system is surrounded by the villages of Pörböly, Báta, Szeremle and by the city of Baja. The river-channel system consists of the regulated main river channel and several side branches such as the Rezéti, Vén-Duna, and the Kádár.

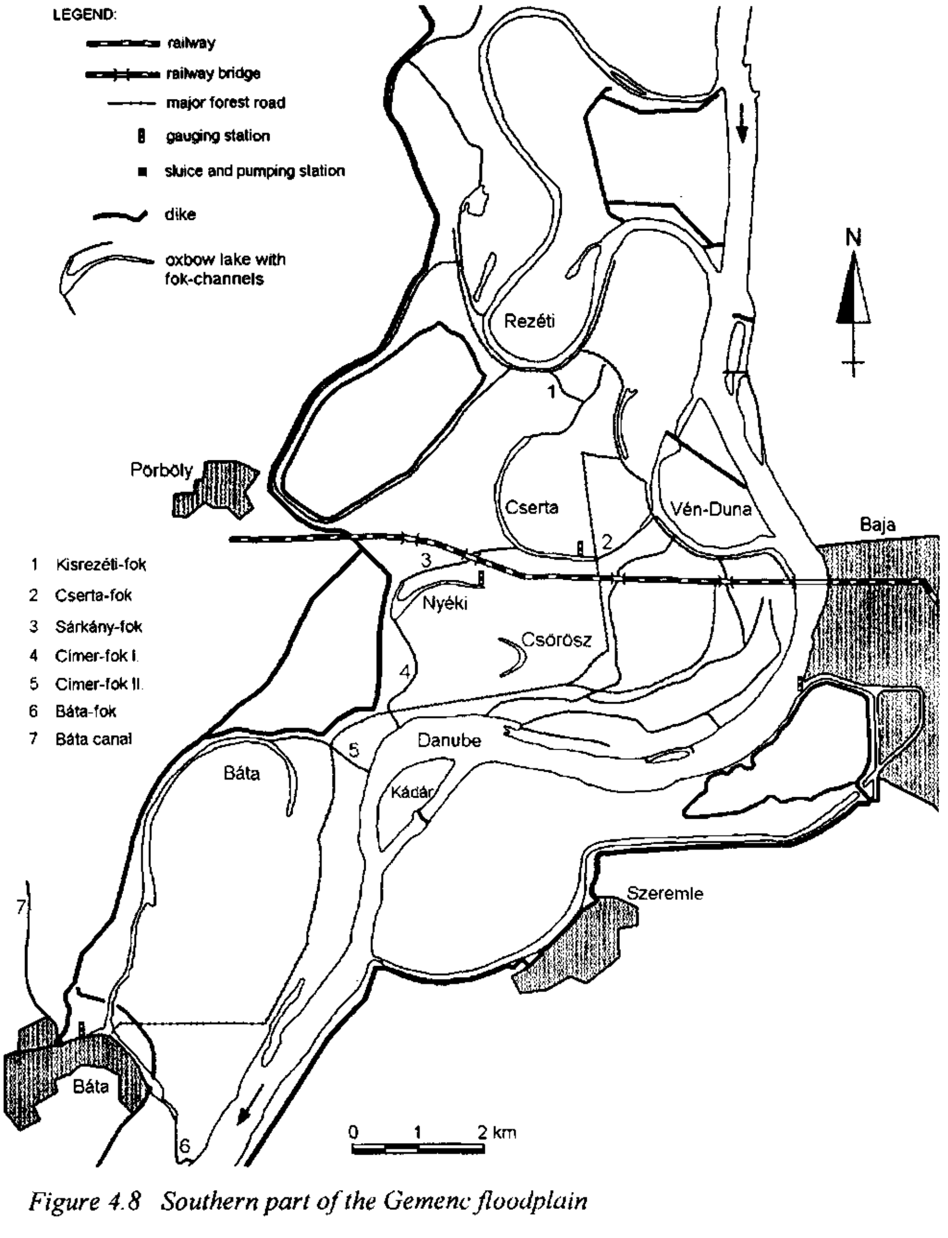

Figure 4.8 Southern part of the Gemenc floodplain

The oxbow lakes and fok-channels of the floodplain form an extensive fok-system. This system contains four oxbows namely the Cserta, Nyéki, Báta and the Csörösz (Figure 4.8). The Cserta oxbow is connected to the river channel system by means of the Kisrezéti and Cserta primary fok-channels. From South, the Sárkány secondary fok-channel connects the Cserta to Lake Nyéki, which is connected to the Danube by means of the Címer I primary fok-channel. The Báta oxbow forms a separate system. This lake is connected to the Danube by the Címer II and Báta primary fok-channels (Figure 4.8). The Csörösz lake can be found East from the Nyéki. It has no fok-channel connection, neither to Lake Nyéki nor to the Danube. Water flows into this oxbow only during high floods when the surrounding natural levees get submerged. In such cases the Csörösz virtually merges to Lake Nyéki.

There is a railway crossing the area in West - East direction. In the floodplain, it runs on a dike. This dike has four 60-100 m wide openings, which are spanned by bridges. The purpose of these openings is to let the water flow downstream during high floods. The Sárkány-fok flows through one of these openings.

The Báta and Cserta oxbows are relatively new geomorphologic structures. They were active meanders in 1825 and were cut-off somewhere around the middle of the 19th Century (Figure 4.3). Nyéki is on the other hand a significantly older oxbow. It was cut-off around the middle of the 18th century. Because of this difference in age, Nyéki is a much more aggraded than the other two oxbows. Its bottom level is on 84.20 maD while the bottoms of Cserta and Báta oxbows are on 83.50 maD and 82.0 maD respectively.

The oxbows are filled and drained through the fok-channels according to the regime of the Danube. The size of an oxbow varies with varying water levels. Its maximum extend is defined by the surrounding natural and artificial barriers. Lake Nyéki for example is delimited by the flood control dike from the West, by the railway dike from the North and by forest roads built on natural levees from Southeast (see Figure 4.8). The so-defined maximum sizes of the oxbows are termed as *'cells'*. Such cell is the basic spatial unit of this study. Hydrological and ecological modelling as well as the other analysis works correspond to such cells. These cells are in fact equivalent to the 'functional units' in the classification of Amoros *et al.* [1987].

Since the decline of fok-management the fok-channels have gradually deteriorated. At present they are not maintained but filled with sediment and tree trunks. Also their beds have been filled with earth at many places during the forest road constructions. Thus, the discharge capacities of these channels are quite restricted, which enhance the isolation problem of the cells. Only few bed fillings are equipped with culverts. The most isolated cell of the system is the Nyéki. The crests of the bed fillings in the Sárkány and Címer I fok-channels are on 86.5 maD. Below this level the lake becomes isolated from the surrounding water bodies and only precipitation and evaporation influence its water balance as it is indicated by Figure 4.9. During the summer months evaporation usually causes significant decreases in water levels. In winter however precipitation balances evaporation and the water level gets stabilised (Figure 4.9). Water may enter or leave the cell also through seepage, even though these processes are of much less influence due to the thick clay layer that covers the surface of the cell. The level of bed filling in the Címer I fok is likely to change time to time as a result of truck traffic or road maintenance works. The rapid fall of water level below 86.5 maD at the end of the recording period (see Figure 4.9) is likely to be the consequence of a lowered bed filling level.

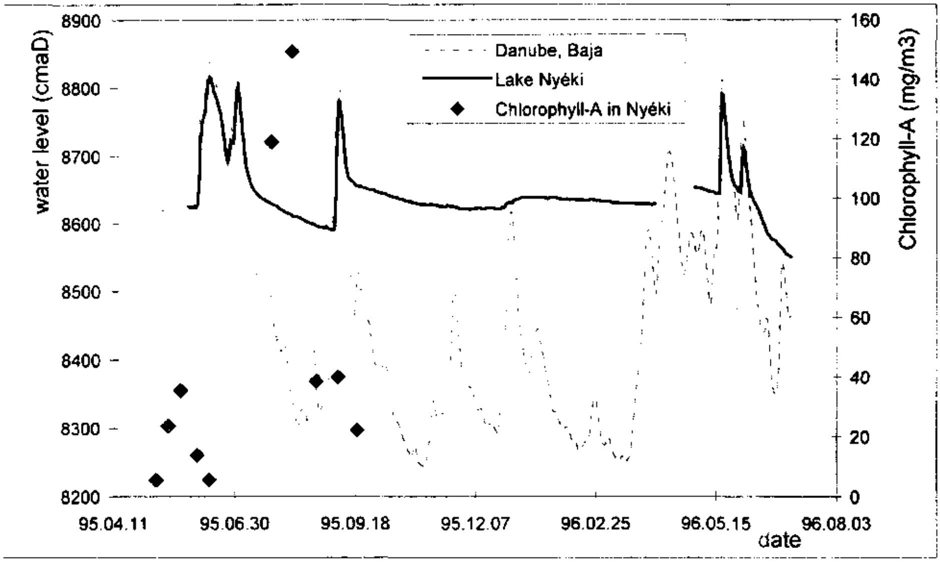

Figure 4.9 Recorded water levels and Chlorophyll-A concentrations in the Lake Nyéki

Figure 4.9 also indicates that whenever high floods of the Danube overtops the inflow threshold, the water level of Nyéki becomes very dynamic and it follows almost immediately the level of the river. This is explained by the small storage capacity of the Cserta-Nyéki system. Because of the fast water level fluctuation, spawning conditions in Nyéki are inadequate.

The high thresholds keep the water in the lake on relatively high levels after floods. This may imply that such thresholds counteract the desiccation problem within the Nyéki cell, below the elevation of 86.5 maD. High thresholds however, result long isolation periods during which the stored water evaporates and desiccation occurs. Hydrodynamic simulation of the fok-system revealed that the Nyéki cell dried out completely in 1984 and in 1990 for 58 and 17 days respectively. These results are in agreement with the observations of local people. If the thresholds had been on a lower level, probably no such dry-outs would have occurred because the smaller floods would have been able to maintain a shallow but stable water level.

During the summer low water periods, planktonic eutrophication may develop in the open parts Lake Nyéki. For example, the mean Chlorophyll-A concentration on the 7th of August 1995 was 150 mg/m^3 (Figure 4.9) while the measured maximum was 325.7 mg/m^3 on the same day. The primary reason was the shallow 1.5 m depths of the lake where light was available along the entire water column. Also evaporation contributed to the concentration increase of phytoplankton and that of dissolved nutrients. Nevertheless, when the lake got connected to the Danube the quality of its water adjusted quickly to that of the river due to the intensive water exchange (see Figure 4.9).

The predominantly shallow depths and the relative few dynamic periods made possible for water plants to colonise Lake Nyéki. Rademakers [1990] surveyed the vegetation of the lake in August 1990, and found *Nuphar lutea* in the water, large reed stands (*Phragmites australis*) on the bank and pioneer species such as *Glyceria maxima*, *Polygonum* spec., *Acorus calamus* and *Rorippa amphibia* along the shoreline. An even denser cover of water plants (with *Trapa natans*) can be found in and around the highly isolated oxbows like the Decsi oxbow in the North of the Gemenc [Rademakers, 1990].

The Cserta oxbow is a less isolated water body since its inflow threshold is on 84.9 maD, which is the bottom level of the culvert built into the Cserta-fok. Above this level the Cserta follows immediately the level of the river, thus creating an unfavourable environment for the spawning fish (Figure 4.10).

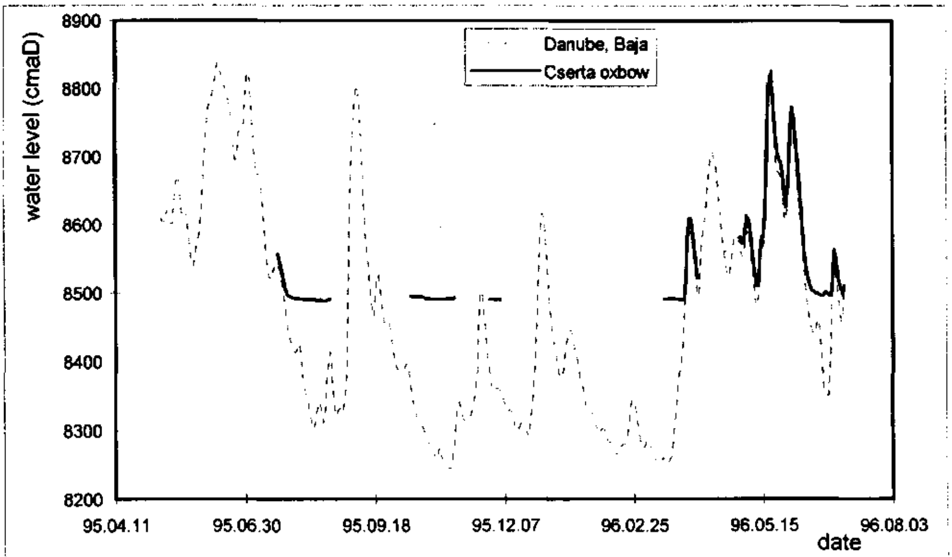

Figure 4.10 Recorded water levels in the Cserta oxbow

Because of the dynamic water regime, reed does not grow on the banks of the Cserta, although *Carex riparia* does [Rademakers, 1990]. The large dried sections of the oxbow bed is overgrown by pioneers like *Polygonum hydropiper* [Rademakers, 1990], while some water plants can be found in the permanently inundated parts.

In contrast to oxbows, the open side arms of the Gemenc like the Rezéti and Vén Duna do not have submerged or emerged water plants at all. Neither reeds nor *Carex riparia* grow on their banks due to the highly fluctuating water level of the Danube [Rademakers, 1990].

The Báta oxbow is also in intensive contact with the Danube thanks to the Báta-fok (Figure 4.8), which is free of any bed fillings. The highest point of its thalweg is around 83.0 maD, thus allowing even low floods to enter the oxbow. The Címer II fok has limited influence on the Báta oxbow due to a high and narrow bed filling. The oxbow is also fed by water from the Báta canal, which enters through a sluice, built into the dike. The sluice is open whenever the water level in the canal exceeds that of the oxbow, otherwise it is kept closed. If the water level in the canal rises above 84.97 maD and the level of the oxbow is even higher, pumps start to lift the excess water into the oxbow. Because of the low discharges in the canal, its influence on the water level of the oxbow prevails only at low water, when it is able to keep the water level around 84.4 maD for a while. If the water level of the canal drops and the inflow, decreases, the level of the oxbow decreases as well. Unfortunately no water level data are available from such situations, because of the insufficient depth of the local gauging bar. The missing data on Figure

4.11 indicate such situations. The only references for figuring these situations are the measurements taken in February 1989 when a minimum of 83.39 maD was recorded. However, levels even lower than this are likely to occur in the Báta oxbow.

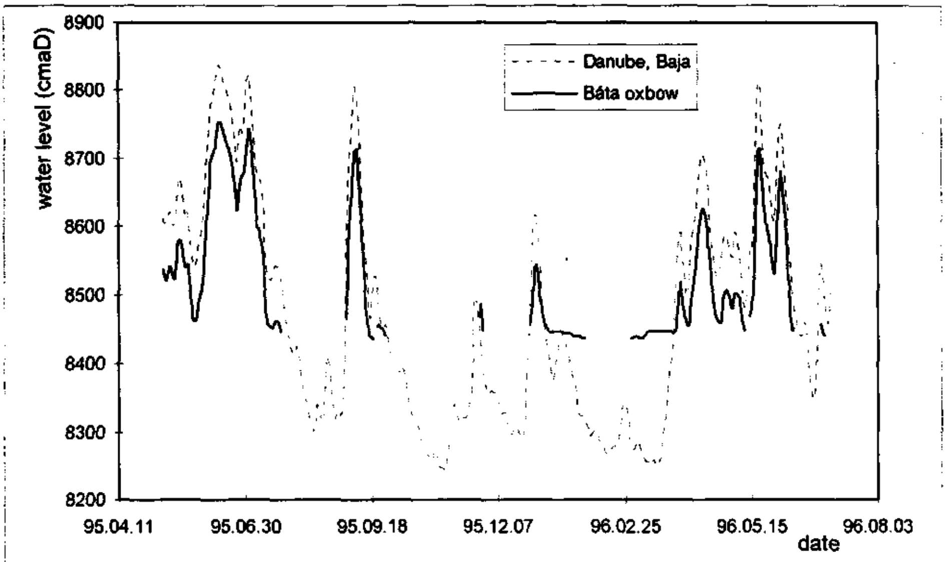

Figure 4.11 Recorded water levels in the Báta oxbow

The water level and water quality data presented in this chapter were collected with the help of the monitoring system that has been installed and operated by the 'Eötvös József' College of Baja using the financial support of the Dutch Institute for Inland Water Management and waste Water Treatment (RIZA).

4.3.2 Land uses

The most influencing human activity in the Gemenc floodplain is timber production, which has been monopolised by the Gemenc State Forestry Company. For the sake of the high profit the Company carries on a very intensive logging activities causing many ecological problems. This intensive use turned the greatest part of the Gemenc into plantations. The quality of these plantations, as habitats for alluvial fauna, is very poor comparing to natural alluvial forests [Kalocsa, 1990]. But even these ecosystems get destroyed when the mature plantations get clear-cut [Kalocsa, 1990]. The wood felling activities themselves result in noise pollution, which further deteriorates the quality of the surrounding habitats. Also the fences defending the young plantations cause troubles, as they have proven to be deadly traps for animals trying to escape from the rising floods [Kalocsa, 1990].

Besides logging, hunting and some forms of recreation are also taking place in the Gemenc. The former is again a profitable business for the Gemenc State Forestry Company, which is therefore interested in sustaining a large game stock. Because of the artificially increased game stock, forests can hardly renew in a natural way as the many deers eat up all the seedlings [Petkó-Szandtner, 1990]. This is why the plantations have to be defended by fences, which however results in additional ecological problems (see above).

In 1997 the Gemenc floodplain was declared as part of the Danube-Dráva National Park, in spite that its actual state didn't (and still doesn't) satisfy the requirements of national parks due to the ecological problems listed above. The reason of this step was probably to create appropriate legal conditions for the ecological revitalisation of the area. Some positive steps have already been taken indeed, such as the introduction of limited authoritative control on wood production and game management. As a result, planting of allochthonous tree species has been forbidden, clear-cutting has been limited and the game-stock was reduced with a small extend [Buzetzky, 2000, pers. comm.]. In addition, some side branches have been reopened with the purpose to make them lotic side-channels again. Nevertheless the bulk of the work is still ahead. The purpose of the present study is just to aid the ecological revitalisation process by providing a computer-based tool, which helps to find a compromise revitalisation solution for the floodplain that is acceptable for all stakeholders.

5. PROBLEM FORMULATION

When dealing with ecological revitalisation of river-floodplain systems one should take into consideration that such systems usually consist of two main parts: the *river channel system* and the *cell-system* (Figure 5.1). River channel system incorporates the interconnected network of river channels, as well as those floodplain areas, which are under the direct influence of the river. This latter refers to islands, reefs and banks situated close to the river channels. The ecosystems hosted by river channel systems are characterised by species adapted to flowing water environment. The cell-system on the other hand is the mosaic-like system of depressions (*cells*) on the floodplain surface. The boundary between two cells, or between the river channel system and a cell, may be a natural levee, or artificial structures such as summer dikes or elevated forest roads. There may be oxbow lakes in a cell, which can be connected to the oxbow of the neighbouring cell, or to the river itself, by means of small channels. Such channel is termed as *'fok'* after its traditional Hungarian name (see Chapter 4). Flooding and draining of the cell system proceed gradually from cell to cell. The flow between two cells, or between the river and a cell may be conveyed through the fok–channels and/or through structures such as weirs or sluices. Above a certain elevation however, the water also flows over the crest of the cell boundary. Cell-systems are habitats for species preferring standing water environment.

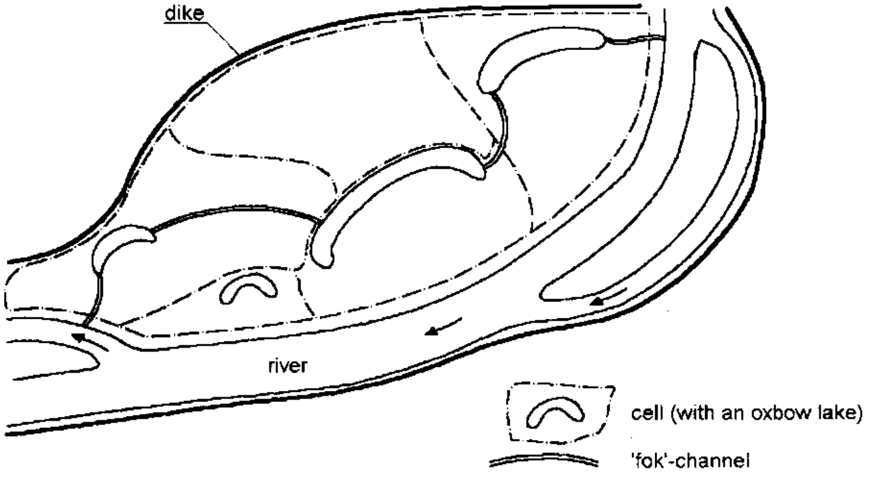

Figure 5.1 Generalised view of river-floodplain systems

The cell system of the case study area of this thesis has been introduced in Chapter 4.

Because of the significant differences, ecological revitalisation of the two subsystems requires different approaches. The very first step of the revitalisation process is thus to draw the boundary between the area envisaged to be developed as cell-system, and the area envisaged to be developed as river channel system. The existing boundary doesn't necessarily need to be adopted. Some oxbow lakes for example, may be foreseen as parts of future side-channels, while some ill-developed side channels might be transformed into oxbow lakes in the future.

5.1 Identification of revitalisation measures

Certain ecological problems can be solved by means of simple administrative measures. The sources of such problems (e.g. pollution or disturbance sources) can be eliminated by creating and enforcing appropriate nature protection laws and rules. In case of lasting problems however administrative measures alone are insufficient. Such problems need active, 'engineering' interventions.

It is also very important to implement ecological revitalisation on self-sustainable way, so that the envisaged ecosystems would need no, or very limited human interference to keep them in the desired state. This implies that revitalisation measures should better not target directly those elements of the ecological influence chains, which are influenced by other, unchanged elements. Typical example for such non-self-sustainable ecological revitalisation is spreading calcium hydroxide ($Ca(OH)_2$) over acidified forest soils. The continuous maintenance of the desired low acidity level requires repeating this process after a few years, because the acid rainfall restores acidity in the meantime (see also Figure 2.6 in Chapter 2).[1]

Thus, revitalisation measures should better influence conditional abiotic factors on the highest level of the ecological influence chains. Once such a measure is implemented, its effect is transmitted to the targeted ecosystems through the ecological influence chains.

In case of river-floodplain ecosystems, the most influencing conditional factors are the hydrological ones. Hydrological conditions can be improved by modifying the *hydrological infrastructure* of the system. For example, habitats of fish preferring sandy substrate and oxygen rich open water (barbel, sturgeon), and that of birds nestling in steep banks near to water (sand martin, kingfisher), can be developed by constructing flowing river channels with appropriate attributes. Because navigation severely constrains actions in the main channel, revitalisation of such lotic biotopes is proposed to be implemented by reopening existing *side channels* and/or digging new ones. The envisaged side channels have diverse habitat conditions with flowing parts, pools, sand reefs and steep banks. Such channels must also be morphologically stable in order to prevent dangerous meandering and to maintain the proper flow distribution between the side and the main channels, so that sedimentation will not endanger navigation and flood control safety. There are several examples for this *side channel approach*. Marchand [1993] for example presented a study with three alternative side-channel revitalisation plans for the Gemenc floodplain, while Schropp & Bakker [1994] worked out a side-channel plan for a Rhine riparian floodplain in the Netherlands. The principles of designing side channels are laid down by Schropp [1994].

Ecological advantages of side channels are limited, since species adapted to lotic conditions would benefit only. Improving habitat conditions for lentic and terrestrial ecosystems on the floodplain needs interventions into the cell-system. As the Flood Pulse Concept [Junk *et al.*,

[1] **Real self-sustainable solution would be the reduction of rainwater acidity, even though that would need global restriction of industrial air pollution.**

1989] suggests (see Chapter 2), interventions should target the improvement of inundation conditions. Inundation of the cells is influenced by the geometry of the fok-channels, the elevation of the cell boundaries and the sizes of the cells themselves. Accordingly, the following revitalisation measures can be taken into consideration:

1. Enlarging existing fok-channels or excavating new ones (Figure 5.2.a)
2. Constructing thresholds in the fok-channels at the section of cell-boundary (Figure 5.2.b)
3. Installing slide gates into the cell-boundary sections of fok-channels (Figure 5.2.c); operating these gates according to appropriate operation policies
4. Elevating cell boundaries by erecting summer dikes (Figure 5.2.d)
5. Excavations within the cells (Figure 5.2.e)

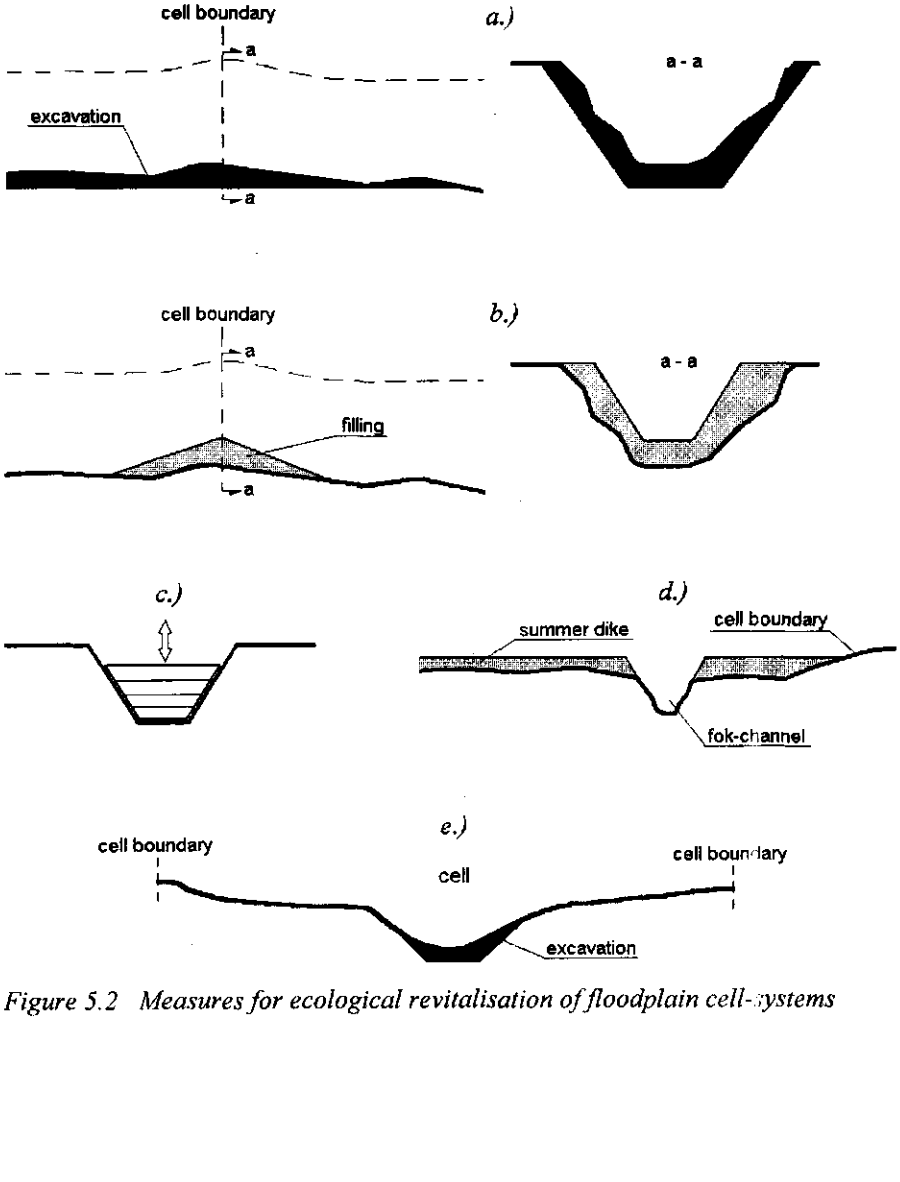

Figure 5.2 Measures for ecological revitalisation of floodplain cell-systems

Based on these measures design alternatives can be constructed for each element of the cell-system. For example, alternative designs can be constructed for each fok-channels based on measures no. 1., 2. and 3.. Similarly, alternatives can be defined for the cell boundaries according to the different design heights of the planned summer dikes. The union of the so defined sets forms a *decision space* where each point stands for a particular revitalisation alternative for the cell-system.

As an example, Figure 5.3 shows a simple cell-system with two cells only. The envisaged discrete decision space consists of six discrete dimensions:

1. The present state plus 3 summer dike alternatives for boundary *a*.
2. The present state plus 3 summer dike alternatives for boundary *b*.
3. The present state plus 3 summer dike alternatives for boundary *c*.
4. 16 alternative designs for channel *1.*; each alternative stands for a specific combination of *bottom elevation*, *bottom width* and *bank slope*
5. 32 alternative designs for a new channel between the two cells (channel *2.*)
6. 4 alternatives for a sluice (different sizes and/or operation policies) planned to be built into channel *1*.

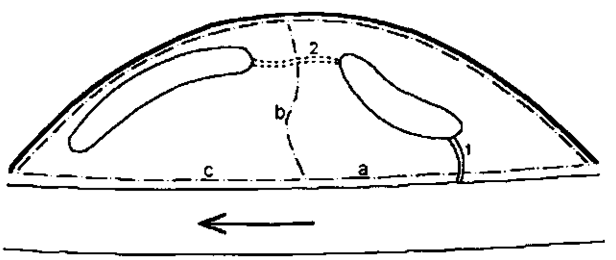

Figure 5.3 A simple cell-system

Thus, the decision space of this simple example contains 131072 cell-system revitalisation alternatives. By increasing the number of system elements and/or that of design alternatives at certain elements, the size of the decision space increases rapidly, which makes the enumerative search an unviable option even if certain inferior and/or infeasible regions of the space can be a priori identified and excluded from the search.

5.2 Identification of evaluation criteria

To evaluate the different cell-system alternatives the Decision Making Group (DMG) has to express its objectives in terms of evaluation criteria. In case of floodplain revitalisation the following types of criteria have to be taken into consideration:

Investment costs

Investment costs consist of the costs of excavation works and the costs of constructions. In case of cell-systems constructions refer to the building of channel thresholds, summer dikes, sluices. Excavation costs are function of the amount of excavated earth, which is in turn calculated on the basis of the present and the desired terrain geometries.

Operational costs

Operational cost arises if the subjected system needs repeated active flow control actions to keep its water regime in the desired state. In case of cell-systems operational costs stands for the costs of operating sluices, which is a function of the number of sluice openings and closings.

Flood control

Interactions in the floodplain morphology may have influence on the water regime of the river. Constructions of channel thresholds, sluices and especially that of summer dikes may lead to increased flood levels as these structures increases the roughness of the floodplain. Expected increase in design flood levels is thus an appropriate criterion expressing the interest of flood control. The score (achievement) of a certain cell-system alternative at the related criterion can be calculated with the help of an appropriate hydrodynamic model.

Ecological criteria

Ecological criteria concern the quantitative and qualitative evaluations of habitats of certain species or group of species. It is a common practice to identify so-called 'indicator' species, because the presence of these species indicates the presence of the desired complex alluvial ecosystems.

Land use criteria

These criteria stand for the interest of forestry, agriculture, recreation and other forms of land uses that may be present on the floodplain.

Ecological revitalisation of floodplain cell-systems is thus a multi-criteria decision problem where the task is to find the best compromise solution within the identified discrete decision space, according to the applied criteria.

6. INTRODUCTION OF THE DECISION SUPPORT SYSTEM

The purpose of this chapter is to introduce the Decision Support System (DSS) created with the aim to help the Decision Making Group (DMG) and the Planning Group (PG) in identifying the best compromise solution for the cell-system revitalisation problem outlined in Chapter 5. The envisaged DSS is based on the ESEMOPS technique of Bogardi & Sutanto [1994]. ESEMOPS has been developed from the SEMOPS method [Monarchi, 1972] that has already been introduced briefly in Chapter 3. This chapter gives a detailed description about the principles of these techniques and also about the adaptation of ESEMOPS to the cell-system revitalisation problem.

6.1 The ESEMOPS based framework of the DSS

The major advantage of SEMOPS based techniques is that they enable the DMG to cope with all of the fundamental aspects of multi-criteria decision problems. Monarchi *et al.*, [1973] summarized these aspects as follows:

1. A decision problem is a 'Gestalt entity' [Köhler, 1947] meaning that it can only be dealt with as a whole, but not in its elements. This implies that the DMG has to be enabled to consider the total set of elements of the decision problem at once.
2. The DMG's preference function or value structure cannot be expressed analytically, yet the DMG has to be enabled to articulate its preference structure in a certain mathematical way.
3. Interrelationships and trade-offs between the criteria are usually unknown or little known for the DMG at the beginning of the decision process. Thus the DMG has to be enabled to learn these relationships and also to modify its preference structure on the basis of what it has been learned (progressive articulation of preferences).

Because of the first aspect, the number of criteria must not be more than 7 (±2), since this seems to be the upper limit of simultaneous human perception [Monarchi, 1972].

SEMOPS actually solves a multi-criteria decision problem as formulated by equation 3.1. For the cell-system revitalisation problem the decision space of the $\bar{x}$ solution vectors and the space of the $\bar{z}$ vector of criteria functions have been identified in Chapter 5. Exact formulation of these spaces, as well as operating the DSS software is the job of the PG, which has the required technical-scientific expertise. The ultimate task of the PG is thus to contribute to the identification of a solution, which would 'satisfy' the DMG the most.

The PG assists the DMG in articulating its preference structure in terms of *aspiration levels* associated with each criterion. Five types of aspirations are used in SEMOPS:

1. *'at most'*: $z_i(\bar{x}) \le AL_i$: DMG desires to keep i-th criterion *below* the AL_i aspiration level
2. *'at least'*: $z_i(\bar{x}) \ge AL_i$: DMG desires to keep i-th criterion *above* the AL_i aspiration level
3. *'equals'*: $z_i(\bar{x}) = AL_i$: DMG desires to keep i-th criterion *equal to* the AL_i aspiration level
4. *'within interval'*: $AL_{i1} \le z_i(\bar{x}) \le AL_{i2}$: DMG desires to keep i-th criterion *within* the AL_{i1} and AL_{i2} aspiration levels
5. *'outside interval'*: $z_i(\bar{x}) \le AL_{i1}$ or $z_i(\bar{x}) \ge AL_{i2}$: DMG desires to keep i-th criterion *outside* the interval of AL_{i1} and AL_{i2} aspiration levels

Where:

$\bar{x}\ (x_1, x_2 ... x_n)$ solution vector in the n-dimensional decision space

$z_i(\bar{x})$ i-th element of the p-dimensional vector of criterion functions

Monarchi [1972] defined a so-called '*d-function*' for each aspiration types as follows:

$$\text{at most: } d_i = \frac{z_i}{AL_i} \tag{6.1}$$

$$\text{at least: } d_i = \frac{AL_i}{z_i} \tag{6.2}$$

$$\text{equals: } d_i = \frac{1}{2} \cdot \left(\frac{AL_i}{z_i} + \frac{z_i}{AL_i} \right) \tag{6.3}$$

$$\text{within interval: } d_i = \frac{AL_{i2}}{AL_{i1} + AL_{i2}} \cdot \left(\frac{AL_{i1}}{z_i} + \frac{z_i}{AL_{i2}} \right) \tag{6.4}$$

$$\text{outside interval: } d_i = \frac{AL_{i1} + AL_{i2}}{AL_{i2}} \cdot \frac{1}{\dfrac{AL_{i1}}{z_i} + \dfrac{z_i}{AL_{i2}}} \tag{6.5}$$

Thus, a value of $d_i \le 1$ implies that the desire of the DMG is satisfied as far as the i-th criterion is concerned. The value of d_i also indicates the 'measure' of satisfaction and dissatisfaction, i.e. the closer the value of d_i to 1 from above the less the DMG dissatisfied, while the farther it from 1 from below the more the DMG satisfied.

In order to prevent the occurrence of zeros, it is advised to scale criterion function values and aspiration levels prior calculating the d-values. The scaling interval of a criterion has to be set such that function values and aspiration levels will stay above and below the interval's lower and upper limits all along the decision making process.

Searching for the best compromise solution with the help of SEMOPS is implemented in an iterative-interactive manner. During each iteration cycle, a *principal problem* and several *auxiliary problems* are solved. The principal problem is defined as follows:

$$\begin{aligned}&\text{minimize } s = \sum_{t \in T'} d_t(\bar{x}) \\ &\text{subject to} \\ &\qquad g_i(\bar{x}) \leq 0 \quad i = 1,2,\ldots m \\ &\qquad d_k \leq 1 \qquad \forall\, k \in T^*\end{aligned} \tag{6.6}$$

Where:

- s — the so-called '*surrogate objective function*' of the principal problem
- $g_1(\bar{x}),\ g_2(\bar{x})\ \ldots\ g_m(\bar{x})$ — constraint functions of the initial constraint set
- T' — subset of the initial set of criteria (T) that is not added to the constraint set ($T'=T$ at the start of the decision iteration process)
- T^* — subset of the initial set of criteria that is added to the constraint set ($T^*=T-T'$)

Auxiliary problems are defined in the following way:

$$\left.\begin{aligned}&\text{minimize } s_l = \sum_{t \in (T'-l)} d_t(\bar{x}) \\ &\text{subject to} \\ &\qquad g_i(\bar{x}) \leq 0 \quad i = 1,2,\ldots m \\ &\qquad d_k \leq 1 \qquad \forall\, k \in (T^* + l)\end{aligned}\right|\ \forall\, l \in T' \tag{6.7}$$

Where:

- s_l — surrogate objective function of the l-th auxiliary problem

Thus auxiliary problems are formed by temporally adding a particular criterion (along with its aspiration level(s)) to the constrain set.

From a pure mathematical point of view the principal and auxiliary problems are in fact optimisation problems. It is however important to emphasize that such surrogate functions are not substitutes for an explicit expression of the DMG's preference function [Monarchi *et al.*, 1973]. By *comparing* and *analysing* the solutions of these problems the DMG only gains information concerning the set of feasible solutions, and learns about the interrelationships (trade-offs) between the criteria [Monarchi *et al.*, 1973]. On the basis of the lessons learned, the DMG (in cooperation with the PG) modifies its preference structure by modifying the aspiration levels and goes for the next iteration cycle. Also the constraint set can be modified by moving certain criteria functions (along with their aspiration levels) from set T' to set T^*. The iteration stops when the DMG accepts a certain solution as the final (best compromise) solution for the problem.

Figure 6.1 below shows how SEMOPS based methods actually guide the DMG and the PG through the decision process displayed on Figure 3.1 in Chapter 3.

Monarchi *et al.* [1973] applied the *Cutting-Plane Technique* (CPT) [Kelly, 1960] to solve the principal and auxiliary problems. CPT is a non-linear programming technique, which requires continuous decision variables and that all criterion and constraint functions must be at least first order differentiable. To eliminate these restrictions Bogardi & Sutanto [1994] replaced CPT with a heuristic search, based on the principles of *Evolutionary Algorithms* (EA). This is in fact the *ESEMOPS* (Evolutionary SEquential Multi-Objective Problem Solving Method) method.

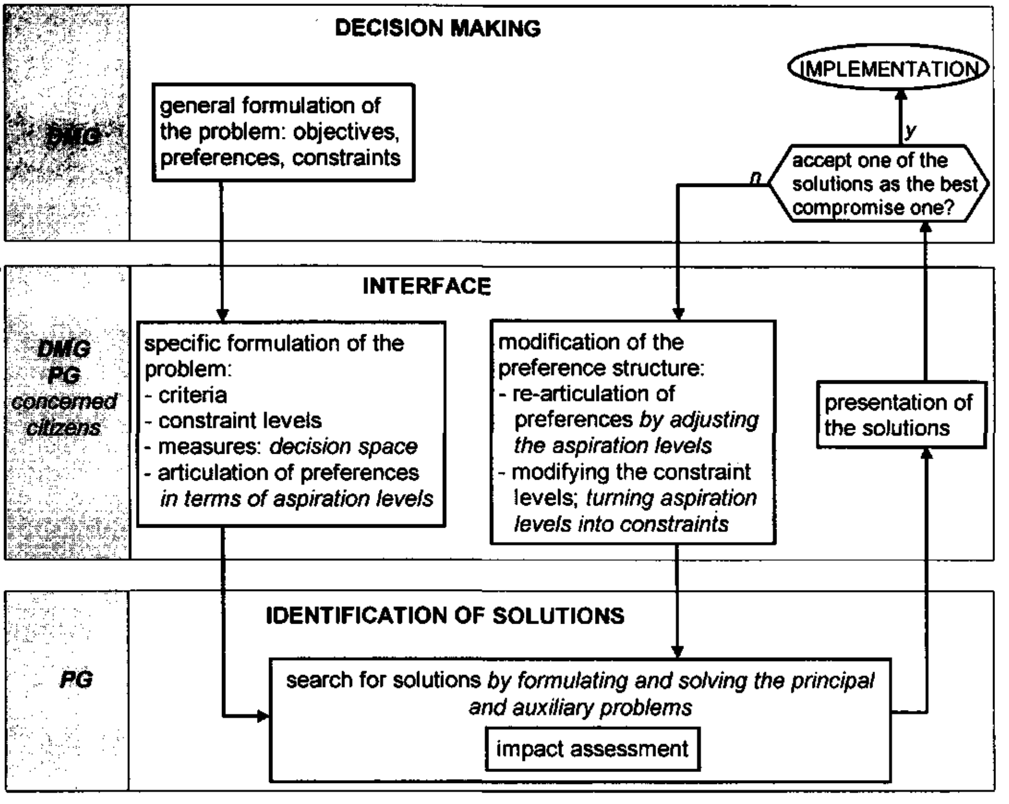

Figure 6.1 ESEMOPS-based implementation of the decision process displayed on Figure 3.1 in Chapter3 (italics are the ESEMOPS specific terms)

The major advantage of EA methods comes from their 'black box' feature, i.e. they rely exclusively on information contained in the input (population of alternative solutions), and output (surrogate objective values) of criteria evaluations throughout the search towards the optimum of the actual (principal or auxiliary) problem. Additional information, such as derivatives, is not needed.

Applying EA opens new horizons for operation research since its black box nature enables theoretically to use any kind of impact assessment tools. This gives the chance to couple search techniques (single- or multi-objective) with today's complex hydrological/ functional models. *In fact this is one of the challenges that have been faced in this study.*

The EA search applied by Bogardi and Sutanto [1994] needs frequent interactions between the PG and the algorithm, as it remains the user's task to control directly the basic EA operations. Instead of this tedious approach, the DSS applied in this study incorporates *Genetic Algorithms* (GA), another EA technique, to solve the optimisation problems at each decision iteration cycle. GA makes ESEMOPS *much faster* and *more robust* as it proceeds the search automatically, without frequent man/machine interactions. In addition to these features GA preserves all the above-described advantages of EA methods.

6.2 The Genetic Algorithms based kernel of the DSS

Genetic Algorithms thus belong to the family of Evolutionary Algorithms. EA methods basically apply the Darwinian mechanisms of 'natural selection' and 'survival of the fittest' on artificial systems. Similar to biological creatures, artificial beings also tend to improve in quality or in performance if one creates an artificial environment where the 'fitter' *individuals* of a *population* get *selected* to *reproduce* new ones.

Among the manifold application of EA techniques function optimisation is one of the most important. In this case individuals stand for points in the domain space of an objective function, while individuals' fitness is measured by means of the associated function values.

Because of the above-mentioned biological analogy, researchers dealing with the development of GA have constructed a system of biological terms standing for the specific features of GA (such as the already mentioned 'individual', 'population', 'selection' and 'reproduction'). This terminology has been adopted by this study too.

6.2.1 Principles of Genetic Algorithms

Foundations of GA were laid down by Holland [1975]. Since then, the method has been developed further, and the mathematical principles have been described by many authors [e.g.: Goldberg, 1989; Michalewicz, 1992; Milutin, 1998]. Herewith only a brief introduction of the method is given. For more details the reader is referred to the works listed above.

What makes GA different from other EA methods is that it requires the individuals (alternative solutions) to be coded as finite-length strings over some finite alphabet. The most widespread used alphabet is the binary system that incorporates only two characters ('0' and '1'). In case of a multi-variable objective function for example, with non-negative integers as independent variables, the binary coding may simply stand for the binary forms of these integers.

Such simple *integer coding* can be applied on any bounded and denumerable domain sets. The binary strings in such cases simply decode to the within-set serial numbers of the set elements[1]. Accordingly, such sets may contain real numbers, arrays, or even design alternatives for the elements of a floodplain cell-system. Figure 6.2 for example shows the binary coding of a certain solution (individual) for the simple cell-system revitalisation problem introduced in Chapter 5 (see Figure 5.3). This solution is composed by the second design alternative for boundary *a* ('00' stands for the first one), the fourth alternative for boundary *b*, the second alternative for boundary *c*, the fourth alternative for channel *1*, the 19th alternative for channel *2* and the second alternative for the sluice to be built into channel *1*.

a	*b*	*c*	*1*	*2*	*sluice*
0 1	1 1	0 1	0 0 1 1	1 0 0 1 0	0 1

Figure 6.2 Binary coding of a solution for the cell-system shown by Figure 5.3

[1] In fact the decoded integers must be increased with one; '000' thus refers to element no. 1., while '111' refers to element no. 8. in a set with 8 elements in all.

Note, that there must be a one-to-one correspondence between the design alternatives formulated for a certain cell-system element on the one hand, and the total set of binary codes that may appear in the related sub-string on the other hand. This means that the number of design alternatives must be a power of two and the length of the related sub-string must equal to this power.

Binary representation of bounded but infinite domains (e.g. intervals on the continuum of real numbers) is possible by means of *linear mapping*. Details about linear mapping are given in Milutin [1998].

Besides code, the other feature of individuals that GA uses is their *fitness*. In case of maximisation problems objective function values of individuals can directly be used as fitness since GA is essentially a maximisation algorithm too. This also suggests that in case of minimisation problems, such as the principal and auxiliary problems of ESEMOPS, the multiplicative inverses of objective function values can be taken as fitness.

Note, that for fitness (objective function) evaluation the actual values of independent variables are used and not their binary codes.

The general steps of a GA based function optimisation search are as follows:

1. *Random generation* of the *initial population* of binary strings. The length of the strings must match the length of encoded individuals from the domain space of the objective function
2. *Decode* each string in the population to get the actual values (meanings) of the individuals
3. Calculate the fitness of each individual
4. If termination condition is met then stop the search, else continue
5. Based on fitness values of the old population, create a new population by means of *selection, crossover* and *mutation* and go back to point 2.

This *iterative* process gradually evolves towards the optimum of the function. For the mathematical proof of this convergence, the reader is referred to Goldberg [1989] and Michalewicz [1992].

The number of strings in a population is usually fixed and that is the *population size*. A population however may contain more than one copies of an individual. These copies are termed as *clones*.

The process of *selection* copies individuals from the old population to an intermediate one by using probabilistic rules: a certain individual gets copied with a probability proportional to its fitness and to the number of its clones present in the old population:

$$P_s(i) = \frac{m_i \cdot f_i}{\sum_{j=1}^{N} m_j \cdot f_j} \tag{6.8}$$

Where:

$P_s(i)$ probability of selecting the i-th individual

f_i	fitness of the i-th individual
m_i	number of clones of the i-th individual in the population
N	number of individuals in the population (thus $\sum_{i=1}^{N} m_i$ equals to the population size)

Thus GA considers the optimal solution of the objective function as a random variable. The set of individuals together with their selection probabilities give an estimate of the probability distribution function of this variable. What the numerical implementation of selection actually does is nothing but using a Monte Carlo method to generate a statistical sample (the intermediate population) of this variable from the set of individuals present in the old population. This way of selection is also termed as 'biased roulette wheel selection' [Goldberg, 1989; Milutin, 1998] as it imitates the spinning of a roulette wheel whose slot-sizes are biased in proportion to the selection probabilities.

Selection alone deals only with a tiny sub-domain of the objective function. The reproductive actions of *crossover* and *mutation* introduce new individuals thus enable the GA to expand the search towards the entire domain. Crossover actually imitates the biological process of breeding. In practice, selection and crossover work simultaneously: after selecting a pair of strings, crossover is applied on these *parents* by cutting them at a randomly selected site and exchanging the resulted sub-strings (Figure 6.3). The so-derived *offsprings* then enter the intermediate population instead of their parents.

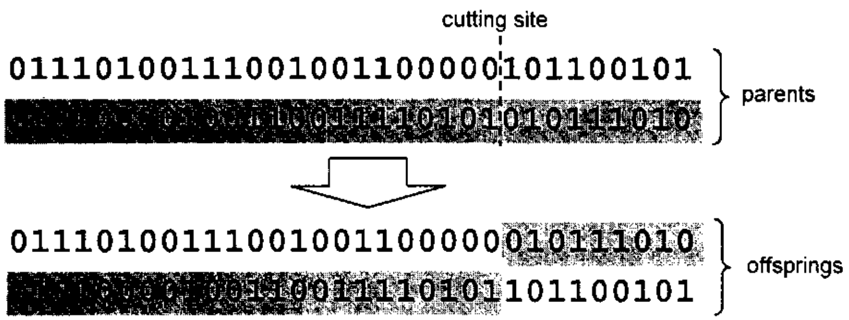

Figure 6.3   Simple (one-point) crossover

Not all selected pairs of strings get crossed over. Crossover is controlled by the *crossover probability* which is usually 0.5-0.6. Based on this probability, actual crossovers are triggered by an appropriate Monte Carlo algorithm.

Although crossover expands the search to a great extend, GA may still be trapped in certain subsets of the function domain. For example, if a certain bit-position takes '1' in each string of the population, then selection and crossover are no more able to move the search to those region of the domain where the coded forms of the individuals contain '0' at that bit-position. If the optimum is in that region, then the search gets inevitable diverted towards local optima. The role of mutation is just to prevent such *degeneration* by stepping along each string and changing the bits from '0' to '1' and vice versa with a certain probability (Figure 6.4). This *mutation probability* must be kept low (0.005 – 0.007) otherwise GA would become a random walk.

01110100111001001100■0010110010

01110100111001001100■0010110010

Figure 6.4 Mutation

Selection, crossover and mutation thus result a new population. Fitness evaluation of the new population results a likely better estimate of the probability distribution function of the optimum, which in turn serves to generate an even fitter population. This iterative search is stopped if no more improvement in fitness is detected, and thus the optimum is assumed to be achieved. In practice, such *termination condition* is met when the convergence rate of the maximum (and/or the mean) population fitness drops below a certain level. Thereafter, the individual with the highest fitness is marked as the GA based solution for the given problem.

Finally the basic features of GA can be summarized as follows [after Goldberg, 1989]:

1. GA works with the coding of individuals and not their actual values
2. GA searches from a population of points and not from a single point
3. GA uses only the fitness of individuals to direct the search, no derivatives or other auxiliary information are needed
4. GA uses probabilistic transition rules not deterministic ones.

6.2.2 Fitness scaling

Diversity of fitness values within the population may cause problems to the GA search. At the start of the iteration, few individuals of the randomly generated initial population may be much fitter than the rest. As a result subsequent generations will predominantly contain clones and offsprings of these few individuals, and thus GA may easily get trapped in sub-domains, from where crossover and mutation can hardly remove it. Low fitness diversity, that may occur at the end of the search, does cause problems too, as the little differences in selection probabilities would degrade GA to a simple random walk.

The solution for these problems is *fitness scaling*. The simple, *linear* fitness scaling (applied prior selection) transforms fitness values as follows [Goldberg, 1989]:

$$f_i^* = a \cdot f_i + b \tag{6.9}$$

Where:

f_i^*	scaled fitness of the i-th individual
f_i	un-scaled fitness of the i-th individual
a, b	scaling coefficients

The a and b coefficients are derived by applying the following conditions on equation 6.9:

$$
\begin{aligned}
f^{*}_{mean} &= f_{mean} \\
f^{*}_{\max} &= C_{\max} \cdot f_{mean}
\end{aligned}
\tag{6.10}
$$

Where:

f^{*}_{mean}, f_{mean} population means of the scaled and un-scaled fitness values (clones counted)

f^{*}_{max} scaled fitness of the best individual in the population

C_{max} scaling factor (usually kept within the interval of 1.2 to 3)

These conditions on the one hand ensure that selection probability of individuals with close-to-average fitness will not change significantly after scaling, on the other hand they maintain a stable ratio between selection probabilities of best individuals and that of population average all along the iteration process, thus preventing diversity problems.

As equation 6.8 indicates fitness values must be nonnegative numbers. Fitness scaling however may result negative values. Therefore, GA first checks the occurrence of such situation by scaling the worst individual of the population. If this check results negative fitness (f^{*}_{min}<0), then GA modifies the C_{max} scaling factor by calculating it from equation 6.9 (along with the a and b coefficients), and resumes the scaling process. The required additional condition ensures non-negativity:

$$f^{*}_{\min} = 0 \tag{6.11}$$

6.2.3 Embedding GA into the DSS

The role of GA in the modified ESEMOPS method is thus to minimize the surrogate objective functions in case of the principal and auxiliary problems.

The domain space of the surrogate objective functions is identical to the decision space of the multi-objective problem, while decision variables stand for the independent variables of the functions. Because principal and auxiliary problems are minimization problems, individuals' fitness is calculated by inverting the surrogate objective values. These values are in turn calculated from criteria achievements and aspiration levels as equations from 6.1 to 6.7 indicate. Criteria achievements are output of impact assessment that evaluates each decoded individual of the actual population.

GA must inevitably cope with constraints, if nowhere else then at the auxiliary problems. The simplest solution for this problem is to replace *stillborns* (individuals violating the actual constraints) with feasible individuals in the population. It does however cause troubles at highly constrained problems as it may degrade GA to a mere random walk searching for feasible individuals. In fact two kinds of searches have to be executed at constrained problems: first the set of feasible individuals have to be located, from where the optimum has to be selected out. The *penalty method* [Goldberg, 1989] enables the GA to do both searches in a simultaneous way. Instead of discarding stillborns this method degrades their fitness in relation to the degree of constraint violation. The penalty function applied in this study is based on this approach, even though it actually penalizes the surrogate objective values:

$$s_i = s_{f\max} + \sum_{j=1}^{nct} \max(0\,, d^i_j - 1) \qquad \forall\, i: \quad d^i_j > 1 \text{ for any } j = 1,\ldots nct \tag{6.12}$$

Where:

s_i	surrogate objective value of the i-th (stillborn) individual in the population
$s_{f\max}$	maximum of the surrogate objective values of feasible individuals within the population; $s_{fmax} = 0$ if all individuals are stillborn
nct	number of constraint functions at the actual decision iteration cycle
d_j^i	d value of the i-th individual at the j-th constraint function[2]

Equation 6.12 thus ensures that surrogate objective values of stillborns stay above that of the worst feasible individual of the population.

For the rest the GA based solution of principal and auxiliary problems follows the general steps of genetic algorithms as Figure 6.5 indicates.

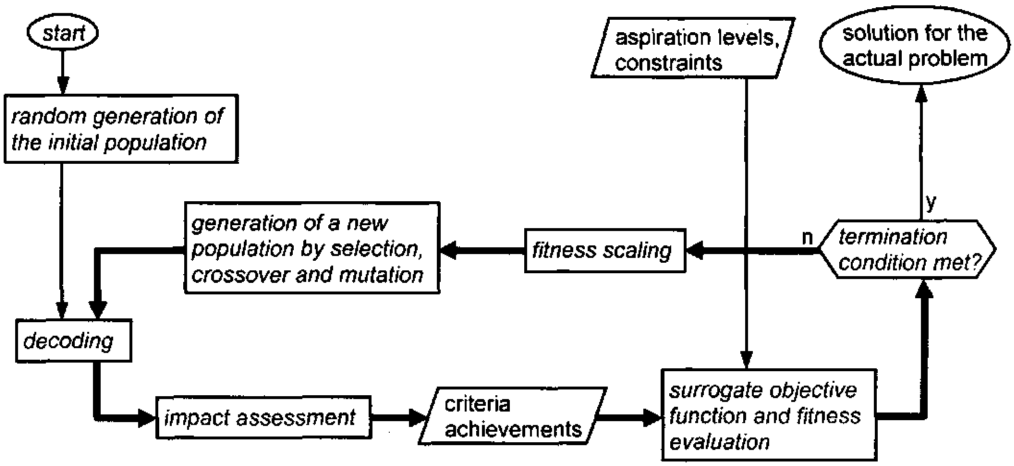

Figure 6.5 GA based iterative search process for locating solutions of principal and auxiliary problems in ESEMOPS

The role of impact assessment is to calculate the achievements of the actual individual at the applied criteria. Evaluation of ecological and land use criteria is based on the outputs of ecological and other functional models. Ecological and land use criteria and the related models applied in this study are introduced in Chapter 8. Input for the functional models are hydrological data, which has to be generated by means of hydrodynamic modelling, as it has been pointed out in Chapter 3 (see Figure 3.2). The hydrodynamic model applied in this study is introduced subsequently in Chapter 7.

[2] This implies that *all* constraint functions have to be transformed into d functions. For example the constraint $g(x) \leq 0$ of the original multi-criteria problem becomes an 'at most' type constraint where the un-scaled 'aspiration level' is zero.

6.3 Rationale of applying ESEMOPS

One of the major advantages of SEMOPS based techniques over other applicable multi-objective decision support tools (e.g. Weighted Average, ELECTRE) is the perceptible way of preference articulation. That is to say, desired levels of criteria attainments are much easier to grasp for the members of the DMG than for example criteria weights. Aspiration levels also support better the process of bargaining among the different interest groups of the DMG, since strengthening and relaxing aspiration levels indicate directly the gains and losses a certain sub-group books during the bargaining process.

Another advantage of ESEMOPS is that it supports progressive articulation of preferences. It enables the PG and the DMG to get acquainted with the hydrological and ecological responses of the subjected cell-system against the different revitalisation approaches. Similarly, the financial aspects of the different approaches get also revealed during the decision iteration process. Based on the revealed trade-offs and inter-relationships among the criteria, the DMG is enabled to accommodate its preference structure to the reality.

7. HYDRODYNAMIC MODELLING

This chapter introduces the hydrodynamic modelling module of the Decision Support System (DSS). In the first section a classification and an overview of existing approaches for hydrodynamic modelling of floodplains is given; thereafter the newly developed model is introduced, while the third section provides the justification of applying this specific model in the DSS.

7.1 Brief overview of approaches for hydrodynamic modelling of floodplains

The simplest way of modelling the water regime of floodplains is using *1-D steady state models*. De Jonge *et al.* [1992] and Marchand [1993] for example used early versions of the SOBEK model [Delft Hydraulics & RIZA, 1997] for calculating water levels at different discharges in the Rhine riparian Millingerwaard and the Danube riparian Gemenc floodplains. These were in fact steady state flow profile calculations with channel cross-sections traversing the entire river-floodplain system.

Note that these 1-D steady-state applications rely on the assumption that a horizontal water surface traverses each cross sections of the river-floodplain system any time. This assumption is however not applicable in those cases when obstacles such as levees, dikes or structures hamper the inundation of the floodplain. In these cases the restricted in- and outflow processes result a hydrograph on the floodplain, which is different from that of the river. To get such hydrograph one needs to employ unsteady *simulation models* (1-D or 2-D).

Cunge [1975] developed the first sophisticated numerical model for simulating the water regime of floodplains. This is a *quasi 2-D cell model* in which the floodplain and the river are subdivided into cells connected to each other by means of links. Cells may represent sections of the river or depressions on the floodplain surface. Each cell has level water surface. Links can be of two types: river or weir links. Obviously, river reaches are connected to each other by river-type links. Weir-type links connect those cells, which are divided from each other by means of summer dikes or levees. Outputs of Cunge's model are simulated water levels in the cells and simulated discharges in the links. This model was applied for several case studies (e.g. Mekong Delta, Senegal river) with the common aim of simulating the propagation of floods in case of different water resources development options, such as constructing barrages, canals and reservoirs.

Weiss [1976] improved Cunge's model by assuming that water levels in river cells are inclining in the general direction of flow, which is normal to the cross sections separating the cells. Furthermore, Weiss' model calculates river discharge from the mean energy heads of the river cells while Cunge's model considers only the water levels of the cells.

The model INUNDA [Duizendstra & Schutte, 1993] was developed for simulating the water regime of those floodplains of the Dutch Rhine branches, which are situated behind summer dikes. INUNDA handles these 'polders' as single cells linked to the river by means of weirs that represent different summer dike sections, or by means of outlet sluices built into the summer dike. Boundary conditions are water levels of the river at the links. Thus, the major difference with respect to the other cell models is that INUNDA does not involve the riverbed into the model.

Another way of quasi 2-D floodplain modelling is to schematise the floodplain morphology into a *network of channels*, thus making the system handleable for *1-D simulation models*. Kjelds *et al.* [1996] for example applied the MIKE 11 model [Danish Hydraulic Institute, 1998] for simulating the consequence of dike ruptures along the Dutch Rhine reach. A complex channel network model was developed which enabled to simulate the flooding of the waste flat areas inside the flood control dikes.

Decreasing the spatial scale requires replacing quasi 2-D models with *real 2-D models*. Weiss [1976] for example applied a real 2-D model for simulating water levels within a river cell of the quasi 2-D model. Weiss' cell model provided boundary conditions for the real 2-D model.

7.2 New hydrodynamic model for floodplain cell-systems

The hydrodynamic model that is to be incorporated into the proposed DSS must satisfy two basic requirements:

1. Its code has to be fully integrable into the DSS software.
2. Its simulation speed must be extremely high in order to facilitate the work with the DSS.

Because of the first condition commercially available softwares can hardly be applicable unless their source codes were available. The second requirement practically excludes the channel network concept because of the time-consuming complicated calculation methods of 1-D models. The desired model is thus a kind of cell model. Existing cell model approaches however cannot be applied directly because of their simple link representations (weirs or prismatic channels). Long 'fok'-channels with highly variable morphology and geometry cannot be simplified into such simple links without loosing characteristic features of the system.

Accordingly a new cell model had to be constructed for simulating the water regime of floodplain cell-systems. The name of this model is '*FOK*', which refers to the ancient Hungarian name of such systems. The schematised system consists of *system cells, boundary cells* and connecting *links*. Definition of system cells is identical to that of the 'cells' given in Chapter 5. The attribute 'system' is needed only to make distinction between system and boundary cells in the model configuration. The case study system of this thesis consists of four system cells, which are the Cserta, Nyéki, Báta and Csörösz oxbows together with their inundation areas (Figure 7.1).

Thus system cells are the maximum extends of the oxbows during floods. Like in case of the INUNDA model, boundary conditions of FOK are water level time series of the river system at those sections where the cell-system is connected. These sections are in fact the boundary cells. The Gemenc cell-system has four boundary cells (Figure 7.1) representing either the Danube water levels or that of the directly interconnected side arms.

Links are composite structures. One link may consist of a *fok-channel* and several hypothetical *overland flow weirs* (Figure 7.2). Overland flow weirs enable to continue simulation even in case if water flows not only in the fok-channel but also over the crest of the cell boundary. Fok-channels can be replaced with *structure weirs*. This is the case when a trapezoid weir is built into the channel resulting that most of the head losses get concentrated at the section of this weir. It is not necessary to have a fok-channel or a structure weir in a link. For example no such structures exist between the Nyéki and Csörösz oxbows (Figure 7.1) and thus the related link consists of only overland flow weirs.

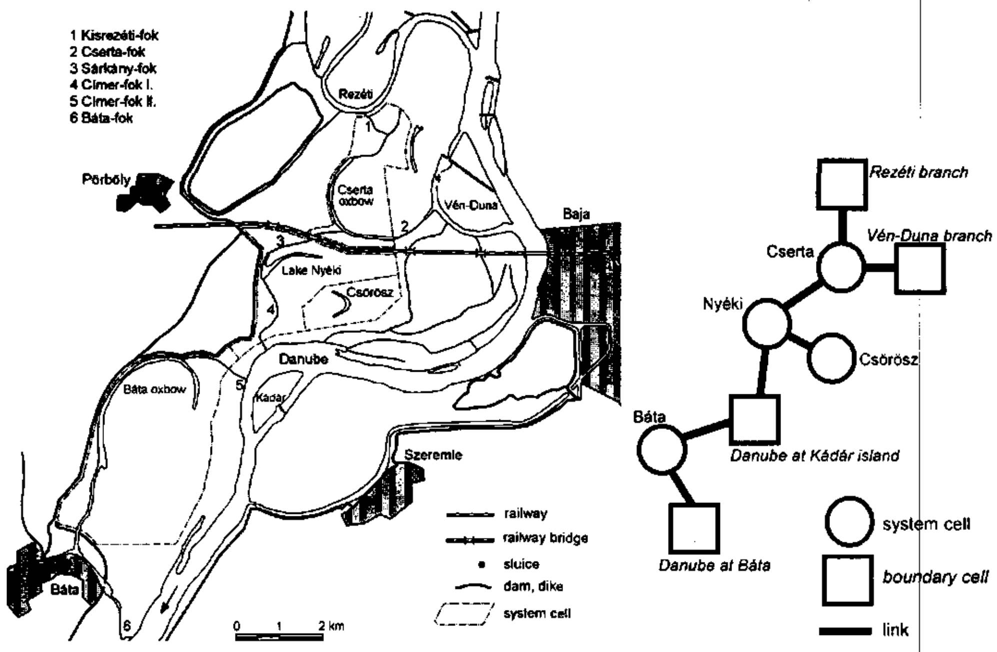

Figure 7.1 The present state of the Gemenc cell-system and its model configuration

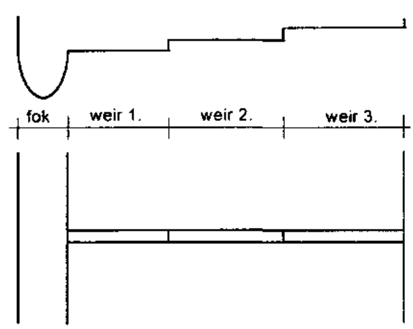

Figure 7.2 Schematised link connecting the cells in the FOK model

At this point it is necessary to state that the accuracy of FOK is restricted to those situations only when no significant overland flow occurs. Accurate modelling of water levels at full inundation of the floodplain is likely to require another model (a real 2-D model), or at least a more refined model configuration to describe the different flow patterns.

The purpose of the FOK model is thus to simulate water levels in the system cells and discharges in the links as a function of water levels in the river.

The governing equations of FOK are based on three fundamental assumptions:

1. The volume of water stored in a system cell depends only on the water level and the topography of the cell [Cunge, 1975].
2. The discharge in a link is a function of link morphology and of the actual water levels in the connected cells [Cunge, 1975].
3. Quantities of water flowing between the river and the cell-system are so small that modifications in the cell-system would not influence water levels in the river.

The governing equation system of the model consists of continuity equations for the system cells:

$$\frac{dV_j}{dt} = \sum_{i=1}^{nl_j} Q_{ij} + Qs_j + (P - E) \cdot A_j \qquad j = 1, \ldots, nsc \tag{7.1}$$

Where:

V_j :	volume of water stored in the j-th system cell (m^3)
nsc :	number of system cells (-)
t :	time (s)
nl_j :	number of links of the j-th system cell (-)
Q_{ij} :	inflow to (or outflow[1] from) the j-th system cell through its i-th link (m^3/s)
Qs_j :	seepage flow between the j-th system cell and the groundwater (m^3/s)
P, E :	precipitation and evaporation intensities in the area of the cell-system (m/s)
A_j :	area of the water surface in the j-th system cell (m^2)

Qs seepage flows can be neglected as clay sedimentation usually makes the floodplain surface quite impermeable. Substituting $dV_j = dz_j \cdot A_j$ into equation 7.1 thus results:

$$\frac{dz_j}{dt} = \frac{\sum_{i=1}^{nl_j} Q_{ij}}{A_j} + P - E = f_j\left(\bar{z}, \overline{zb}, P, E, t\right) \qquad j = 1, \ldots, nsc \tag{7.2}$$

Where:

$\bar{z}\,(z_1, z_2, \ldots, z_{nsc})$: water levels of the system cells (maD)

$\overline{zb}\,(zb_1, zb_2, \ldots, z_{nbc})$: water levels of the boundary cells (maD) (*nbc*: number of boundary cells)

[1] Outflow from a cell is interpreted in the model as negative inflow.

Since $\overline{zb}$, P and E are known functions of t (boundary conditions), the equation system is in fact a system of first order ordinary differential equations:

$$\frac{dz_j}{dt} = f_j(t, \bar{z}) \qquad j = 1,....nsc \tag{7.3}$$

The simplest way for the numerical solution of this equation system is applying the Euler method, which advances the solution from t^n to $t^{n+1} = t^n + \Delta t$ as follows:

$$z_j^{n+1} = z_j^n + \Delta t \cdot f_j\left(t^n, \bar{z}^n\right) \qquad j = 1,....nsc \tag{7.4}$$

This scheme is however numerically quite unstable. Unconditionally stable scheme can be constructed by substituting t^{n+1} into the right hand side [Cunge, 1975]:

$$z_j^{n+1} = z_j^n + \Delta t \cdot f_j\left(t^{n+1}, \bar{z}^{n+1}\right) \qquad j = 1,....nsc \tag{7.5}$$

This scheme is however very complicate to calculate because the unknown z^{n+1} variables are present in the non-linear link discharge terms of the right hand side. Cunge [1975] resolved this problem by developing the discharge terms in Taylor series and disregarding the higher order terms. Hence discharges and their derivatives are needed only from time point t^n where they can be calculated from the cell water levels computed by the previous step. The resulted implicit linear equation system is then solved by means of the 'double sweep' method.

The calculation efficiency of Cunge's method enabled to model systems with several hundreds of cells, even on the computers of the seventies. The number of cells on the floodplain of a medium river hardly reaches the level where the advantages of Cunge's method become significant. Furthermore Cunge's method would need the derivatives of discharges, which are rather complicated to derive due to the complex morphology of fok-channels.

Thus, an alternative numerical method has been applied, which is the *fifth order Runge-Kutta scheme with adaptive stepsize control* [Press *et al.*, 1992]. The step equation of this method has the following general form:

$$z_j^{n+1} = z_j^n + \Delta z_j\left(\Delta t, t^n, \bar{z}^n, f_j\right) \qquad j = 1,....nsc \tag{7.6}$$

Where $\Delta z_j\left(\Delta t, t^n, \bar{z}^n, f_j\right)$ stands for the complex fifth order Runge-Kutta increment.

Adaptive stepsize control estimates the error of the time step, and if it is higher than a pre-specified limit the step is repeated with a smaller Δt stepsize. If the error is lower, the algorithm goes for the next step with an appropriately increased stepsize. This dynamic stepsize adjustment satisfies the desired accuracy on one hand, on the other hand it reduces computational efforts by increasing the stepsize at the smooth sections of the function where even high stepsizes satisfy the desired accuracy. This efficiency is however likely to decrease with increasing number of cells, since always the maximum of estimated errors of calculated cell water levels is taken as characteristic error of the actual time step.

Detailed description of the fifth order Runge-Kutta method with adaptive stepsize control can be found in Appendix I.1.

7.2.1 Calculation of discharges in the links

In the course of numerical integration the FOK model continuously calculates discharges in the links as a function of water levels in the connected cells. The total discharge of a link is given by the following equation:

$$Q = Qf + \sum_{k=1}^{nw} Qw_k \tag{7.7}$$

Where:

Qf: discharge in the fok-channel (or structure weir) of the link (m^3/s)

nw: number overland flow weirs in the link (-)

Qw_k: discharge over the k-th overland flow weir of the link (m^3/s)

Discharge over a general trapezoid weir is calculated by superimposing a rectangular and a Thomson weir [Haszpra, 1987]:

$$Qw = \delta \cdot \left(\frac{2}{3} \cdot \mu \cdot t \cdot \sqrt{2 \cdot g} \cdot (z_u - zw)^{\frac{3}{2}} + \frac{8}{15} \cdot \mu \cdot \mathrm{ctg}\alpha \cdot \sqrt{2 \cdot g} \cdot (z_u - zw)^{\frac{5}{2}} \right) \tag{7.8}$$

Where:

z_u: water level upstream (maD)

μ: weir discharge coefficient (-)

t: width of the weir crest (m)

α: inclination of the weir side wall

δ: submergence coefficient (-)

zw: elevation of the weir crest (maD)

The δ submergence coefficient is a function of the ψ relative submergence (Figure 7.3). This latter is calculated from the following equation:

$$\psi = \frac{z_d - zw}{z_u - zw} \tag{7.9}$$

Where:

z_d: water level downstream (maD)

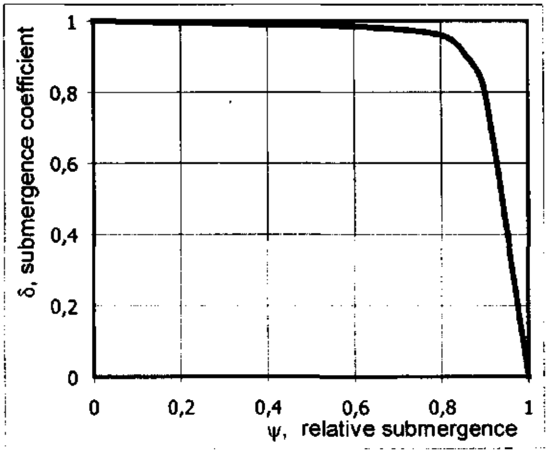

Figure 7.3 Relation between relative submergence and submergence coefficient in case of trapezoid weirs [after Starosolszky, 1970]

If floodplain channels were simplified into short prismatic channels, then it would be possible to calculate the discharge directly from the upstream and downstream cell water levels, by using the Chézy equation. Cunge's [1975] cell model actually does so. Such simplification is however far too rough in the case of fok-channels due to their highly variable geometry. Variable geometry results variable flow conditions. In the wide and deep sections the water flows slowly, while it may speed up even to *supercritical flow* in the narrow contractions or over the bed fillings.

Consideration of variable geometry and flow conditions would make runtime flow calculation complicated and time consuming. Hence, FOK calculates fok-channel discharges by means of *linear interpolation* among the known points of their *delivery functions*. These points of the delivery functions are determined by the FOKBUILD program, *prior* simulation. FOKBUILD actually performs flow profile calculations with the purpose to derive upstream cell levels at different combinations of discharges and downstream cell levels. Two delivery functions are generated for each fok-channels according to the two possible flow directions. Figure 7.4 shows one of the delivery functions of Címer-fok I. in the Gemenc cell-system (see also Figure 7.1).

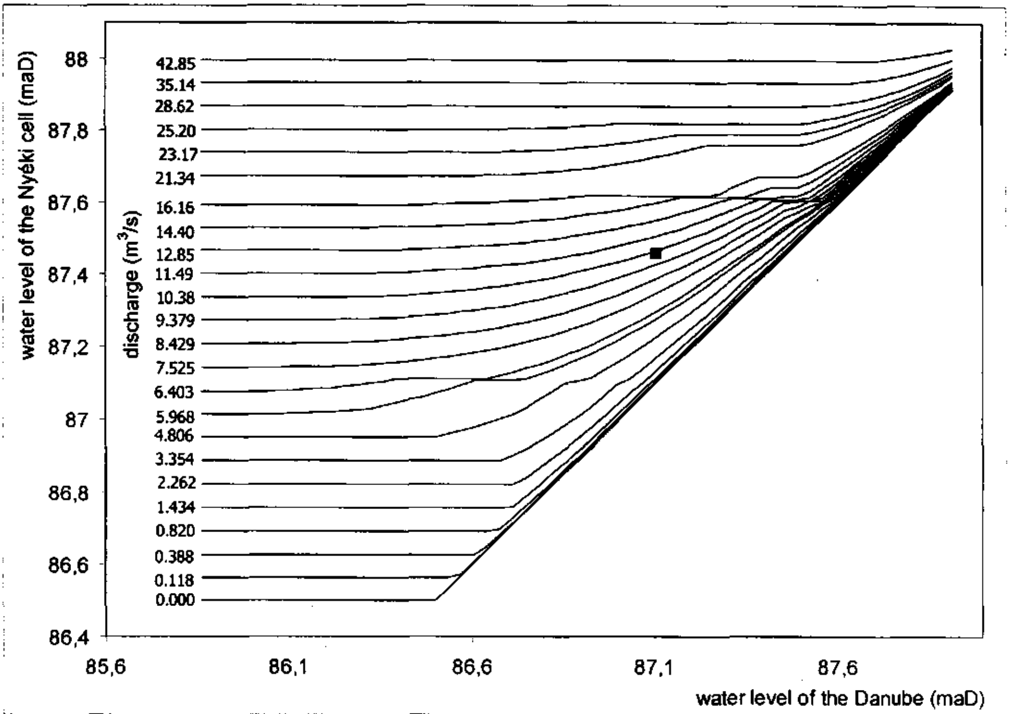

Figure 7.4 Delivery function of the Címer-fok I. for the Nyéki-Danube flow direction (the flow profile calculated for the marked point is displayed on Figure 7.8)

Calculation of delivery functions for fok-channels

According to the second fundamental assumption of FOK, the flow in a fok-channel is considered *steady state* at any time point. Steady state flow in natural channels is assumed to be *gradually varied*. Mathematical description of such flow is based on the steady state form of the dynamic de Saint-Venant equation:

$$v \cdot \frac{dv}{dx} + g \cdot \frac{dh}{dx} + g \cdot \left(S_f - S_0\right) = 0 \qquad (7.10)$$

Where:

v : mean flow velocity (m/s)

x : distance along the channel measured in the direction of flow (m)

g : gravitational celerity (m/s^2)

h : depth above the deepest point of the section (m)

S_0 : bed slope (-)

$S_f = \frac{Qf^2}{K^2}$: friction slope (-)

Qf: discharge of the fok-channel (m^3/s)

$K = k \cdot A \cdot R^{2/3}$: conveyance of the flow section (m^3/s)

k : Manning-Strickler smoothness coefficient ($m^{1/3}/s$)

A : wetted area of the cross-section (m^2)

R : hydraulic radius of the cross-section (m)

By substituting $v = \frac{Qf}{A}$, equation 7.10 takes the following form:

$$\frac{Qf}{A} \cdot Qf \cdot \frac{d\left(A^{-1}\right)}{dx} + g \cdot \frac{dh}{dx} + g \cdot \left(S_f - S_0\right) = 0 \tag{7.11}$$

Arranging further the equation:

$$\frac{-Qf^2 \cdot A^{-3}}{g} \cdot \frac{dA}{dh} \cdot \frac{dh}{dx} + \frac{dh}{dx} = S_0 - S_f \tag{7.12}$$

By substituting $\frac{dA}{dh} = T$ and $\frac{dh}{dx} = \frac{dz}{dx} - S_0$, and reversing the direction of the x axis, the equation takes the form applied by Chow [1959]:

$$\frac{dz}{dx} = \frac{S_f - S_0}{1 - \left(sf_c / sf\right)^2} + S_0 \tag{7.13}$$

Where:

T : width of the water surface (m)

z : water level in the fok-channel (maD)

$sf = \sqrt{\frac{A^3}{T}}$: section factor ($m^{5/2}$)

$sf_c = \frac{Qf}{\sqrt{g}}$: critical section factor ($m^{5/2}$)

Thus, the FOKBUILD program carries out flow profile calculations based on the numerical integration of equation 7.13. Since it is again a first order ordinary differential equation, the numerical solution is based on the fifth order Runge-Kutta scheme with adaptive stepsize control [Press *et al.*, 1992] (see Appendix I.1).

In the course of integration, conveyance (K) and section factor (sf) values have to be calculated at the actual cross sections. To reduce computational efforts and to avoid complications arising from compound channel sections, the actual values are derived by linear interpolation among the given points of conveyance and section factor functions of the cross sections. These functions are determined in discrete points for each input cross section of each fok-channel by a pre-processor module of FOKBUILD. Detailed description of the calculation of these functions is given in Appendix I.2.

It is also very important to consider that two sorts of water flow may develop in a fok-channel:

1. *Submerged flow*: the flow is *subcritical* all along the channel.
2. *Free flow*: the flow is supercritical in certain sections.

In the first case, flow profile is calculated in discrete Runge-Kutta steps starting from the downstream cell level and proceeding towards the upstream cell level, which is the ultimate goal.

In case of free flow, the transition from subcritical to supercritical flow takes place at the section of ***hydraulic drop*** where the flow is critical. Hydraulic drop must be accompanied by a ***hydraulic jump*** at the end of the supercritical reach unless the level of the downstream lake is so low that supercritical outflow occurs at the downstream end of the channel. It is possible however that more than one supercritical reach develop in a fok-channel.

Flow profile calculation in channels with supercritical reach(-es) becomes rather complicated because of the following reasons:

1. The flow profile is not continuous in the section of hydraulic jump.
2. Locating the hydraulic jump requires additional computations based on equilibrium calculations of momentum, pressure, friction and gravity forces acting on the jump.
3. For the sake of numerical stability subcritical reaches should be calculated from downstream to upstream, while supercritical reaches should be integrated from upstream to downstream [Chow, 1959].

Given all these complications the question is justified whether it is really necessary to calculate the flow profile all along the channel.

Recall that the ultimate goal of flow profile calculation is to determine the upstream cell level, which means that the computation can be started at any section, provided that the water level is known at that section. If there is no supercritical reach upstream this section then the flow profile calculation ends up at the upstream cell level. In case of free flow such *control section* is obviously the first hydraulic drop from upstream where the flow is critical. That is to say, critical water level can unequivocally be calculated from the discharge and from the geometry of the section, since the section factor is equal to the critical section factor [Chow, 1959]:

$$\sqrt{\frac{A^3(z_c)}{T(z_c)}} = \frac{Qf}{\sqrt{g}} \tag{7.14}$$

Where:

z_c : critical water level (maD)

Equation 7.14 also means that the denominator of the ratio on the right hand side of equation 7.13 ($1-(sf_c/sf)^2$) is zero. If the denominator is zero then the numerator, which is S_f-S_0, should also be zero, otherwise $\lim_{x \to x_c}\left(\frac{dz}{dx}\right) = \pm\infty$, which is not feasible in case of gradually varied flow. Accordingly, $\lim_{x \to x_c}\left(\frac{dz}{dx}\right)$ is a finite boundary value that equals to the critical slope. Such point is also called as the *singular point* of the differential equation [Chow, 1959].

Thus, critical flow may occur in those sections only where S_f=S_0 and sf=sf_c, in other words: where the *normal depth* [Chow, 1959] is equal to the *critical depth*. Whether critical flow really develops in such sections is also dependent on the upstream and downstream conditions. For example, if downstream water levels are so high that the hydraulic jump is pushed upstream of the point (or even the entire supercritical reach disappears), then the flow remains subcritical in the section.

Accordingly, the FOKBUILD program calculates the discrete points of the delivery function in two steps. In the first step it calculates upstream levels at different discharges assuming free channel flow. In the second step FOKBUILD computes upstream levels at the same discharges but at different downstream levels (Figure 7.5).

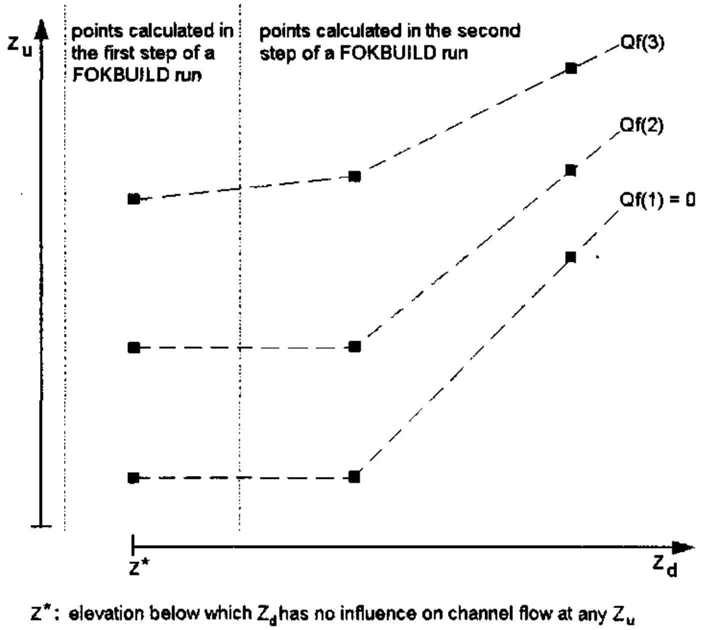

Figure 7.5 Discrete points of a fok-channel delivery function

In case of free flow calculations, water is supposed to enter the downstream cell in supercritical state, so the numerical integration can be started from the critical level of the first potential control section, which is the first singular point from downstream. The critical water level itself is calculated from equation 7.14. Now if the calculation does not go below the critical level, then the starting section is the real control section and the Runge-Kutta integration ends up at the upstream cell water level. If calculation goes below the critical level then it indicates that the flow is supercritical at that location. It is not necessary to calculate this supercritical reach neither to locate the hydraulic jump. For further calculation the integration can be continued from the next potential control section, which is the next singular point upstream. The last such potential control section, above which no supercritical flow occurs, is the actual control section in the channel (figures 7.6 and 7.7).

link that connects them. The reason of deceleration is that even small differences in water levels of such 'merged' cells could result in very high discharges, which in turn may lead to numerical instability, unless the time step has been decreased appropriately. This is why the adaptive stepsize control automatically decreases the time step in such situations. Such periods of low calculation speed sustains as long as the water surface drops below a level where the decreased discharges enable to increase the time step.

To overcome this problem the FOK model has been supplemented with an algorithm that virtually 'merges' neighbouring cells into one *composite cell* if hydrodynamic conditions enable to do so. For example, the Nyéki and Csörösz oxbows of the Gemenc cell-system (Figure 7.1) practically merge into one lake whenever the natural levee, that divides them, gets submerged. Accordingly the merging algorithm modifies the model configuration in such situations as displayed on Figure 7.9.

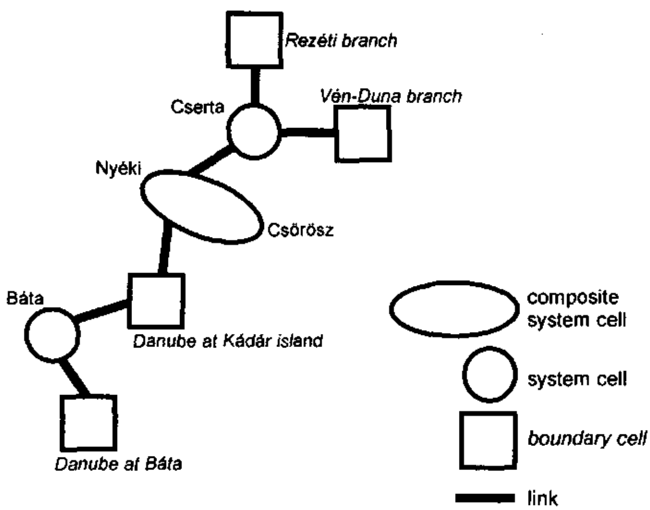

Figure 7.9 Modified model configuration of the Gemenc cell-system that accounts for the mergence of Nyéki and Csörösz cells

The link between two merged cells (*submerged link*) thus being automatically eliminated from the calculations. The elevation–area ($A(z)$) function of the composite cell is derived by adding the $A(z)$ functions of the component cells. Having the calculation bottleneck removed in such a way, the simulation becomes on average ten times faster, without compromising on the accuracy.

The condition upon which a link gets submerged (and the connected system cells get merged) is as follows:

$$z_i > zl_k \quad \wedge \quad z_j > zl_k \quad \wedge \quad \left|z_i - z_j\right| < \varepsilon \quad \wedge \quad \left|\frac{dz_i}{dt} - \frac{dz_j}{dt}\right| < \varepsilon \qquad (7.15)$$

Where:

z_i, z_j : water levels in the i-th and j-th cells (maD)

zl_k : flow threshold of the k-th link that connects the i-th cell with the j-th cell (maD)

ε: accuracy of the integration

This condition is checked at each internal link (link between system cells) at the start of each time step. It may even happen that more than two system cells get merged into one composite cell.

It is also very important to split up composite cells if hydrodynamic conditions *demand* to do so. Accordingly, the submergence of *each* submerged link has to be checked right after each completed calculation step. This check has the following steps:

1. Split up temporally the composite cell at the link into two cells (cell *a* and cell *b*)[2]
2. Calculate the time derivatives of water levels ($\frac{dz_a}{dt}, \frac{dz_b}{dt}$) in these cells with the help of equation 7.2
3. Make temporally an ε high difference between the water levels of the two cells according to the derivatives:

$$\begin{aligned} z_a^\bullet &= z_a + \frac{\varepsilon}{2}\ ;\quad z_b^\bullet = z_b - \frac{\varepsilon}{2} \quad \text{if} \quad \frac{dz_a}{dt} > \frac{dz_b}{dt} \\ z_a^\bullet &= z_a - \frac{\varepsilon}{2}\ ;\quad z_b^\bullet = z_b + \frac{\varepsilon}{2} \quad \text{if} \quad \frac{dz_a}{dt} < \frac{dz_b}{dt} \end{aligned} \tag{7.16}$$

4. Calculate again the derivatives of water levels ($\frac{dz_a^\bullet}{dt}, \frac{dz_b^\bullet}{dt}$)
5. If these derivatives indicate an increasing difference in water levels then it means that the link is no more submerged, else the link can still be considered submerged since the water level difference tends to stay within the accuracy limit

If the submergence tests result that any of the composite cells has to be split up, then the program modifies cell configuration accordingly, repeats the last calculation step and goes for the subsequent step.

Note, that the above-described cell-merging algorithm is applicable only if the graphs formed by the merged system cells are always trees. That is to say, a loop cannot be cut into two pieces merely by cutting one of its arcs. Of course, this shortcoming of the FOK has to be eliminated in the future.

[2] Cell *a* and cell *b* may still be composite cells.

7.3 Rationale of the new hydrodynamic model

One of the most important reasons of developing a new hydrodynamic model was the extremely high simulation speed demanded by the DSS. The FOK model is indeed much faster than any other software capable to do the job, thanks to the following special features:

1. Efficient numerical integration provided by adaptive time step control.
2. Applications of pre-calculated delivery functions that enable to skip runtime flow calculations in fok-channels.
3. Automatic, runtime composition and decomposition of composite system cells.

If the Gemenc cell-system were modelled by a 1-D model using channel network configuration, then it would take about 10-15 minutes on a computer with Celeron 366 processor to complete a 21 year long simulation [Sziebert, 1999, pers. com.]. For the FOK model it takes only 6 seconds!

Another advantage of FOK (and of cell models in general) over 1-D models is the ease in handling discontinuities in the water surface. Discontinuity occurs for example when the water level drops below the flow-threshold of a link. FOK simply sets the discharge of the link to 0 and continues the simulation. 1-D models however would get confused unless special 'tricks' such as the 'Preissman funnel' [Delft Hydraulics & RIZA, 1997] are applied in order to maintain a virtually continuous water surface.

Discontinuity occurs at the section of hydraulic jump too. Transitions between supercritical and subcritical flows cause in general a lot of numerical problems as it has already been pointed out. When the FOK was developed the actual version of the SOBEK model for example could only deal with subcritical flow conditions; it stopped the calculation whenever the flow turned to supercritical [Delft Hydraulics & RIZA, 1997][3]. The FOKBUILD program (pre-processor of FOK) however is able to locate and 'bridge' supercritical sections when calculating delivery functions for the channels.

One must however keep in mind that these advantages of FOK are due to its special design, which restricts its applicability to hydrodynamic modelling of floodplain cell-systems. 1-D models (like the SOBEK) on the other hand are able to assist a much wider spectrum of water resources development projects.

Finally, the flow chart displayed on Figure 7.10 summarises the most important steps of modelling with the FOK.

[3] The latest version of SOBEK is capable to calculate both subcritical and supercritical flows [Verwey, 2000, pers. com.].

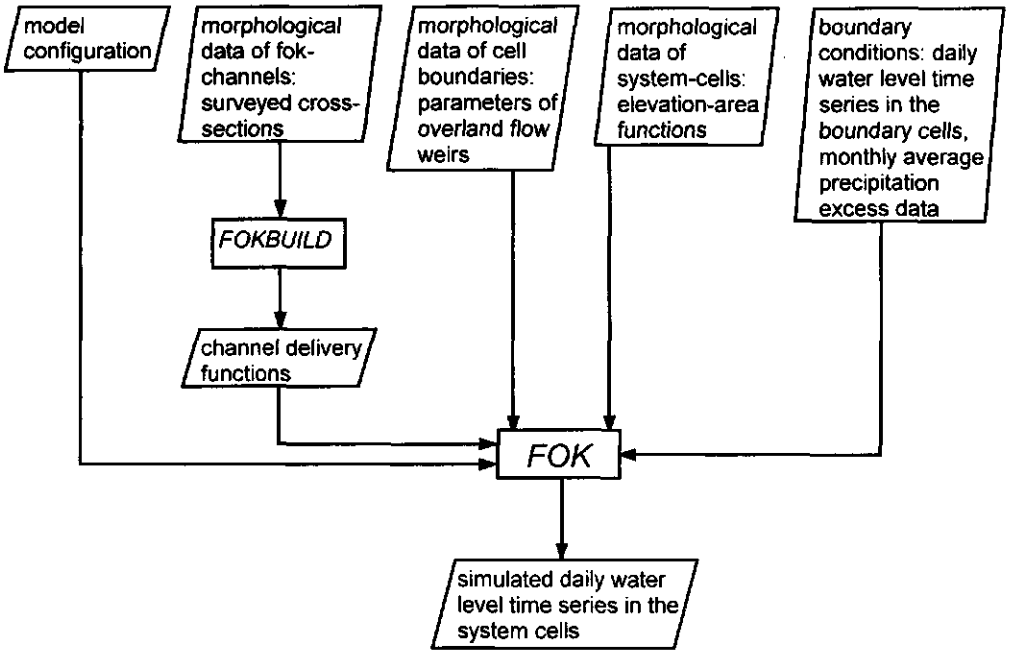

Figure 7.10 Flow chart of the FOK model

8. ECOLOGICAL MODELLING

The purpose of this chapter is to introduce the ecological models and assessment tools embedded into the Decision Support System (DSS). The role of these tools is to evaluate ecological criteria in case of each alternative cell-system solution that is generated during the multi-criteria search process.

After discussing the basic principles in Section 8.1, an extended overview, classification and evaluation of ecological models found in the literature are given (Section 8.2). Finally Section 8.3 introduces the models, assessment tools and the related evaluation criteria actually applied in the DSS. These models and tools have been selected and developed on the basis of the conclusions derived from model evaluations.

8.1 Principles of ecological modelling

Ecological models are mathematical interpretations of the internal and external relations of ecosystems. Ecological models consist of five main components [after Jørgensen, 1989]:

1. *Independent* or *input variables*: characterise the internal and external factors having influence on the modelled elements of the ecosystem. Internal factors are abiotic or biotic elements of the ecosystem, while external factors come from the environment surrounding the ecosystem. Those independent variables, which can be modified arbitrarily by the modeller (within limits of course), are also called as *control variables*.
2. *Dependent variables*: these can be of two types: *target* (or *output*) *variables* and *auxiliary variables*. Target variables characterise those elements of the biocenosis, which are actually targeted by modelling. Auxiliary variables are often needed to be involved because of the complex relations of the target variables.
3. *Equations*: describe mathematically the relations between the dependent and independent variables. *Core equations* are the ones, which are directly applied by the model (e.g.: numerical schemes of differential equations).
4. *Parameters*: the constant elements of the equations that are subjects of calibration.
5. *Universal constants*: constants, which usually do not need to be calibrated.

The purpose of ecological modelling is to enable quantitative predictions of consequences of changes in influencing factors on the targeted biotic elements of the ecosystem.

Output of ecological models can take several different forms. Biogeochemical models [Jørgensen, 1989] result masses, concentrations or other type of variables indicating the biomass of certain species or group of species. These models consider the flow of material and the law of mass conservation conditions them. Bioenergetic models [Jørgensen, 1989] on the other hand, are based on energy conservation and they consider the flow of energy in the system. Their target variables are measured in energy units. The close relation between biomass and its energy content however, makes quite simple to transfer a biogeochemical model to a bioenergetic model and vice versa [Jørgensen, 1989]. Therefore this study does not make distinction between models of these types, but treats them uniformly as ***biomass models.***

Habitat models calculate the quality and the spatial extend of habitat available for a certain species or group of species. Core equations of habitat models indicate only the preference of the modelled species towards the different biotic and abiotic variables characterising the habitat. These core functions can either have a *binary* or *continuous* form. Binary functions tell only whether the species is present in, or absent from the habitat. Continuous functions result in a number between 0 and 1, indicating the dependence of the species on the habitat conditions. This number can either be a probability of presence (*P*) or a ratio of spatial extend within a unit area (*ratio*) or a fictive index indicating the suitability of the habitat for the species (*SI*). 0 indicates that the habitat is totally unsuitable for the species while 1 means sure presence, full cover or optimal conditions (Figure 8.1).

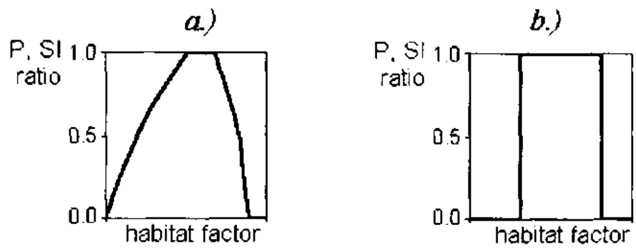

Figure 8.1 Examples for continuous (a.) and binary (b.) core functions for habitat models

Dynamic ecological models involve the time as independent variable. Dynamic biomass models are based on the dynamic differential equations of the state (s) with the corresponding initial conditions [Djordjević, 1993]:

$$\frac{ds}{dt} = f(x,s,u,a,t); \quad s(t_0) = s_0 \tag{8.1}$$

Static models on the other hand disregard the time, either by modelling the expected state of the ecosystem, or by assuming that the ecosystem is in steady state.

8.2 Overview of ecological models for floodplains

8.2.1 Vegetation models

Ecological models, whose target variables characterise the vegetation life, are called vegetation models. Certain vegetation models are termed as *physiological*, as their equations describe real physiological processes. The rest of the models are called *conditional*, because the equations of these models relate vegetation directly to the conditional level of the vegetation influence chain[1].

[1] For more about vegetation influence chains see Chapter 2.

Input variables however do not necessarily refer to the level of the model. Physiological models for example usually receive input from the conditional level. In these cases however, it is the task of the model to bridge the gap from the conditional level to the physiological level, which, on the other hand, increases complexity and requires several auxiliary variables.

Habitat type vegetation models are called *ecotope* models. Ecotope is a specific vegetation community whose survival depends on the specific conditions of the hosting biotope. Ecotopes are defined by their vegetation composition and measured by the areas they are occupying. Thus, ecotope classification of vegetation is different from the taxonomic classification, since it is based on common abiotic requirements and not on structural and evolutional similarities of the component species. The ultimate outputs of ecotope models indicate the spatial distribution of ecotopes over the considered geographical space.

Input for dynamic vegetation models are time series of hydrological and meteorological variables from the considered time period, plus the time invariant variables such as soil factors or terrain elevations. It is possible however, that all input variables are time invariant. For example, this is the case of simulating successional developments under constant hydrological and meteorological conditions.

Static vegetation models for floodplains describe the expected state of the dynamic equilibrium maintained by the influencing water system along the flooding gradient. In case of static ecotope models, expected states are ecotopes on the expected stages that the succession achieves at different locations of the floodplain. Input for static models corresponds to the expected state of the abiotic environment.

Binary ecotope models are also called matrix models [Witte, 1990; Jørgensen, 1989] since their equations can be aggregated into matrices. Each dimension of such matrix represents an independent variable. The dimensions of the matrices are subdivided into classes. Each combination of these classes specifies an element in the matrix, which is the ecotope expected to develop at the site.

An overview of models found in the literature, is given in the subsequent sections. The selected models represent specific combinations of model classes described above.

Static conditional binary ecotope models

The multidimensional matrix models of Duel [1991] and Pedroli [1993] are examples for this type of models.

Duel's Rhine Matrix Model (RMM) has been developed for the floodplains of the river Rhine in the Netherlands. It has five dimensions namely: geomorphological unit, soil type, expected annual inundation duration, isolation and vegetation management. The variable 'isolation' represents the influence of natural levees or summer dikes on inundation conditions. Thus, the hydrological input for RMM (the expected annual inundation duration) is calculated directly from river water levels and not from water levels measured or calculated on the site.

The Gemenc Matrix Model (GMM) of Pedroli [1993] has been developed for the Danube riparian Gemenc floodplain. It has only two dimensions: geomorphological unit and expected annual inundation duration (Table 8.1). Like the RMM, the GMM uses hydrological input derived directly from river levels, although it does not take into consideration the isolation factor. This later implies that the GMM can only be applied for those parts of the Gemenc floodplain, which are in open connection to the Danube.

Spatial distribution of inundation duration is calculated from the river levels and from the elevations of the floodplain terrain. Having the spatial distribution of all influencing variables in hand, matrix models enable to derive the spatial distribution of expected ecotopes in the form of vegetation maps. All these calculations involve processing of geographical data, which can effectively be done by GIS, as it has been demonstrated by Marchand [1993] and de Jonge *et al.* [1992].

The primary objective of the RMM model was to describe the consequences of lowering or elevating the floodplain surface by means of excavation or filling-up. This implies that only the surface elevation and the soil type were considered as control variables. The GMM model was created to analyse the consequences of different floodplain restoration alternatives, which involve the creation of new side channels and reopening old ones [Marchand, 1993]. Such interactions may change the hydrological regime of the Danube, which means that besides terrain elevation, the river water levels are also control variables. This also means that a hydrodynamic model, with which the altered hydrological regime can be modelled, was needed. Marchand [1993] applied the 1-D, unsteady WENDY model (the predecessor of SOBEK [Delft Hydraulics & RIZA, 1997]) for the Gemenc.

Table 8.1 The matrix of the GMM vegetation model [after Pedroli, 1993]

Expected annual inundation	geomorphological units				
Duration (d/y)	natural levee	point bar	channel fill-up	open water	other
< 18	A	A	A		
11 – 26	B	B	B		
26 – 37	C	C	C		
37 – 51	E	E	D		
51 – 73	F	F	G		
> 73	H	H	I		J
> 110				K	

Ecotopes:

A : hardwood forest
B : poplar-willow forest
C : poplar-willow or willow-monostand forest
D : mixed rough herbage
E : willow floodplain forest
F : willow dead arm vegetation
G : willow dead arm vegetation and/or reedland
H : young willow vegetation or pioneer vegetation or no vegetation
I : *Carex riparia* or pioneer vegetation
J : water vegetation
K : main channel

Dynamic conditional binary ecotope model

Tait [1990] introduces the Everglades Vegetation Model (EGVM), which is a module of a complex hydrodynamic-ecological model developed for the Everglades wetland in Florida, USA. The common spatial units of the complex model are the 4x4 km rectangular cells arranged in a grid covering the entire 23 300 km^2 large wetland.

The EGVM is a matrix model too. The matrix of EGVM has two dimensions, namely the annual hydroperiod averaged over the 5 year-long time step, and the initial ecotope at the start of the time step. Hydroperiod is the number of months in a year that a certain cell is inundated by more than 15.2 cm of water. This annual hydrological statistical variable is calculated from the cell's surface elevation and from the water level time series of the cell generated by the hydrodynamic simulation module (EGHM) of the Everglades model. Each combination of initial ecotope and average hydroperiod points to an element in the matrix, which is the expected ecotope in the cell at the end of the 5 year-long time step. For example, the ecotope of 'sawgrass marshes, tree islands, wet prairies, and sloughs on peat' will change to 'wet prairie with native woody species on peat' if the 5-year average hydroperiod is less than 8 month/year in the cell. Note that EGVM considers the soil type (peat or calcareous) too, although it is implicitly accounted for by the definition of ecotopes.

The EGVM model takes into consideration the effect of fire too. The model checks a random number against the fire probability parameter (Monte Carlo method), and in the event of fire the initial ecotope of the cell changes to the ecotope determined by the fire transition matrix of the model [Tait, 1990]. The probability of fire is adversely proportional to the hydroperiod.

By considering elevation, soil type and structure type (channel, levee, etc.) of cells as control variables, the complex Everglades model enables to analyse the effect of a wide range of interventions such as excavation, deposition, levee construction and installation of sluices.

Dynamic conditional continuous ecotope model

Toner & Keddy [1997] developed a vegetation model for the floodplains of the Ottawa River in Canada. The model's space of dependent variables consists of only two, rather general ecotopes: the zone of woody species and the zone of herbaceous species. The hydrological independent variables are annual hydrological parameters averaged over the considered multi-annual simulation time steps. These parameters are derived directly from the recorded levels of the Ottawa River and from the elevations of the modelled floodplains. Thus the Ottawa Vegetation Model (OVM), like the GMM model, is restricted to the open floodplains of the river.

In the course of model development, regression analyses were carried out on field ecotope data on one hand, and on combinations of hydrological parameters averaged over different time steps on the other hand. The hydrological parameters were derived from the growing seasons of the years and the time steps were year groups preceding the year of ecotope data collection. The regression analyses resulted in several alternative models based on the formulated regression equations. These models were subsequently evaluated by statistical techniques, and the one with the best performance was selected as the ultimate vegetation model for the Ottawa River floodplains. Other independent variables such as soil drainage and characteristics of wind-induced waves were also involved in the regression analysis, although they had proven to be insignificant and were not involved into the ultimate model.

The resulted model has two independent variables: the expected last day of the first flood (*ld*) and the expected first day of the second flood (*tsc*) within the growing season. The time step (over which the annual *ld* and *tsc* values are averaged to get their expected values) is 12 years. The *ld* variable characterises the effect of the entire first flood, as first floods of the Ottawa River usually start before the onset of the growing season [Toner & Keddy, 1997]. Because of similar inter-specific reasons, *tsc* alone proved to be appropriate for representing the effect of the second flood.

The core equation of OVM is the regression equation giving the probability of occurrence of woody cover (p) at a certain location of the floodplain:

$$\ln\left(\frac{p}{1-p}\right) = -0.23 \cdot ld + 0.16 \cdot tsc - 1.42 \qquad (8.2)$$

As Toner & Keddy [1997] concluded, the above regression model corresponds to the establishment of woody seedlings rather than survival of adult woody trees.

Dynamic conditional biomass model

The GTREE model, developed by King & Grant [1996], simulates the populations of seedlings of hardwood species in the so-called 'green-tree reservoirs' in the USA. Green tree reservoirs are stands of hardwood forest that are impounded with levees, equipped with water control structures and flooded during the fall and winter to provide mast and invertebrates for waterfowl. The forests are dominated by three species: overcup oak (*Quercus lyrata*), willow oak (*Quercus phellos*) and the water elm (*Planera aquatica*). Each reservoir is subjected to spatially uniform floods, which enables to consider them as spatial units for the model. Seedling biomass of each of the three dominant species is represented in the model by two series of 10 dependent variables standing for the number and height of age classes from 1 to 10 years in a reservoir.

The GTREE model is based on the following state equations:

$$\frac{dN_{ij}}{dt} = -PMR_{ij} \cdot N_{ij} \qquad \frac{dH_{ij}}{dt} = GR_{ij} \qquad j = 1,\dots 3 \quad i = 1,\dots 10 \qquad (8.3)$$

Where:

N_{ij}	number of seedlings in age class i of species j (-)
PMR_{ij}	proportional mortality rate of age class i of species j (s^{-1})
H_{ij}	height of seedlings in age class i of species j (m)
GR_{ij}	growth rate of age class i of species j (m/s)

The core equations of GTREE were derived by applying the Euler numerical integration form on these differential equations (equation 8.4). Simulation time step (Δt) is set to 6 months, which enables to divide each year of the simulation period into a growing and a dormant season.

$$N_{ij}^{t} = N_{ij}^{t-1} - PM_{ij} \cdot N_{ij}^{t-1} \qquad H_{ij}^{t} = H_{ij}^{t-1} + G_{ij} \qquad (8.4)$$

Where:

N^{t}_{ij}	number of seedlings in age class i of species j at time t (-)
H^{t}_{ij}	height of seedlings in age class i of species j at time t (m)
PM_{ij}	proportional mortality of age class i of species j during the actual season (-)
G_{ij}	growth of age class i of species j at the actual season (m)

If the simulation reaches the turn of a year, the model advances the dependent variables of each age classes one class upward. For the first age class, a constant input of seedlings is considered at the start of each year.

G is calculated from the maximum potential growth rate of the species reduced by coefficients standing for flooding, desiccation and shading stresses:

$$G_{ij} = FC_j \cdot LC_j \cdot MG_j \tag{8.5}$$

Where:

FC_j flood coefficient (-)

LC_j light-availability coefficient (-)

MG_j maximum potential growth during the actual season (m)

Height growth occurs during each growing season. Flood coefficient (*FC*) is a function of the percentage of time flooded during the growing season (*GF*). As Figure 8.2.a indicates *FC* expresses both the flooding and desiccation stresses. Each modelled seedling in a green tree reservoir has its optimal flooding where *FC* equals to 1. Light-availability (*LC*) is a function of the tree basal area (*BA*) of the forest (Figure 8.2.b), as *BA* indicates the extent of light extinction caused by the forest itself.

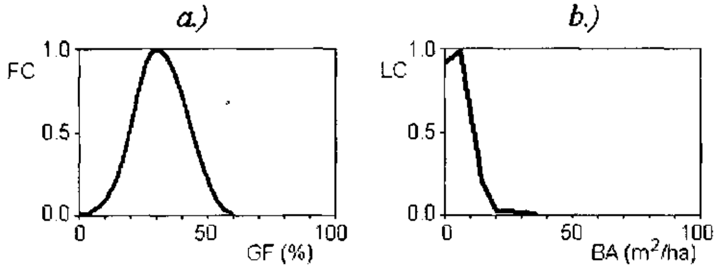

Figure 8.2 Flood and light-availability functions of water elm in a green tree reservoir [after King & Grant, 1996]

Mortality occurs both in the growing and in the dormant season. Growing season mortality is minimal if *GF* is optimal for the species. Shorter or longer flooding increases mortality because of desiccation and flooding stresses (Figure 8.3). Dormant season mortality is a function of percentage of time flooded during the dormant season (*DF*) and the depth of dormant season floods (*DD*).

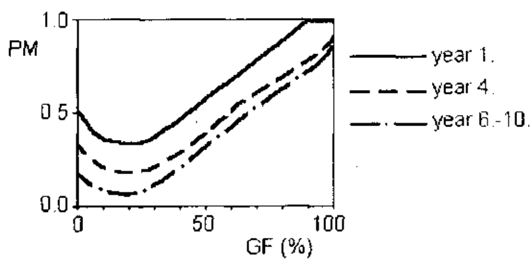

Figure 8.3 Growing season proportional mortality functions (PM) of different age classes of water elm in a green tree reservoir [after King & Grant, 1996]

The above functions were derived by extensive regression analyses on recorded botanical and hydrological data.

The purpose of the GTREE model was to simulate the effects of alternative management strategies in the green tree reservoirs. Management strategy consists of timber harvesting plans and inundation strategies. This implies that the hydrological statistical variables (listed above) and the forest basal area are all control variables.

King & Grant [1996] do not mention any hydrodynamic model where the data for hydrological input come from. Nevertheless, the evaluation of management strategies implies the existence of a hydrodynamic model (let's call it GTREEH), which simulates the water levels in a green-tree reservoir.

Dynamic physiological biomass models

Dynamic physiological models simulate vegetation growth by modelling the complex physiological processes the plant species perform.

The MEGAPLANT model [Scheffer *et al.*, 1993] was created for simulating the biomass of submerged water plants (g/m^2) at a certain location in a water body. The total biomass is distributed among four plant organs: overwintering structures (seeds, tubers, turions etc.), roots, sprouts, and the upper layer (shoots spreading beneath water surface). By the onset of the growing season the plant starts its annual growing cycle. From that moment onwards a fixed percentage of the actual overwintering biomass is spent on building the other organs of the plant. Additional biomass is produced by means of net primary production. The distribution of the total available biomass among roots, sprouts and the upper layers is controlled by plant specific parameters. At the end of the growing season, the vegetation biomass (roots, sprouts, upper layers) is transformed into overwintering biomass with a fixed efficiency.

Net primary production (P_n) equals to gross primary production (P) minus the maintenance respiration (R_m). Maintenance respiration is proportional to the vegetation biomass and doubles by every 10 °C:

$$R_m = 2^{\frac{T-20}{10}} \cdot r_{m20} \cdot (WU + WS + WR) \tag{8.6}$$

Where:

R_m : maintenance respiration (g/m^2/d)

T : water temperature (°C)

r_{m20} : (maximum) specific maintenance respiration at 20 °C (g/g/d)

WU, WS, WR : dry weights of upper layer, sprouts and roots (g/m^2)

Daily gross primary production is calculated by Gaussian integration [Goudriaan, 1986] of specific gross primary production (p) over time and depth. Specific gross primary production is calculated by means of the following equation:

$$p = p_{max} \cdot f(I) \cdot f(T) \cdot f(D) \tag{8.7}$$

Where:

p : specific gross primary production (g/g/h)

p_{max} : maximum specific gross primary production (g/g/h)

$f(I)$: response function of in situ light intensity (I (μE/m^2/s)) (-)

$f(T)$: response function of temperature (-)

$f(D)$: response function of the distance (D (m)) between the tissue and the plant top (-)

This implies that growth-respiration and nutrient limitation are assumed to be constant, and they are implicitly accounted for by the value of the p_{max} parameter. In case of the eutrophic water bodies of floodplains, constant (zero) nutrient limitation is a feasible assumption indeed.

The light response function is formulated in a Monod fashion:

$$f(I) = \frac{I}{I + I_H} \tag{8.8}$$

Where:

I_H : half-saturation light intensity ($\mu E/m^2/s$)

Temperature dependence of photosynthesis is described by a Hill function:

$$f(T) = \frac{1.35 \cdot T^3}{T^3 + 14^3} \tag{8.9}$$

The $f(D)$ function stands for the decreased photosynthetic activities of aged tissues situated on the lower parts of the plant:

$$f(D) = \frac{D_H}{D_H + D} \tag{8.10}$$

Where:

D_H : half-saturation distance (m)

In situ light is a function of the distance from the water surface, solar radiation, water surface reflection, periphyton shading, turbidity, and self-shading. The applied formula is the *Lambert-Beer equation* [Scheffer *et al.*, 1993].

Three causes of mortality are explicitly included in MEGAPLANT: wave damage, grazing and mortality owing to competition at high plant densities. Grazing is modelled by means of a fixed grazing rate while competition mortality follows the thinning law [Westoby, 1984]. Wave damage affects the upper layer and the sprout, and it decreases in a Monod fashion by the increasing water depth:

$$MWU = WU \cdot mrt_{max} \cdot \frac{H_H}{H_H + H} \;;\quad MWS = WS \cdot mrt_{max} \cdot \frac{H_H}{H_H + H} \tag{8.11}$$

Where:

MWU, MWS : upper layer and sprout mortality caused by waves ($g/m^2/d$)

mrt_{max} : maximum mortality rate at the shoreline (where $H=0$) (1/d)

H : water depth at the subjected location in the water body (m)

H_H : half-saturation water depth (m)

The simulation time step of MEGAPLANT is 1 day, since respiration, growth and mortality are calculated on daily basis.

Although MEGAPLANT is essentially a physiological model, it still demands several simplifications and assumptions in order to overcome the problems that would arise from modelling all the complex physiological processes a rooted plant actually performs. In contrast to higher order vegetation however, phytoplankton enables to cope with all relevant physiological processes without significant compromises, thanks to the following reasons:

1. Physiological processes of such simple organisms are much less complex, mathematically well described in the literature and require the consideration of relatively limited number of dependent and independent variables
2. Modelling of auxiliary variables in water, such as concentrations of dissolved nutrients, is also relatively straightforward
3. The homogeneous distribution of abiotic factors in water enables to work on large spatial scales, which makes modelling faster and easier

The DELWAQ model [Delft Hydraulics, 1995] for example, which is another representative of dynamic physiological biomass models, has been designed to simulate phytoplankton concentrations in water. This model is based on the advection-diffusion equation describing the dynamism of dissolved and suspended substances:

$$\frac{\partial c}{\partial t}=-\frac{\partial(c\cdot u)}{\partial x}-\frac{\partial(c\cdot v)}{\partial y}-\frac{\partial(c\cdot w)}{\partial z}+\frac{\partial}{\partial x}\left(D_x\cdot\frac{\partial c}{\partial x}\right)+\frac{\partial}{\partial y}\left(D_y\cdot\frac{\partial c}{\partial y}\right)+\frac{\partial}{\partial z}\left(D_z\cdot\frac{\partial c}{\partial z}\right)+S(c,x,y,z) \tag{8.12}$$

Where:

c concentration of dissolved or suspended substance (g/m^3)

u, v, w components of the water velocity vector (m/s)

D_x, D_y, D_z components of the diffusion tensor (m^2/s)

S source or sink of substance (g/m^3/s)

The S source (or sink) term stands for bio-chemical reactions producing or consuming modelled substances in the water column. Suspended phytoplankton is produced by means of primary production. The related source equation is as follows:

$$S_{np}=(rgp-rrsp)\cdot c \tag{8.13}$$

Where:

S_{np} : net algae production flux (gCarbon/m^3/d)

rgp : rate of gross algae production (1/d); it is a function of available light, temperature and dissolved nutrient concentrations in the water column

$rrsp$: rate of respiration (1/d)

Accordingly, concentrations of dissolved nutrients (NH_4, NO_3, PO_4, Si) have to be involved into the simulation as auxiliary variables, which in turn involve further substrates and flux equations. Phytoplankton disappears from the water column in the course of mortality, which is described by another flux equation. Ultimately, DELWAQ involves all significant substances and processes related to phytoplankton dynamics (see also Figures 2.2-2.4), except allelopathy and zooplankton grazing, although the open design of the model enables the user to construct and involve related process equations.

The core equations of DELWAQ are derived by applying different numerical integration forms on the partial differential equation. The high discretisation freedom provided for the user enables to adopt the model to water bodies with sizes and shapes of any kind. The core equations require hydrodynamic input such as time series of volumes, inflows and outflows of water per computational cell. These data have to be provided by hydrodynamic models. Fintor & Zsuffa [1995] applied the FOK model to generate such time series for each system cell of the Gemenc cell-system before simulating their phytoplankton dynamics by DELWAQ.

Comparative evaluation of the presented vegetation models

Figure 8.4 below indicates the time scales of the presented vegetation models according to their simulation time step.

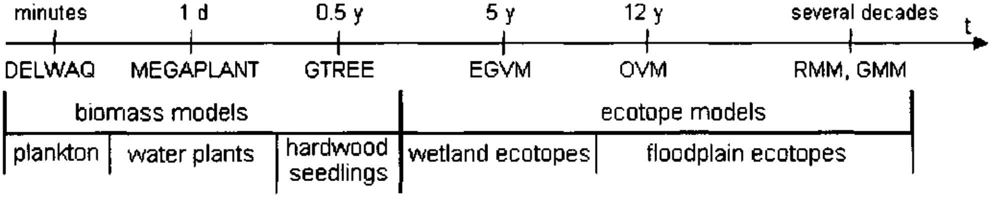

Figure 8.4 Time scales of the models based on their simulation time steps

Biomass models thus have much lower time scales than ecotope models owing to the fact that vegetation biomass is much more dynamic in time than spatial extents of ecotopes.

There are two general processes stimulating the temporal dynamism of ecotopes: succession and the dynamism of abiotic environment. Under steady abiotic conditions, succession of proceeds on multi-annual scales (except the pioneer stages). Dynamic abiotic conditions of floodplains induce a more dynamic ecotope system, although it still takes several years for most floodplain ecotopes to undergo definite changes. That is to say, increased inundation stress needs a time period from 1 year to several decades to cause definite changes in a woody ecotope thanks to the preserved reproduction capacities of flood resistant adult trees. Decreased inundation stress would not result sudden changes either (unless the succession is at starting phase), as it only removes the 'obstacle' from the way of succession.

Plant biomass on the other hand shows strong within-year dynamism, not only in case of annual and perennial plants but also in case of seedlings of woody species. This dynamism is determined by four processes: growth, reproduction, mortality and export-import (only phytoplankton). Growth and reproduction of algae is highly influenced by solar radiation and dissolved nutrient concentrations both of which may change significantly from one day to another. In floodplain water bodies, the in- and outflow processes enhance further the dynamics of algae biomass. This is why the time step of DELWAQ had to be decreased to some minutes when it was applied to the small water bodies of the Gemenc floodplain [Fintor & Zsuffa 1995]. The dynamism of herbaceous and woody biomass is of course much slower not just because of the lack of export-import but also because the production and mortality of such species are much slower processes than that of algae. That is why the MEGAPLANT and the GTREE models have 1 d and 0.5 year long time steps respectively.

Short time steps for physiological models are also demanded by the modelled physiological processes. Primary production and respiration proceed in daily cycles, which imply that the simulation time step must not be longer than one day.

Long time steps of conditional models require abiotic input on the same long time scales. For hydrological input it implies to use variable, which contain the relevant information over the hydrological regime within that time step. This information is stored in the simulated time series of influencing hydrodynamic parameters. This implies that influencing hydrological variables has to be derived by extracting this information from the time series, by means of *statistical analysis*. Accordingly, the RMM, GMM, OVM, EGVM and GTREE models require such statistical analysis prior modelling (Figure 8.6).

Conditional approach disregards the internal mechanism of relevant links in the vegetation influence chain. Thus, it is the modeller's task to formulate alternative equations with which the resulted gaps can be bridged. The substituting equations are called *'black boxes'* [Jørgensen, 1989; Runhaar, 1991] (Figure 8.5). Matrices of the RMM, GMM and EGVM models as well as the *MPR* and *GR* functions of GTREE and the regression equation of OVM are typical examples for black boxes.

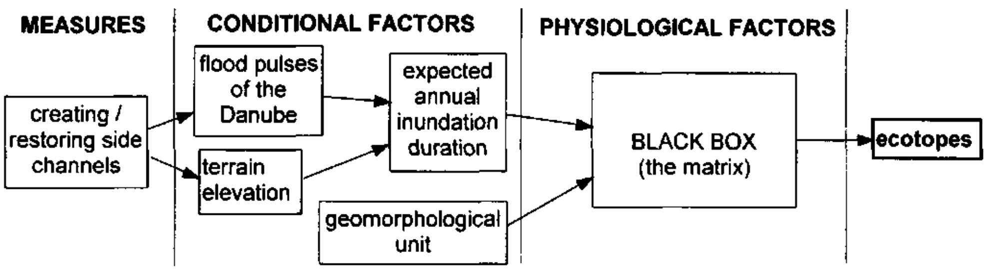

Figure 8.5 Flow-chart of the GMM model (see also Table 8.1)

Models have to be *calibrated*. For matrix models this means extensive *regression* analysis of measured field data. As a result, the tables of matrix models get filled in. In case of conditional continuous models regression analysis can be employed for locating the most suitable model equation (see OVM model of Toner and Keddy [1997]). In case of physiological models (and at some conditional models too) the form of the core equations is determined on a theoretical basis. These equations however do contain several parameters (besides global constants) that have to be calibrated. Calibration in this case means adjusting the parameters so that the output of the model get as close to measured field data as possible.

Adequacy of hydrological input of conditional models is different. The two hydrological variables of the OVM model (*ld* and *tsc*) for example mean adequate interpretation of the effect of floods on vegetation, since the length of the recovery time (*tsc-ld*) is also taken into consideration, above the stress effects of the floods of the Ottawa River. The RMM, GMM and EGVM models on the other hand, are based on quite simple hydrology-vegetation relationship as the influence of the entire hydrological environment is considered by the expected (or 5 year average in case of EGVM) value of only one variable. Furthermore, these hydrological variables correspond to the entire year, so the effect of seasonality is ignored, which otherwise plays a significant role in the temperate climate. (That is why the OVM and GTREE models separate the growing and dormant seasons.)

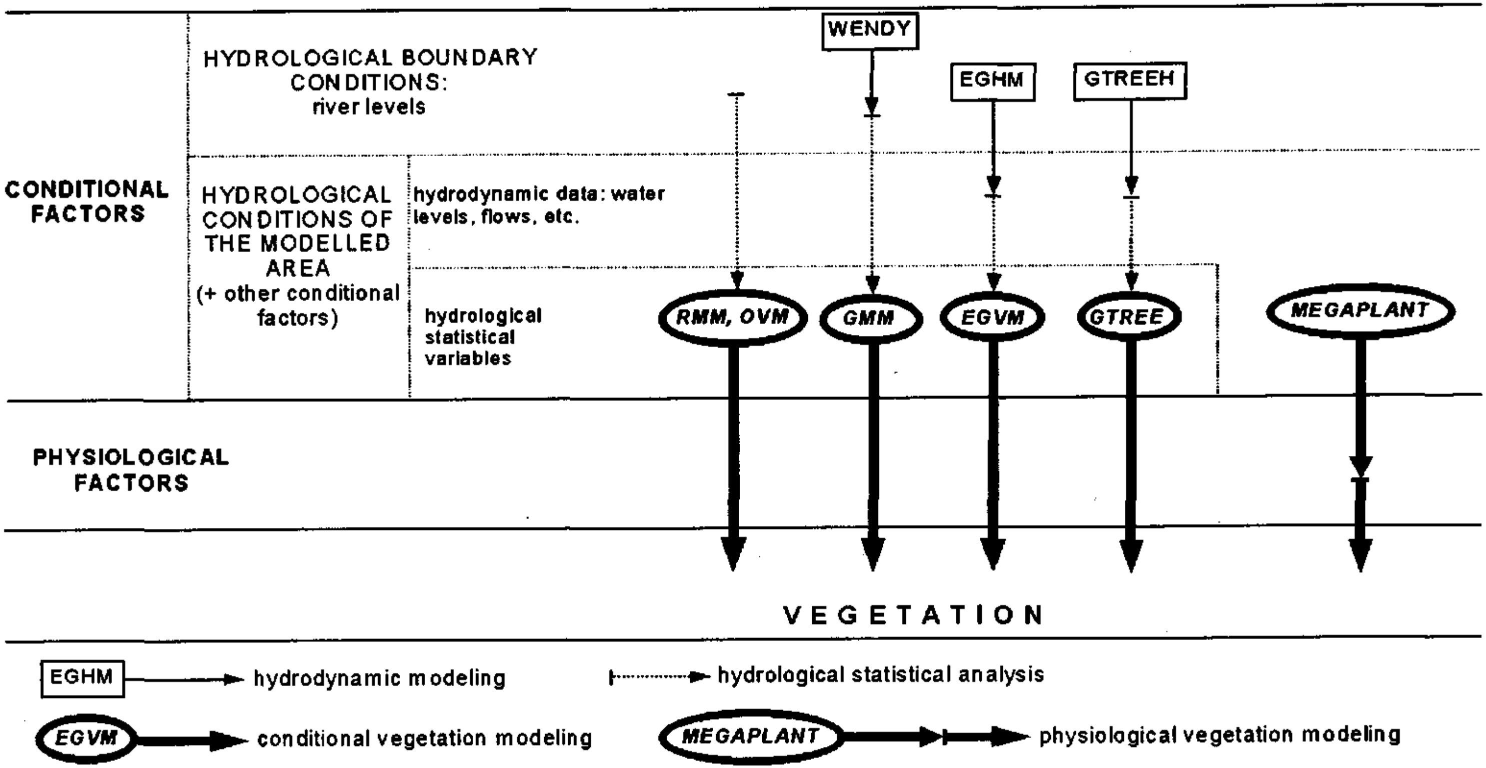

Figure 8.6 Position of the vegetation models in the influence chain of vegetation (abbreviations are defined in the preceding text of Section 8.2.1)

Ecological models are inevitable *specific* to those abiotic factors that have not been considered explicitly as independent variables. The presented conditional models are therefore all very *site-specific*. They can only be applied for those regions where data came from for calibration. These data implicitly account for the influence of climate, water quality, soil etc.. In addition to such regional restrictions, the applicability of GMM and OVM models are restricted to the riparian parts of the Gemenc and Ottawa floodplains being directly influenced by the river.

Even site-specificity would not be a big problem unless all envisaged control variables are taken as explicit independent variables. This is however not the case with the RMM, GMM, OVM, EGVM and GTREE models as they are also *specific to the influencing hydrological regimes*. The OVM model is especially specific to the flood regime of the Ottawa River as its two independent variables implicitly consider the general, 'two floods per growing season' pattern of the river. The RMM, GMM models are also quite hydrology specific since they consider the effect of inundation only by means of the single variable of annual inundation duration, thus relying on the characteristic annual distribution of flood waves of the Rhine and Danube rivers. In fact, hydrological specificity of conditional models is inevitable because the variation of the water regime within their large time steps is disregarded.

Hydrological specificity however prevents applying these models for evaluating the consequences of changes in the influencing hydrological regime. Thus, the presented conditional models, or models based on such approaches, cannot be applied directly for evaluating ecological criteria within the envisaged Decision Support System for floodplain restoration.

Hydrological specificity can be avoided if hydrological input comes from an appropriately low time scale. For floodplain conditions this implies daily hydrological input. Such a short time scale however requires sophisticated, physiologically based models.

8.2.2 Fauna models

Ecological models, whose target variables characterise the fauna life of the modelled ecosystem, are called fauna models. According to the general classification of ecological models, fauna models can be biomass or habitat models on the one hand; or they can be dynamic or static models on the other hand. Within habitat models distinction can be made between binary and continuous models according to the form of the core suitability functions. Unlike vegetation models however, it is not possible to construct physiological models for fauna due to the complexity of physiological processes of animals. Fauna models on the other hand must consider the ethological and phenological relations of animals to the ecosystem. Migration, reproduction, hiding, feeding are the activities that have to be integrated into the model with the help of ethological and phenological analyses.

An overview of fauna models found in literature, is given in the subsequent sections. The selected models represent specific combinations of model classes described above.

Dynamic biomass model

Tait [1990] introduces the Everglades Ecological Model (EGEM), which is a module of the complex Everglades model (see also Section 8.2.1). The EGEM simulates the weight concentration of three generic type groups: small fish, invertebrates and *centrarchids*. The concentration dynamism of these aquatic organisms is assumed to follow the principles of dispersion:

$$\frac{\partial c}{\partial t} = \frac{\partial}{\partial x}\left(D_x \cdot \frac{\partial c}{\partial x}\right) + \frac{\partial}{\partial y}\left(D_y \cdot \frac{\partial c}{\partial y}\right) + S(c, x, y) \tag{8.14}$$

c : concentration of aquatic organisms (g/m^2)

D_x, D_y, D_z : components of the dispersion tensor (m^2/s)

S : source or sink of aquatic organisms ($gm^{-2}s^{-1}$)

The dispersion tensor components are proportional to the temporal gradient of water level. Both increasing and decreasing water levels result higher dispersion. No dispersion takes place below a certain depth. The S source (or sink) term stands for *heterotypical* and *homeotypical* coactions in the course of which aquatic organism biomass is produced or consumed in the water column.

The source term of reproduction is assumed to be a rectangular hyperbolic function of the concentration:

$$S_{rp} = maxrp \cdot h \cdot \frac{c}{c_m + c} \tag{8.15}$$

$maxrp$: rate of maximum recruitment ($gm^{-3}s^{-1}$)

h : water depth (m)

c_m : concentration of aquatic organisms ($gm^{-2}d^{-1}$) at which $S_{rp} = 0.5 \cdot maxrp$

Mortality sink is a linear function of aquatic organism concentration, describing the effect of increased homeotypical competition for food:

$$S_{mr} = -c \cdot \min(bmr + \delta mr \cdot c;\ maxmr) \tag{8.16}$$

bmr : base mortality rate (s^{-1})

δmr : mortality-concentration gradient ($s^{-1}g^{-1}m^2$)

$maxmr$: maximum mortality rate (s^{-1})

Additional mortality is resulted by predation:

$$S_{pr} = -\min\left(\sum_{i=1}^{np} cp_i \cdot con_i(c);\ maxpr \cdot c\right) \tag{8.17}$$

np : number of predator species feeding on aquatic organisms (-)

cp_i : density of predator species i (m^{-2})

$con_i(c)$: consumption rate of predator species i at concentration c (gs^{-1})

$maxpr$: maximum predation rate (s^{-1})

The $con_i(c)$ is a linear function between a lower and an upper limit of aquatic organism concentration. Below the lower limit, no predation is assumed to take place, while above the upper limit the consumption does not increase any further because the maximum consumption capacity of the predator is assumed to be reached.

The numerical solution of this equation is based on the 4x4 km grid applied generally for all modules of the complex Everglades simulation model.

Habitat models

The presence and size of populations of aquatic organisms depend on the size and on the quality of the hosting habitat. The size of habitat can be characterised by several hydrological parameters depending on the behaviour of the species. For example habitat of species living on the land-water *ecotone* can be characterised by the perimeter of the water surface, while the habitat of benthic invertebrates can be quantified by the bed surface area of the water body. Size of habitat of species living in the medium of water however is not necessarily characterised by the volume of water. Most fish are dependent on a certain layer of the water column. Benthos feeders (e.g. the carp) are feeding on the bottom, while surface feeders feed below the water surface. As all freshwater fish are substrate spawner, reproduction is again a surface-, and not volume dependent process. This surface dependency is even more enhanced in shallow lakes like those in the river floodplains. These all imply that the size of fish habitat can be characterised by the area of water surface. This however does not mean that the depth is negligible as influencing factor.

The quality of an aquatic habitat is determined by the following factors:

1. Quality of the water: dissolved oxygen content, turbidity, temperature
2. Type of the substrate
3. Density of aquatic vegetation
4. Hydrological variables: depth and velocity of the water, water level fluctuation

Habitat Suitability Index (HSI) models for aquatic species describe the quality of the habitat according to the above factors. A HSI model has continuous core functions each of which indicates the suitability of the habitat for the species according to a specific condition of the site. 0 index value indicates that the habitat is totally unsuitable, while 1 means optimal conditions from that certain point of view.

Figure 8.7 shows the *HSI* curves for northern pike (*Esox lucius*) developed by Inskip [1982]. The specific *HSI* graphs correspond to the following habitat conditions [Inskip, 1982]:

I_1 : ratio of spawning habitat to summer habitat (area during the spawning season that is less than 1 m deep and vegetated, divided by the total midsummer area of the water body). The quality of spawning substrate is indicated by the different curves: *A*: vegetation obscures most (>80%) of the bottom, plant material dense throughout the 15 cm of the water column above the substrate (flooded sedge or grass meadow); *B*: plant growth less lush than in *A* but more than 60% of the bottom obscured in vertical projection from depth of 15 cm above the bottom; *C*: vegetation or debris covers much of the bottom but plant material does not occupy much of the water column immediately above the substrate (compacted vegetation, fallen leaves, woody branches); *D*: thinly scattered vegetation or debris only

I_2 : drop in water level during embryo and fry stages; *A*: embryo and early fry stage (until the yolk sac absorbed) during which it is sticking on plant surfaces; *B*: late fry stage: moving ability

I_3 : percent midsummer area with emergent or submerged vegetation

I_4 : least suitable pH in spawning habitat during embryo and fry stages

I_5 : average length of frost free season

I_6 : maximal weekly average temperature of the surface layer

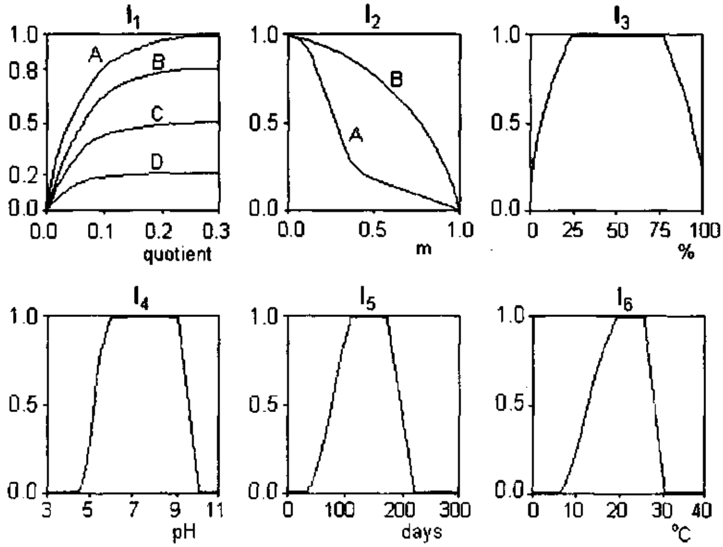

Figure 8.7 Habitat suitability index graphs for northern pike [after Inskip, 1982]

For the common carp (*Cyprinus carpio*), Edwards & Twomey [1982] developed a similar HSI model.

Aggregation of the specific *HSI* values results the overall *HSI* of the habitat. The model of Inskip [1982] selects the lowest specific *HSI* as the overall *HSI*. This approach is based on the assumption that the critical (limiting) factor determines the overall habitat quality [Djordjević, 1993]. Other aggregation techniques, such as multiplication or geometric mean, can also be applied. Multiplication of the specific *HSI*-s is based on the assumption that all habitat factors are of equal importance and the habitat is optimal only if it is optimal from all aspects [Djordjević, 1993]. Geometric mean implies compensation effect, i.e. if the majority of specific *HSI*-s is in the optimal range then the overall *HSI* is also in a good range even if some specific *HSI* values indicate that the habitat is not suitable at certain aspects [Djordjević, 1993].

Multiplying the surface area of the water body with the overall *HSI* results the Weighted Usable Area (*WUA*) [Djordjević, 1993], which characterise both the quality and the quantity of habitat of the species.

Based on the concept of *WUA*, the U.S. Fish and Wildlife Service developed the Instream Flow Incremental Methodology (IFIM) for calculating the *WUA* of aquatic organisms in lotic water bodies. The IFIM subdivides the investigated river or creek reach into component cells and calculates the *WUA* for these cells separately. Then the total *WUA* of the reach is derived by summing up the component *WUA*-s.

The IFIM is based on the following ecological assumptions [NERC, 1993]:

1. The modelled species exhibit microhabitat selection strategy. It means that the species tend to move to small sub-regions (cells) of the water body where the conditions are optimal for crucial activities such as feeding or reproduction. Conditions in the neighbouring cells have negligible influence on the organisms living in the cell.

2. Individuals select the most desirable conditions within the stream but will use less favourable areas as they become more crowded.

3. Individuals of species respond directly to available hydraulic conditions. This means that the temporal variations of hydrological variables do not influence the modelled fauna. Always the actual values of hydrological variables determine the *WUA* at a certain time point. (Note that this is not valid for fish species preferring the lentic water bodies of floodplains as habitats.)

Bray [1996] applied the IFIM for rainbow trout (*Oncorhynchus mykiss*) and caddishfly (*Hydropsyche* sp.) in the rapids of the St Marys River in Canada. The total *WUA* of the rapids was calculated by summing the *WUA*-s of four component cells. The suitability of the cells was characterised only by the index of mean water depth. *WUA*-s were calculated for four discharges for each life stages of the two species. The depths and flooded areas of the cells were calculated by steady state hydrodynamic modelling. The relationship between discharge and total *WUA* was derived by fitting a curve on the four calculated points. Finally, time series of *WUA*-s were created on the basis of monthly historical discharge time series of the river. The *WUA* time series were then subjected to time series analysis in order to reveal the relation between the river regime and the habitat conditions.

8.3 Ecological models and related criteria applied in the DSS

The Decision Support System (DSS) for floodplain revitalisation needs ecological models, which enable to calculate the achievements of different cell-system solutions at the criteria related to the floodplain ecosystems.

8.3.1 Vegetation models applied in the DSS

The most important requirement towards vegetation models is that they must not be specific for the water regime since the identified revitalisation measures (see Chapter 5) aim just the modification of water regime of the floodplain cell-systems. For this reason, the envisaged models must preferably be physiologically based ones.

Model and criteria related to aquatic flora

For modelling water plants, the MEGAPLANT model [Scheffer *et al.*, 1993] has been applied (see Section 8.2.1). The authors of this model made the FORTRAN source code available, which enabled to integrate it into the DSS.

In its original form, MEGAPLANT assumed constant water depth, which is not valid for floodplain water bodies. In case of fluctuating water depth however, the model should also account for stranding. Stranding causes stress on the plant leading to growth inhibition, injuries and even to death. Accordingly, the modified MEGAPLANT model does the following when stranding occurs:

1. Halts the growth process for the time of stranding

2. Decreases the vegetation biomass at the end of the stranding period; the biomass loss is assumed to be proportional to the stranding time:

$$WU = WU - \left(WU \cdot \frac{t_s}{mt_s} \right); \quad WS = WS - \left(WS \cdot \frac{t_s}{mt_s} \right); \quad WR = WR - \left(WR \cdot \frac{t_s}{mt_s} \right) \quad (8.18)$$

Where:

t_s duration of the continuous stranding period (d)

mt_s stranding time lethal for the plant (d)

WU, WS, WR dry weights of upper layer, sprouts and roots (g/m^2)

Hydrological inputs for the modified MEGAPLANT model are daily water levels in the cells, simulated by the FOK model.

Evaluation criteria related to water plants are thus calculated on the basis of water plant biomasses simulated by MEGAPLANT. The applied criterion refers to the area that is considered to be occupied by the subjected water plant in the cell. This is the *water plant zone*. A certain location is considered to be occupied by the water plant zone if the average plant biomass during the growing season exceeds a given threshold. In this study the value of 5 g/m^2 has been specified for this threshold. By assuming homogeneous conditions in the horizontal directions, the lower and upper elevation limits of the water plant zone can be derived by means of linear interpolation between biomasses computed on discrete elevations. Having the lower and the upper limits in hand, the area of the water plant zone can be calculated for each simulation year on the basis of the elevation-area functions of the cell (Figure 8.8).

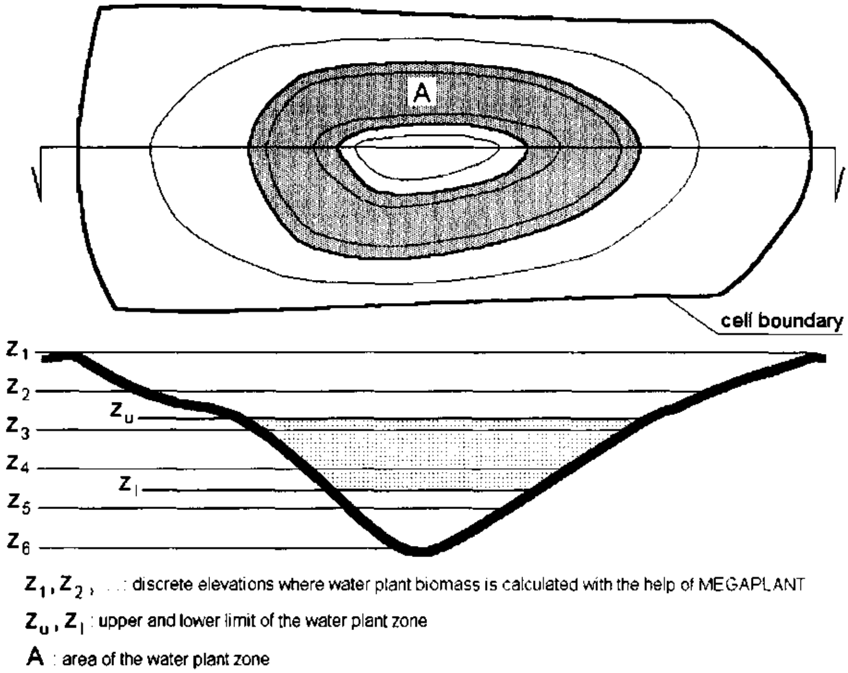

Figure 8.8 Water plant zone within a cell

The so-defined water plant zone is thus an annual random variable. The evaluation criterion, applied in the DSS, refers to a certain point of the distribution function of this variable that is, water plant zone with a given *exceeding probability*. This value is estimated by means of statistical analysis of time series of water plant zones derived by long-term (at least 20 years [Zsuffa sr., 1994]) multi-level simulations with MEGAPLANT. The exceeding probability applied in this study is 0.5.

Other vegetation models and criteria applied in the DSS

It would be ideal if physiological models for other vegetation existed too, and were integrable into the DSS. For algae the DELWAQ or similar models would be an appropriate choice unless its integration was not hampered by the lack of the program code. As far as terrestrial plants are concerned no physiological models were available at the time of development of the DSS. The available conditional models are on the other hand not applicable due to their site and hydrological specificity. Since developing new and sophisticated vegetation models does not fit into the scope of this study, alternative, simplified models had to be constructed with which criteria standing for terrestrial vegetation can be evaluated. Simplification however inevitable leads to conditional modelling.

The applied conditional model predicts the occurrence of only one, rather general ecotope, which is termed as *'forest zone'*. This ecotope comprises alluvial forests of all types ranging form willows to hard wood species. Meadows and grasslands are also included. The extent of the forest zone is assumed to be determined by the growing season inundation. Accordingly, a certain spot in the cell is assumed to be within this zone if the following condition holds:

$$GF_{p1} < GFF_{\max} \quad \wedge \quad GF_{p2} > GFF_{\min} \tag{8.19}$$

Where:

- GF_{p1} growing season inundation (d) of the spot with exceeding probability $p1$
- GF_{p2} growing season inundation (d) of the spot with *non-exceeding probability* $p2$
- GFF_{max} maximum growing season inundation the forest zone tolerates (d)
- GFF_{min} minimum growing season inundation the forest zone requires (d)

$T_1 = p1^{-1}$ is thus the minimum tolerable *return time* (in years) of growing season inundations longer than GFF_{max}, while $T_2 = p2^{-1}$ is the minimum tolerable return time of inundations shorter than GFF_{min}. The upper and lower elevation limits of the forest zone (z_u and z_l) can thus be determined from the following conditions:

$$GF_{p2}(z_u) = GFF_{\min} \quad ; \quad GF_{p1}(z_l) = GFF_{\max} \tag{8.20}$$

Actually, z_u and z_l are calculated by means of linear interpolation within the appropriate intervals of discrete elevations where GF_{p1} and GF_{p2} values are calculated by means of statistical analysis of long term water level time series simulated by the FOK model. The criterion itself (which is the expected area of the forest zone) is then calculated form the elevation-area function of the cell.

The GFF_{max}, GFF_{min}, T_1 and T_2 parameters have to be calibrated by means of regression analysis. Such analysis however falls out of the scope of this study. Instead the values applied for the case study (the Gemenc floodplain) are derived from information found in the relevant literature [Schoor, 1992; Kozlowski, 1984; Gill, 1970]. Accordingly:

$GFF_{max} = 90$ d ; $GFF_{min} = 1$ d ; $T_1 = 3$ y ; $T_2 = 2$ y

The 1 day minimum inundation (which has to occur at least in every second year) is required for forestry purposes, since the amount of rainwater is insufficient for the optimal growth of timber trees in the Gemenc floodplain [Kalocsa, 1997, pers. com]. This also means that, forests do grow above the z_u elevation too, although their growth rate is less than optimal due to the lack of water.

This approach is thus similar to that of the RMM and GMM models, although it considers only one, rather general terrestrial ecotope. Improving the ecotope resolution to the same level (see Table 8.1) is not advised because the low adequacy of this conditional approach does not bear proportion to such adequate ecotope classification.

Besides water plant and forest zone, also a third ecotope criterion is applied in the DSS, which is the *water zone*. Water zone is the habitat of all aquatic life including algae, water plants but also fish and invertebrates. In fact water zone stands for the permanent water body within the cell. Water zone is defined in a pure hydrological-statistical way: it is the part of the cell, which is under water for more than a certain number of days during the growing season (*GFW*), and the return time of violation of this condition cannot be lower than a certain number of years (T_3). Accordingly, water zone is the area below a certain z_w elevation, which is derived form the following condition:

$$GF_{p3}(z_w) = GFW \quad \text{where} \quad p3 = T_3^{-1} \tag{8.21}$$

For this thesis the *GFW* is set to 130 days, which ensures water cover for at least 85% of the 153 days long growing season. Desiccation of the water zone is tolerated only in every third year, thus T_3=3 y.

8.3.2 Fauna models applied in the DSS

The envisaged fauna models cannot be based on the biomass approach because of the following reasons:

1. A floodplain cell system is connected to the river channel system, which means that significant amounts of fauna biomasses may leave or enter the modeled system.
2. Biomass exchange between the cells is the result of migration through the fok-channels. Such migration is a complicated process controlled by several factors, so it cannot be modeled by the simple, density dependent diffusion like in case of the EGEM model of Tait [1990].

These all implies that only habitat models are applicable in the DSS. The direct application of available HIS models [Inskip, 1982; Edwards & Twomey, 1982] is not possible because these models essentially assume steady state hydrological conditions. Furthermore these models give qualitative evaluation only, which is not sufficient because habitat sizes may also be different in case of the alternative cell-system solutions. Thus, new models had to be developed for modeling habitat conditions for aquatic fauna in floodplain cell-systems.

The fish habitat model

This model is developed especially for the common carp (*Cyprinus carpio*) although it can be applied for other cyprinide species too, after adjusting model equations and parameters. The spatial unit of the envisaged model is the cell. Both the quantitative and the qualitative habitat analysis correspond to individual cells. Because of the significant differences in habitat requirements, distinction should be made between spawning, embryo, juvenile and adult stage. The hereby-presented model deals only with the spawning and embryo stages.

For the spawning and embryo stages, the following *model assumptions* have been derived from the relevant literature [Inskip, 1982, Edwards & Twomey, 1982; Welcomme, 1985; Pintér, 1993]:

1. Spawning takes place within well-defined range of temperature. In temperate regions this implies that spawning takes place in spring and early summer
2. Spawning takes place in shallow, 0.4-0.8 m deep waters.
3. Spawning may occur at low water, rising water or peak flood but only very rarely during falling floods. Water level drawdowns interrupt spawning, while rising water levels stimulate spawning.
4. Vegetation is preferred as spawning substrate against gravel sand or clay.

Additional assumptions are also applied, which are specific for the case study system (the Gemenc cell-system):

5. Water quality conditions are assumed to be optimal for spawning
6. Conditions for spawning are homogeneous in the horizontal directions

Because of the first assumption the model deals only with the period that ranges from April till June. The second assumption specifies the zone in the cell where spawning may occur (Figure 8.9).

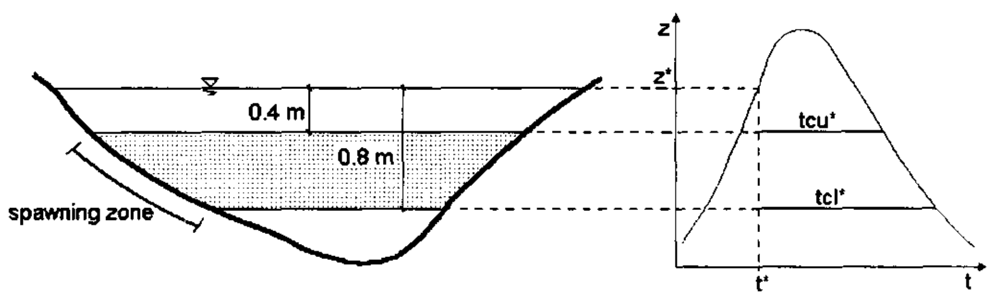

Figure 8.9 Spawning zone and periods of water cover available for fish and embryos at a certain t time point*

The so-defined spawning zone thus provides a quantitative evaluation of the spawning habitat for a certain day. For qualitative evaluation the following habitat suitability index functions are applied (see also Figure 8.10):

I_1 : Effect of water level change. This index refer to the third model assumption i.e. it says that spawning is inhibited if significant drawdown occurs ($I_1 = 0$ if $dz < -0.05$ m/day) while it is stimulated in case of rising water levels ($I_1 = 1$ if $dz > 0.15$ m/day)

I_2 : Effect of water cover on the embryo. This index stands for the detrimental effect of stranding. It is assumed that 5 day or less water cover is lethal for all embryos since this time is not enough for hatching, and even if some eggs could hatch they would get killed too, because hatched larvae tend to remain immobile for some days after hatching

[Pintér, 1992; Edwards & Twomey, 1982]. 16 days water cover on the other hand seems to be enough for all carp embryos for reaching the mobile phase when they are able to leave the spawning site before stranding [Pintér, 1992; Edwards & Twomey, 1982]. The time of water cover available for embryos mated on a certain day (t^*) on the upper and lower limits of the spawning zone, is indicated on Figure 8.9 (tcu^* and tcl^*).

I_3 : Effect of spawning substrate. This index corresponds to the fourth model assumption. Vegetated substrate refers to water plants and inundated terrestrial plants, while open substrate corresponds to the scarcely vegetated or non-vegetated substrate. In the model a certain site is assumed to be vegetated if it is above the lower boundary of the water plant zone, which is determined by the vegetation-modelling module of the DSS (see Section 8.3.1). This approach is based on the assumption that a continuous plant cover ranges from the water plant zone, through riparian vegetation till the terrestrial herbaceous species. If the vegetation model results that no water plant zone develops in the cell during the actual year, then the substrate is assumed to be vegetated only above the lower boundary of the forest zone; below the forest zone only scarce riparian and water vegetation could grow due to the unfavourable hydrological conditions.

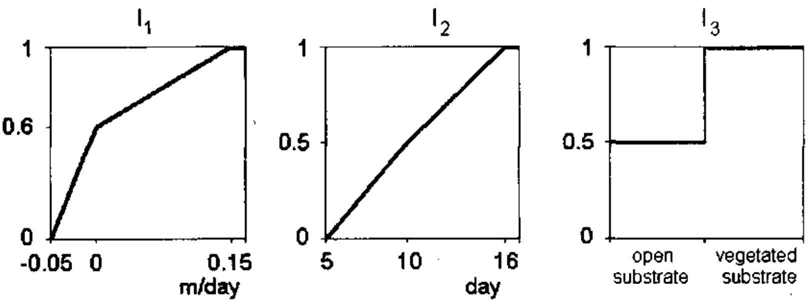

Figure 8.10 Habitat suitability index graphs for fish spawning

HSI values for the entire spawning zone are derived by averaging of the HSI-s calculated at the upper and lower limits of the zone. When calculating the overall HSI, the model applies the assumption that the critical (limiting) factor determines the overall habitat quality [Djordjević, 1993]. Accordingly, the lowest of the three specific HSI values is taken as the overall HSI of the spawning zone on a certain day.

Weighting the area of spawning zone with the overall HSI results the Weighted Usable Area (WUA), which gives a quantitative and a qualitative evaluation of spawning conditions. Such WUA values are calculated for each day of the spawning season. Mean values of these daily WUA-s can thus be derived for each simulation year. This mean WUA is again an annual random variable determined by its probability distribution function, which can be estimated on the basis of long-term simulation. The *criterion related to fish spawning habitat* refers to a specific point of this function, i.e. a mean WUA with a certain exceeding probability. The exceeding probability applied in this thesis is 0.6667, which means that the return time of occurrence of mean WUA-s less than the specified value, is 3 years.

Modelling habitat for foraging waders

Stagnant water bodies of river floodplains are very important feeding places for rare wading birds. One of Europe's most valuable waders is the black stork (*Ciconia nigra*). The favourite nesting and foraging habitats of this species are the remote sites of river floodplains where it can feed on juvenile fish in the shallow, wadable water bodies. Unfortunately, only very few places have been left in Europe, which satisfies these habitat demands. One of them is the Gemenc floodplain. Preserving and improving habitat conditions in these places are important on continental ecological scale too, as these places provide resting and foraging opportunities for storks and for other waders during migration [Kalocsa, 1999, pers. comm.].

The hereby-presented habitat model deals with the foraging conditions of black storks. The following assumptions are applied [Kalocsa, 1999, pers. comm.]:

1. The most important foraging period is the late summer and early autumn (August – September). This is the time when the storks prepare themselves for migration by eating much more than usual. Also storks from other nesting places may take a rest in the floodplain during this period and feed on the juvenile fish stock of the lakes.

2. A good foraging place is a shallow, wadable water body rich in juvenile fish. It is important that the water body must be wadable in its entire area. If it contained deep areas of significant extent, then juvenile fish would escape from the foraging birds to these places.

A floodplain cell is rich in juvenile fish if spawning was successful. Accordingly, the WUA of spawning is a good indicator for the quantity of prey fish available in the cell. Whether the stork can have access to this food or not depends on the presence of the conditions specified by the above model assumptions. These all suggests to construct suitability index functions for these foraging conditions with which the WUA of spawning habitat can be weighted to derive a kind of numerical evaluation of the stork foraging conditions in the cell.

The suitability index functions for stork foraging conditions are as follows (see also Figure 8.11):

I_1 : Ratio of wadable area to the total area of the water body. A certain site of the water body is assumed to be wadable if the depth is less than 0.8 m. This index can be calculated for each day of the feeding season.

I_2 Ratio of the number of foraging days to the total number of days during the foraging period. The number of foraging days is weighted sum of days within the foraging period where the weighting factors are the I_1 index values.

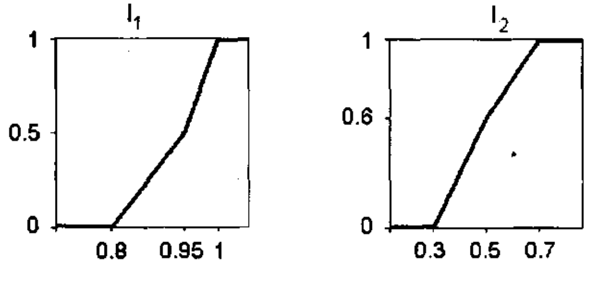

Figure 8.11 Suitability index graphs for stork feeding conditions

Thus, the WUA of stork foraging habitat in a cell is calculated by weighting the WUA of spawning habitat with the I_2 index.

This WUA is again an annual random variable. The criterion applied in the DSS for evaluating stork foraging habitat is the WUA with 0.6667 exceeding probability. This value is derived by means of statistical analysis of long time series of simulated WUA-s.

9. APPLICATION OF THE DECISION SUPPORT SYSTEM ON THE CASE STUDY PROBLEM

The purpose of this chapter is to demonstrate the use of the Decision Support System (DSS) with the help of a case study. The selected case study area is the southern part of the Gemenc floodplain situated along the right bank of the river Danube in Hungary. The main features of this area, as well as its present ecological problems have already been described in Chapter 4. The objective of the case study itself is to find a solution for the identified ecological problems, while considering the other functions of the areas. Obviously a compromise solution is to be sought.

Ecological problems, which are the direct consequences of land use activities, can usually be solved by means of administrative measures. Accordingly, noise and communal pollution, caused by the different recreation activities, can be restricted by creating and enforcing appropriate rules regulating the access to, and the settlement in the floodplain. Similarly, ecological problems caused by intensive wood production also need administrative regulation. The forestry company has to be forced to shift from the present clear-cutting method to ecologically sound forest management. Marchand [1993] also suggests to divide the floodplain into different land use zones. Accordingly, no activities would be allowed in the most valuable parts of the floodplain; even the entrance would be forbidden to these places. These ecological nuclei would be surrounded by protective buffer zones where only very limited forestry and recreation activities would be allowed. The rest of the floodplain might be exposed to more intensive land use, which however should be practiced in ecologically sound ways.

Administrative measures alone are insufficient for solving those eco-hydrological problems, which are the results of the altered hydrological regime. These problems need active, hydraulic-engineering interventions. The hydro-ecological revitalisation program of the river-channel system of Gemenc has already been started. In 1993 and 1997 the closing stone dams of the Vén-Duna and Kádár-Duna branches (see Figure 4.8) were partially removed making them flowing side channels again. It is now time to take the necessary steps towards the revitalisation of the floodplain cell-system. The DSS introduced by this study has been developed with the purpose to aid such projects in the future.

9.1 Data acquisition and preparation

Application of the DSS on the case study system requires the following base data:

1. Geometrical data of existing elements of the cell-system: elevation – surface area functions of the cells; cross sections of the existing fok-channels; elevations of the cell boundaries.

2. Hydrological boundary conditions for hydrodynamic modelling: water level time series of the Danube at the boundary cells.

3. Meteorological boundary conditions for hydrodynamic modelling: monthly average precipitations and evaporations.

4. Parameters for the ecological models.

Geometrical data were derived from the results of land surveys carried out by the personnel of the Eötvös József College within the period 1993-1995. During these surveys the Sárkány, Címer I, and Címer II fok-channels as well as the beds of the Cserta and Nyéki oxbow lakes were surveyed in cross sections of appropriate density. These data form the basis for calculating the geometry of the channel design alternatives and the quantities of required earthworks (excavation and threshold construction).

Digitalized topographical maps formed the basis for calculating the elevation – area functions of the cells, which are used by the continuity equations of the FOK model. Calculation of these functions has been carried out with the help of the IDRISI [Eastman, 1992] GIS package. As a first step of this calculation procedure a Digital Elevation Model (DEM) has been generated for the subjected cell. This DEM was then input to a GIS routine, which calculated surface areas on different elevations[1]. The so-derived elevation-area functions were improved further on the basis of the surveyed cross sections of the oxbows.

Reliable daily water level data of the Danube was available from the gauge of Baja (see Figure 4.8) for the period 1901-1996. Before using this data it was necessary to check its homogeneity and if necessary to identify a sub-series, which is homogeneous and represents the present hydrological conditions. Accordingly, a series of homogeneity tests were executed on time series of different statistical parameters extracted from the given daily water level data. These tests resulted that only the water levels from the last 20-25 years can be accepted as homogeneous. Even this acceptance needed considerable relaxation in the significance levels as the tests resulted rather low probabilities of homogeneity. Ultimately, water levels from the period of 1976–96 have been singled out as boundary conditions for hydrodynamic simulations within the DSS. A detailed description of the homogeneity tests is given in Appendix II.

Monthly average precipitation and evaporation data have been derived from appropriate meteorological maps. It was also possible to calibrate these data on the basis of recorded water levels. Especially data from Lake Nyéki (see Figure 4.9) have proven to be applicable for this purpose as its time series is continuous for the low water periods too, when no in- and outflows occurred and also no significant water exchange took place between the lake and the groundwater due to its thick clay bed. This means that the major causes of water level changes were precipitation and evaporation indeed. The intensity of precipitation excess (precipitation – evaporation) can thus easily be estimated on the basis of the temporal gradients of recorded water levels in Lake Nyéki.

Finally, the acquired and generated base data have been stored in appropriate *databases* that can be accessed by the different programmes of the DSS.

[1] Details about this GIS application can be found in Stégner [1999].

9.2 Establishing the envisaged configuration of the cell-system

To simulate the decision process related to the revitalisation of the subjected cell-system, a virtual Decision Making Group (DMG) have been set up with members representing the main objectives and constraints. Accordingly, an ecological stakeholder group within the DMG stands for ecological objectives. Stakeholders are delegated by the forestry company and by the water authority too, in order to represent the interest of wood production and flood control. Last but not least a fourth stakeholder group is responsible for the financial feasibility of the revitalisation project. Its objective is to minimize the investment and operational costs. The DMG is assisted by a virtual Planning Group (PG) with appropriate theoretical and practical knowledge about the applied DSS software. This cooperation refers in fact to the 'interface' component of the decision process that has been discussed in Chapter 3 in general and in Chapter 6 in particular.

The first step of planning the ecological revitalisation is to establish the configuration of the cell-system that forms the common basis for alternative solutions. Setting up the configuration thus means positioning the weirs, sluices and fok-channels in the given system. This is in fact the first decision problem the DMG has to face.

The configuration, formulated for this case study, is shown on Figure 9.1. Accordingly new fok-channels are planned to be excavated between the Nyéki and Báta, as well as between the Nyéki and Csörösz cells. This results a contiguous cell-system with primary water intake through the Kisrezéti-fok. The purpose of the upstream intake is to raise water levels in the entire system in order to counteract desiccation. The new channel between the Nyéki and Báta cells results in a system with large storage capacity that has the potential to mitigate the fast water level fluctuation for the benefit of fish reproduction. To keep the water on the desired high levels, the downstream outlets of the system have to be closed totally or partially. This is why the Cserta, Címer I and Címer II channels (see Figure 4.8) are planned to be closed completely. Because of similar reasons a stone weir is planned to be built into the boundary section of the Báta fok-channel (Figure 9.1).

Connecting the system to the Rezéti branch is advantageous also from the point of view of sediment inflow. Rezéti is a very gently sloping, long side-branch of the Danube where most of the incoming sediment gets settled down already in its upstream reach. The little island in the branch for example (see Figure 9.1) has been built up by sand deposition. These all means that the sediment content of the water flowing into the cell-system through the Kisrezéti-fok will be much lower than that of the Danube. Thus, the Rezéti branch would function as a sediment trap, which hampers the acceleration of the aggradation processes in the cells. Nevertheless, it would be worthwhile to analyse thoroughly sedimentation and erosion processes that would occur in the proposed cell-system. Such research however could not be fitted into the scope of this study.

According to the envisaged configuration a new channel is proposed to be constructed between the Csörösz cell and the Danube too. It is believed that this connection would improve the water regime control in this cell, which might be needed by the special ecological function (see later) associated with Csörösz.

Installing sluices is also envisaged. These would be simple manually operated sliding gates. One location of such potential sluice is the Kisrezéti-fok, as it would provide a better control on the water regime of the entire system (Figure 9.1). Sluices are also envisaged to be installed into the channels of the Csörösz cell. These sluices make possible to improve further the water regime control in this cell for the benefit of its special ecological function.

The above-mentioned special ecological function of Csörösz is to provide good foraging conditions for black storks and for other waders. Black stork (*Ciconia nigra*) is the most valuable bird of the area. Its favourite food is juvenile fish. Good foraging condition in the Gemenc floodplain is essential not just on local, but also on continental scales, since storks migrating from Central- and Northern Europe use the Gemenc as a resting and foraging place [Kalocsa, 1999, pers. comm.]. The shallow and flat Csörösz cell would be an excellent foraging site, provided that hydrological conditions are proper. The role of the planned channels and sluices is just to provide such proper conditions as much as possible.

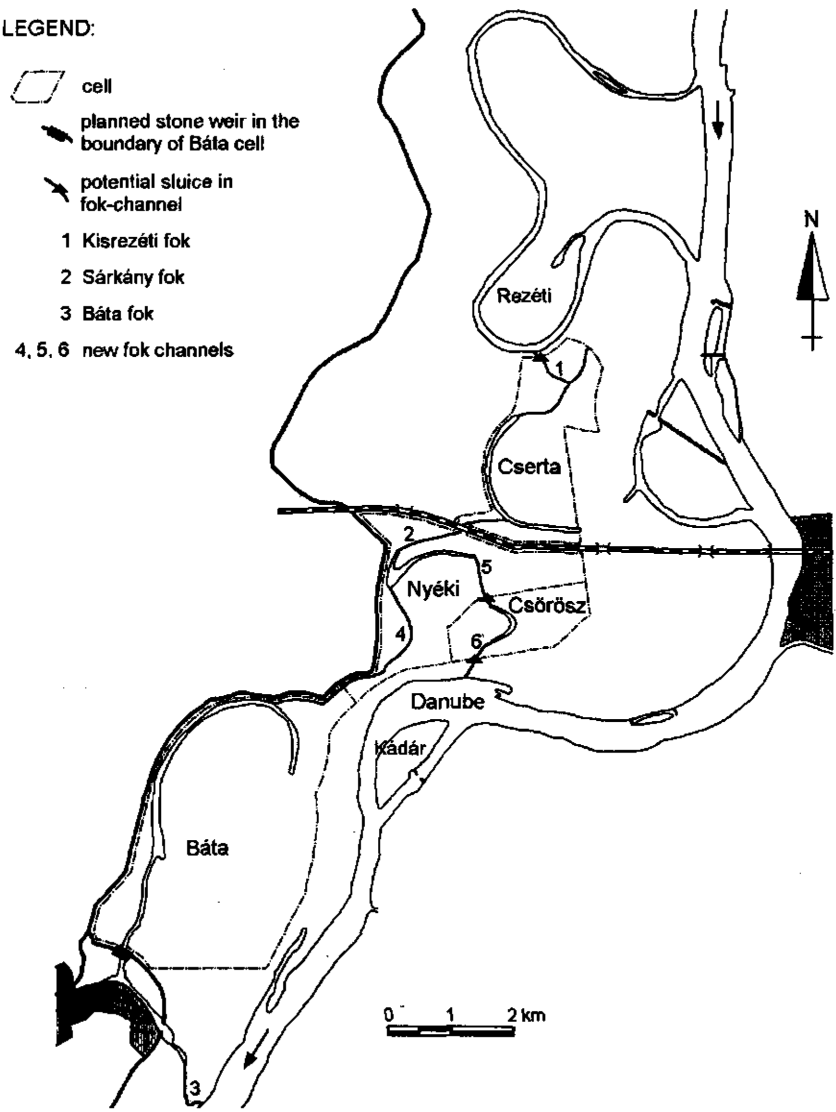

Figure 9.1 The envisaged configuration of the case study cell-system

Figure 9.2 shows the model configuration of the envisaged cell-system. In spite that the Címer I and Címer II fok-channels are planned to be closed the model configuration still contains links at these locations. The purpose of these links is to model the overland flow that still occurs at these locations during floods. These links thus contains only overland flow weirs while the rest of the links incorporate fok-channels too.

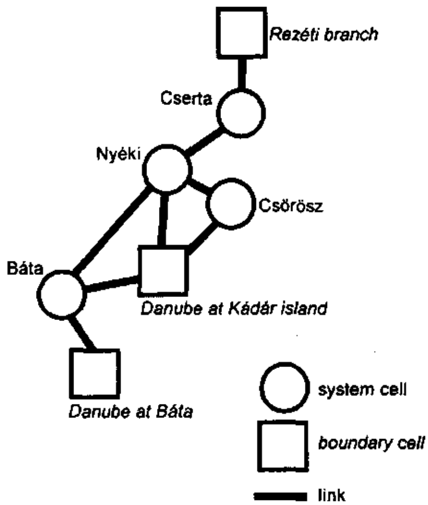

Figure 9.2 Model configuration of the case study system for hydrodynamic simulations with FOK

As Figure 9.2 also indicates the graph formed by the system cells is a tree, which prevents the occurrence of looped cells within any potential composite system cell. This is an important precondition for the proper work of FOK because the actual cell-merging algorithm is not able to handle such composite cells as it has been pointed out in Section 7.2.2.

9.3 Formulation of the decision space

The above outlined cell-system configuration thus gives the common basis for generating the decision space where the DMG can search for the compromise solution with the help of the DSS. The decision space is composed by discrete sets of design alternatives generated for the different system elements, according to the measures introduced in Chapter 5. The sets are generated on a way to cover the total range of feasible design options. In case of fok-channels this means that design alternatives are ranging from channels with high and narrow thresholds to channels with deep and wide beds. For example a set of 256 design alternatives has been developed for the Kisrezéti-fok, and the spectrum of this set is ranging from a channel alternative with 84.3 maD bottom level, 3.1 m bottom width and 1:1 bank slope, to the one that has a constructed threshold with 87.3 maD crest level, 1 m crest width and 1:2 side slope.

Channel alternatives may also differ in terms of their courses. The new channel between the Báta and Nyéki cells for example has two alternative courses. These courses differ only in their upper sections: one utilizes the bed of the Címer I fok-channel, while the other uses the ditch[2] along the flood control dike (Figure 9.3). The lower section of both courses is placed into the lower section of the same ditch, thus both course alternatives utilize existing channel beds, which enable to reduce excavation costs.

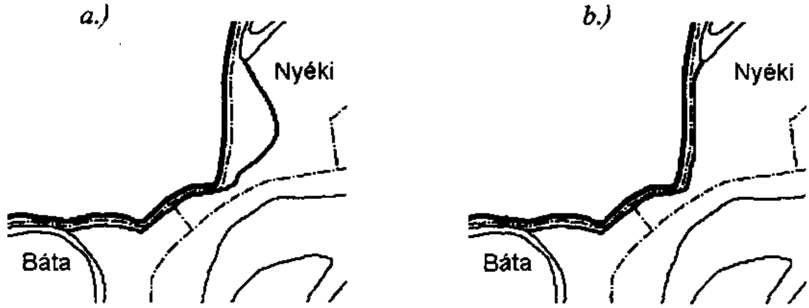

Figure 9.3 Alternative courses for the new fok-channel between the Nyéki and Báta cells

Summer dike alternatives are ranging from the highest feasible dike to the zero option. This latter refers to the case when no dike is built on the boundary at all. There are for example 4 summer dike alternatives for the boundary between the Nyéki cell and the Danube. The first one is the zero option while the second, third and fourth alternatives prescribe the building of a summer dike with a crest elevation of 87.8, 88.1 and 88.4 maD respectively.

The sets of sluice alternatives comprise different gate designs as well as the zero option (when no sluice is built into the boundary section of the channel). Gate designs differ only in their gate heights. The shape of the gate is the same as that of the modified channel at the cell-boundary section (see Figure 5.2.c), where the sluice is to be installed. The effect of different gate heights play role when the water flows over the top of the closed gate.

Operation policy of the sluice in the Kisrezéti-fok prescribes active gate operation only for the growing season. For the rest of the year the sluice is kept closed. For the growing season the policy prescribes to open the gate only if water level in the Rezéti branch is higher than that of the Cserta cell; otherwise the gate has to be closed. The purpose is to keep the water levels in the system as high as possible. This policy is implemented on a daily basis, which means that the person in charge checks the water levels every day and if necessary goes to the site and opens or closes the gate.

The sluice between the Nyéki and Csörösz cells is kept closed during the foraging period of storks (August and September), while it is kept open during the rest of the year. The third sluice, which connects the Csörösz to the Danube, is kept closed for the whole year except for the foraging period when it gets open whenever the Danube level drops below that of the Csörösz. The purpose of these policies is twofold: on the one hand it is desired to generate good spawning conditions in the Csörösz by 'merging' it to the Nyéki cell where high water levels with slow fluctuations are expected to occur; on the other hand it is aimed to turn this lake into a shallow, wadable water body for the foraging period by disconnecting it from

[2] This ditch was excavated in the 19th Century with the purpose of winning earth for building the neighbouring dike.

Nyéki and by decreasing its water levels down to the threshold (bottom) level of the sluice between the Csörösz and the Danube.

Sluice operation policies are thus the same for each sluice alternative, even though it would be possible to enlarge the decision space by formulating several alternative policies.

Each point in the decision space thus refers to a particular cell-system revitalisation solution.

Binary coding of the solutions, required by the Genetic Algorithms (GA) kernel of the DSS, refers to the within-set serial numbers of the design alternatives. The code given on Figure 9.4 for example refers to the following cell–system solution:

- 88-th design alternative for the Kisrezéti-fok
- 2-nd alternative for the envisaged sluice in the Kisrezéti-fok
- 63-rd alternative for the Sárkány-fok
- 72-nd alternative for the new channel between the Nyéki and Báta cells
- 1-st alternative for the summer dike between the Danube and the Nyéki-cell (zero option: no summer dike)
- 5-th alternative for the summer dike and stone weir built into the downstream boundary of the Báta-cell
- 4-th alternative for the new channel between the Nyéki and Csörösz cells
- 1-st alternative for the summer dike between the Nyéki and Csörösz cells
- 1-st alternative for the sluice in the new channel between Nyéki and Csörösz cells (zero option: no sluice)
- 6-th alternative for the new channel between the Danube and the Csörösz cell
- 1-st alternative for the sluice in the new channel between the Danube and the Csörösz (zero option: no sluice)
- 1-st alternative for excavations within the Nyéki cell (zero option: no excavations)
- 1-st alternative for excavations within the Csörösz cell (zero option: no excavations)

88.	2.	63.	72.	1.	5.	4.	1.	1.	6.	1.	1.	1.
01010111	01	0111110	01000111	00	0000100	11	00	0	101	0	0	0

Figure 9.4 Binary coding of a certain solution for the Gemenc cell-system

As Figure 9.4 also indicates there are several system elements not being represented in the binary coding. It is because no design alternatives have been developed for them due to different constraints. For example, no summer dike alternatives have been created for the boundary between the Cserta and Nyéki cells. This is because the representatives of the water authority within the DMG have vetoed such ideas, as the gaps on the railway dike must be kept free of any obstacles in order to ensure the required flow passage during high floods. Building summer dike on the railway dike itself makes no sense as the top of this dike is above the highest flood levels. Because of similar reasons, no summer dike alternatives have been formulated for the high natural levee, which forms the northern boundary of the Báta to the Danube (Figure 9.1).

The lengths of the binary sub-strings indicate the sizes of the component sets. The first two sub-strings for example indicate that altogether 256 design alternatives and 4 sluice alternatives have been formulated for the Kisrezéti-fok. The length of the full string on the other hand indicates the size of the decision space itself. Accordingly, the decision space formulated for this case study contains altogether *35 184 372 088 832* cell-system solutions.

The Planning Group (PG) thus searches for the best compromise solution within this decision space, according to the criteria, constraints and aspiration levels specified by the Decision Making Group (DMG).

Before starting the ESEMOPS based search it is necessary to build up a database for the decision space, which contains all the necessary data of each element of each component set. In case of a channel alternative for example this database contains the delivery functions (needed by the FOK model), the geometry of the modified cross sections and the quantity of earth and stone excavated and/or filled in. The modified geometry and the quantities earthwork are calculated on the basis of the present geometry and the desired bottom level, bottom width and bank slope. These calculations are executed by the FOKBUILD pre-processor prior calculating the delivery functions. The database also contains the geometrical and earthwork data of the different summer dike alternatives, as well as the parameters of hypothetical overland flow weirs, which model the effect of the different summer dike alternatives in the FOK model. These data are calculated by means of the BNDBUILD pre-processor. Finally, the database contains the elevation-area functions and the required earthworks of the different cell alternatives too. Calculation of these data is the task of the CELLBUILD pre-processor.

As the representation of the alternative cell-system solutions within the GA engine of the DSS implies, accessing the database of the decision space must be based on the serial numbers of the different system element alternatives. Technically this means that that it must be a direct access database where the data of the alternatives are stored in records addressed by their serial numbers.

9.4 Formulation of evaluation criteria

Ecological criteria are calculated from the results of ecological modelling, as described in Chapter 8. For this case study the following ecological criteria have been formulated:

- z_1 : area of the water plant zone in the Nyéki and Báta cells
- z_2 : area of the water zone in the Nyéki and Báta cells
- z_3 : Weighted Usable Area (WUA) for spawning in the Nyéki and Báta cells
- z_4 : area of the forest zone in the entire system
- z_5 : WUA for foraging storks in the Csörösz cell

These area-type criteria are dimensionless, as they refer to relative areas (zone areas divided by the total area of the cell(s)).

Investment cost (z_6) is an essential evaluation criterion too. Investment cost of cell-system revitalisation consists of the costs of excavations and that of constructions (channel thresholds, summer dikes, sluices). These costs are function of the amounts of earth- and construction works (Table 9.1), which is to be downloaded from the database of the decision space.

Operation costs arises only if the envisaged cell-system comprises sluices. These costs are function of expected annual numbers of closings and openings of all sluices in the system, which are calculated on the basis of the 21 years long simulation with the FOK model. Accordingly, this expected number of sluice operations is applied as criterion indicating operational costs (z_7).

As the selected criteria indicate, no special ecological priority has been assigned to the Cserta cell. It is because this is the most upstream cell and it has a direct connection to the river channel system, which all limit the possibilities of rising water levels and mitigating water level fluctuations in the cell.

Table 9.1 Unit costs of the different revitalisation measures

Channel excavation (HUF/m^3) [3]	Channel threshold construction (HUF/m^3)	Summer dike construction (HUF/m^3)	Cell excavation (HUF/m^3)	Sluice installation (HUF/piece)
1,000	3,000	2,000	500	1,000,000

9.5 The simulated decision making procedure

In order to demonstrate the ESEMOPS based DSS developed for ecological revitalisation of river floodplains, a decision making procedure has been simulated. The subject of this simulated decision making was the case study cell-system in the Gemenc floodplain. The tool was the computer based DSS and the participants were the different imaginary stakeholder groups of the virtual DMG. During the simulated decision process the virtual PG was assisting the DMG by operating the software and helping the DMG in interpreting the outputs and in directing the search.

Zsuffa *et al.*, [2000, a] and Zsuffa *et al.*, [2000, b] present alternative decision making simulations implemented on the same case study system with the help of the proposed DSS.

Before launching the decision iteration process it is important to locate the criterion-specific optima within the given decision space. Having this *ideal point* [Tecle & Duckstein, 1994] in hand the DMG becomes aware of the best possible results it can achieve at each criterion. This is especially useful in those cases when interpretation and evaluation of criteria scores are difficult (for example the WUA-s of criteria z_3 and z_5). By knowing the targeted level of such criteria the DMG is provided with a basis where it can easily evaluate criteria achievements - at least on a relative scale.

Solving the criterion-specific optimisation problems can be done with the help of the DSS software without modifying its algorithm. First the aspiration level of the criterion (that is to be optimised) has to be set on an unfeasible extreme level; now if this aspiration level is taken as a constraint then the applied penalty method forces Genetic Algorithm (GA) to search for the solution closest to this constraint level without taking into account the scores of the other criteria. The so-derived criterion-specific optima are presented on Table 9.2

[3] HUF: Hungarian Forint

Table 9.2 Criteria scores of the ideal point of the problem

z_1	z_2	z_3	z_4	z_5	z_6	z_7
0.085	0.165	0.041	0.656	0.034	7.172	0

Figure 9.5 below shows the convergence of the GA search that located the optimum of criterion z_6 within the given decision space. As the figure indicates it took about 100 generations to reach a level from where no further improvement was expected to occur.

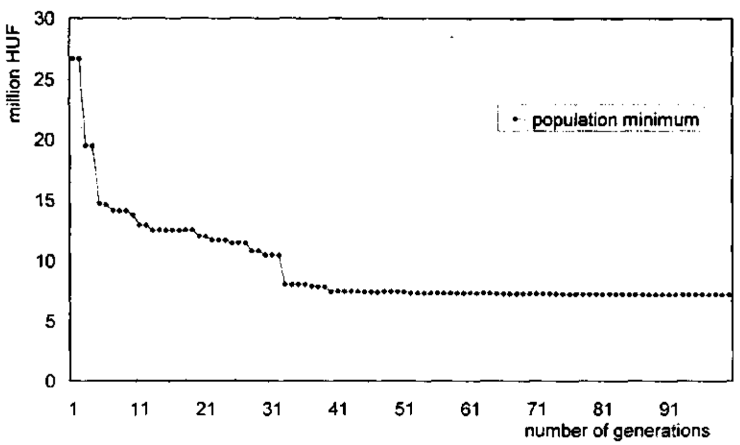

Figure 9.5 Convergence of the GA search that located the goal level of criterion z_6

The conflicting nature of the subjected multi criteria problem prevails by looking at all criteria achievements of the criterion-specific optimal solutions (Table 9.3). It can easily be concluded that there are strong conflicts among the interests of the stakeholder groups standing for ecology, forestry and finances within the DMG.

Table 9.3 Criteria achievements of the criterion-specific optimal solutions

Criteria	Optimal solutions for:					
	z_1	z_2	z_3	z_4	z_5	z_6
z_1	*0.085*	0	0.075	0	0.005	0.008
z_2	0.101	*0.165*	0.15	0.054	0.052	0.062
z_3	0.032	0.015	*0.041*	0.007	0.006	0.007
z_4	0.306	0.35	0.429	*0.656*	0.256	0.317
z_5	0.001	0	0	0	*0.034*	0
z_6	53.51	106.65	130.18	127.14	98.27	*7.172*
z_7	7.429	7.333	7.143	19.62	3.905	0

Thus the DMG must establish its initial aspiration levels by relaxing the levels specified by the ideal point; otherwise the desired compromise solution will never be achieved. Accordingly, the DMG initiated its aspiration levels by relaxing the levels of the ideal point with 10%[4]. These aspiration levels along with the GA based solutions of the related principal and auxiliary problems are presented on Table 9.4.

Table 9.4 Aspiration levels and criteria scores in the first decision iteration cycle

Criteria	Initial aspiration levels	Principal problem	Auxiliary problems						
			1.	2.	3.	4.	5.	6.	7.
z_1	0.077	0.015*	*0.078*	0*	0.069*	0.004*	0.007*	0.015*	0.015*
z_2	0.148	0.07*	0.098*	*0.157*	0.147*	0.061*	0.052*	0.07*	0.069*
z_3	0.037	0.007*	0.034*	0.016*	*0.037*	0.007*	0.006*	0.008*	0.008*
z_4	0.59	0.322*	0.402*	0.332*	0.411*	*0.591*	0.289*	0.337*	0.338*
z_5	0.031	0*	0*	0*	0*	0*	*0.031*	0.019*	0.019*
z_6	7.889	7.173	26.84*	27.49*	47.83*	49.34*	29.58*	*7.855*	7.792
z_7	5	0	8.48*	7.43*	7.14*	14.86*	3.81	0	*0*

* aspiration is not satisfied

Note that the numbering of auxiliary problems refers to the number of criterion, which has been fixed as constraint. Also note that all aspirations are of 'at least' type except investment costs (z_6) and sluice operations (z_7), which are of 'at most' type.

Solution of the principal and auxiliary problems indicates clearly that the aspirations of the DMG are still too strict. Satisfying the aspiration level of one criterion results in dissatisfaction at the rest of the criteria. Accordingly the DMG decided to relax further its aspirations at each criterion and to go for another iteration cycle (Table 9.5).

As Table 9.5 shows the scores of z_5 are rather uniform and close to the aspiration level (except at aux. prob. 3). This indicates that z_5 is quite independent from the other criteria and that it is likely possible to get close to this 0.02 aspiration level regardless to what is desired at the other criteria. These all convinced the DMG to relax this level a bit (to 0.018) and to fix it as a constraint for the subsequent iteration cycles.

Otherwise, the results indicate that the aspiration levels of z_1, z_2, z_3, z_4 and z_6 are still too strict and need further relaxation. Especially satisfying the aspiration level of the forest area (z_4) costs too much both financially and ecologically.

[4] Except for z_6 where this initial aspiration level was set on 5.

Table 9.5 Aspiration levels and criteria scores in the second decision iteration cycle

Criteria	Aspiration levels	Principal problem	Auxiliary problems					
			1.	2.	3.	4.	5.	6.
z_1	0.065	0.016*	*0.065*	0.019*	0.06*	0.005*	0.012*	0.016*
z_2	0.13	0.07*	0.093*	*0.13*	0.093*	0.069*	0.065*	0.07*
z_3	0.03	0.008*	0.014*	0.025*	*0.032*	0.007*	0.007*	0.008*
z_4	0.5	0.337*	0.441*	0.389*	0.403*	*0.51*	0.339*	0.337*
z_5	0.02	0.019*	0.019*	0.019*	0*	0.019*	*0.021*	0.019*
z_6	15	7.85	38.61*	29.73*	22.83*	33*	9.649	*11.69*
z_7	10	0	9.24	7.9	8.19	11.33*	2.952	0

The relaxed aspirations as well as the constraint were input for the third decision iteration cycle (Table 9.6).

Table 9.6 Aspiration levels, constraint level and criteria scores in the third decision iteration cycle

Criteria	Aspiration levels	Constraint levels	Principal problem	Auxiliary problems					
				1.	2.	3.	4.	6.	7.
z_1	0.055		0.016*	*0.057*	0.063	0.023*	0.012*	0.015*	0.01*
z_2	0.1		0.069*	0.091*	*0.101*	0.093*	0.064*	0.07*	0.065*
z_3	0.025		0.008*	0.014*	0.031	*0.025*	0.007*	0.008*	0.007*
z_4	0.44		0.337*	0.421*	0.381*	0.36*	*0.449*	0.387*	0.317*
z_5		0.018	0.019	0.019	0.024	0.024	0.024	0.023	0.023
z_6	20		7.823	36.57*	48.42*	38.51*	12.09	*19.47*	8.921
z_7	10		0	13.62*	14.67*	14.38*	15.52*	2.857	*3.048*

The results of the third cycle strengthen the belief that a relatively strong correlation exists between z_1, z_2 and z_3 on one hand and z_6 on the other hand. Cheap solutions have low ecological scores while ecologically sound alternatives are quite expensive. Auxiliary problem no. 2 resulted an especially good ecological solution even though its extremely high costs was unacceptable for the stakeholder representing finances, and the representative of forestry was not satisfied either. Accordingly, the ecological group of the DSS got convinced to do a final relaxation in the first three criteria in order to achieve better scores at the costs and if possible at the forest area too.

The relaxed ecological aspiration levels were input for the fourth iteration cycle where they were added to the constraint set. By this it has become possible to locate either the cheapest solution, or the solution with the biggest forest area within the set of solutions satisfying the ecological aspirations. To solve these constrained optimisation problems the aspiration level of the criterion being optimised has to be set on an extreme level and the rest of the criteria that have not been added to the constraint set have to be disregarded. These *special auxiliary problems* along with the principal problem associated with the given aspiration and constraint structure are solved in the fourth decision iteration cycle (Table 9.7).

Table 9.7 Aspiration levels, constraint levels and criteria scores in the fourth decision iteration cycle

Criteria	Aspiration levels	Constraint levels	Principal problem	Optimal solutions for:	
				z_4	z_6
z_1		0.05	0.058	0.064	0.061
z_2		0.08	0.093	0.01	0.093
z_3		0.02	0.031	0.025	0.031
z_4	0.44		0.396*	*0.512*	0.374*
z_5		0.018	0.025	0.018	0.019
z_6	20		27.16*	147.65*	*27.06**
z_7	10		13.71*	8.48	12.1*

The principal problem of the fourth cycle resulted an excellent solution. Scores of ecological criteria significantly outperform the aspiration levels while that of the forest area and costs do not cause unacceptable high violations. In fact the investment costs (z_6) of this solution is very close to the lowest possible value related to this constraint structure, as it is proven by the optimal solution for z_6 (see Table 9.7). Optimal solution for z_4 however shows that it is still possible to increase the forest area even though it likely causes rapid increase in investment costs. The still unsatisfied forestry stakeholder therefore demanded a last search targeting the cheapest solution that satisfy the ecological constraints plus a forest area constraint which has been derived by slightly relaxing its aspiration level (Table 9.8).

As Table 9.8 indicates satisfying both the needs of ecology and forestry doubles investment costs. This convinced the DMG to stop the decision iteration process and to choose the solution of the principal problem of the fourth iteration cycle as the ultimate (best compromise) solution for the given multi criteria decision problem. The forestry stakeholder got finally convinced that increasing the forest area from 39.6 % to 42 % does not bear proportion with the boom in costs.

Note that scores of z_6 were being disregarded after the second decision iteration. It was realized that these scores tend to stay below 15, which the DMG considered to be an acceptable level of operational efforts.

Table 9.8 Constraint levels and criteria scores in the fifth decision iteration cycle

Criteria	Constraint levels	Optimal solution for z_6
z_1	0.05	0.072
z_2	0.08	0.107
z_3	0.02	0.034
z_4	0.42	0.421
z_5	0.018	0.024
z_6		*54.86*
z_7		14.48

Figure 9.6 below shows the convergence of the GA search that located the best compromise solution. The applied GA parameters are given on Table 9.9.

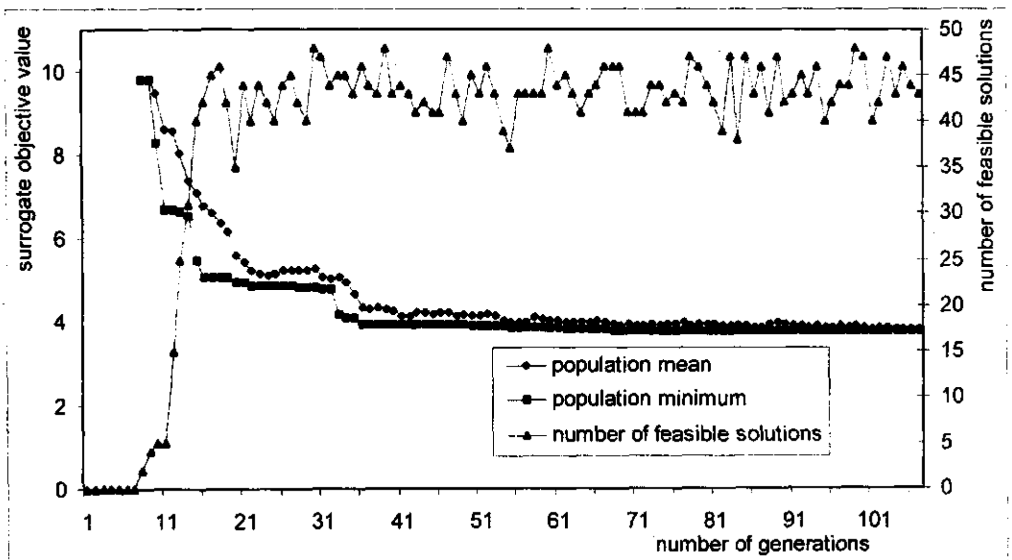

Figure 9.6 Convergence of the GA search that located the solution of the principal problem in the fourth decision iteration cycle

Table 9.9 GA parameters applied in the DSS

Population size	Crossover probability	Mutation probability	Scaling factor
51	0.6	0.007	3

Because of the applied penalty method, GA actually implemented two subsequent searches whenever it dealt with constrained problems: it started searching for the feasible region of the decision space and then it gradually shifted the search towards the optimum of the actual auxiliary or principal problem. In case of the GA search shown on Figure 9.6, it took a lot of effort to locate the feasible region. The first solution, which satisfied all the four constraints[5], was found only in the seventh generation, and the effective search for the optimum could only be started somewhere around the 15-th generation when feasible solutions reached a stable high proportion (around 43/51) within the population. The solution of the problem was assumed to be achieved at the 107-th generation when the convergence rate of population means and minimums have dropped below a pre-specified limit.

It is important to state that the best compromise solution of the multi-criteria problem should not necessarily be a principal problem. Depending on the choice of the DMG it may also be an auxiliary problem.

9.5.1 Introduction of the identified best compromise solution

The compromise solution located by the decision iteration game is composed by the following design alternatives:

- 104-th alternative for the Kisrezéti-fok: building a threshold in the boundary section of the channel with a crest elevation of 85.7 maD, crest width of 2.8 m and 1:1 side slope
- 2-nd alternative for the sluice in Kisrezéti-fok: installation of a sluice with a 1 m high gate
- 68-th alternative for the Sárkány-fok: a threshold with crest elevation: 85.2 maD, width: 1 m and side slope: 1:2
- 220-th alternative for the new channel between the Nyéki and Báta cells: bottom level: 85.2 m, bottom width: 1.9 m, bank slope: 1:2; the course of the channel is the one displayed on Figure 9.3.a
- 1-st alternative for the summer dike between the Danube and the Nyéki-cell: zero option
- 22-nd alternative for the summer dike and stone weir built into the downstream boundary of Báta-cell: the top of the summer dike is on 87.3 maD, the crest of the stone weir (built into the summer dike) is on 86.8 maD, its crest width and side slope is 2 m and 1:2 respectively
- 2-nd alternative for the new channel between the Nyéki and Csörösz cells: bottom level: 85.2 maD, bottom width: 2 m, bank slope: 1:1
- 1-st alternative for the summer dike between the Nyéki and Csörösz cells: zero option
- 2-nd alternative for the sluice in the new channel between Nyéki and Csörösz cells: the height of the gate is 2 m
- 7-th alternative for the new channel between the Danube and the Csörösz cell: bottom level: 85.1 maD, bottom width: 2 m, bank slope: 1:1
- 2-nd alternative for the sluice in the channel between the Danube and the Csörösz: height of the gate is 2 m
- 1-st alternative for excavations within the Nyéki cell: zero option
- 1-st alternative for excavations within the Csörösz cell: zero option

[5] These are the constraint levels of z_1, z_2, z_3 and z_5.

Criteria achievements of the best compromise solution are presented in Table 9.7. Accordingly, 5.8 % of the total area of Nyéki and Báta cells belongs to the water plant zone, 9.3 % belongs to the water zone and 3.1 % is the Weighted Usable Area for spawning fish. The Weighted Usable Area for foraging storks in the Csörösz cell is 2.5 % with respect to the total cell area. The expected size of the forest zone in the entire system is 39.6 % of the total area of all four cells. Investment costs is 27.16 million HUF, and the expected number of annual sluice operations is 13.71.

Figure 9.7 below shows the effect of the best compromise solution on the water levels of the Báta cell. It shows two water level time series: one is recorded data from 1995-96, while the other is the result of simulating the best compromise solution with the help of the FOK model. The positive ecological effects are indicated by the significantly increased low water levels, which will counteract the desiccation problem to a great extent. Also the flashy water level fluctuation has been mitigated for the benefit of spawning fish. Decreased amplitudes of water level fluctuation indicate the positive effect on water plants as the plants have become less exposed to stranding and submergence stresses.

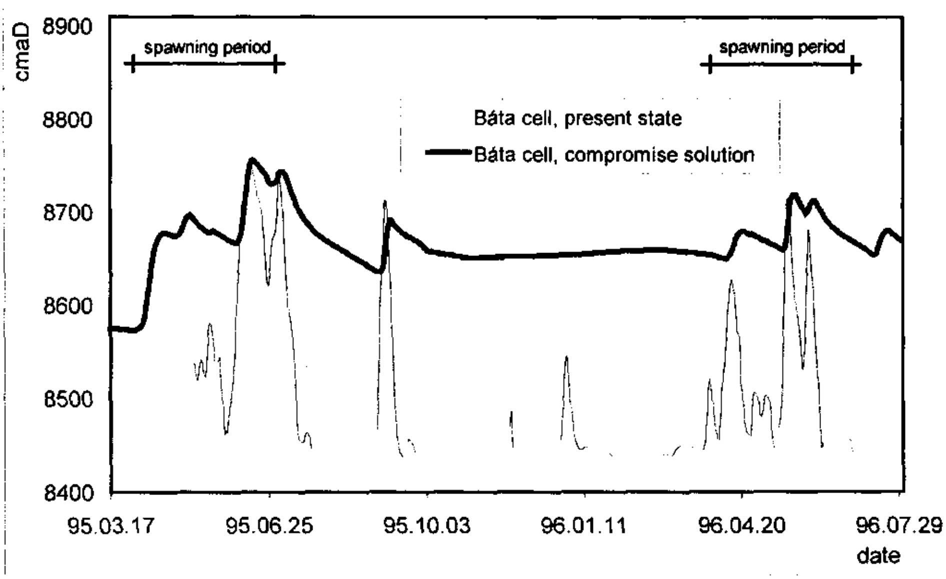

Figure 9.7 Effect of the compromise solution on the water levels of the Báta cell

The water regime of the Nyéki cell would not undergo such extreme changes as that of the Báta (Figure 9.8). Although low water levels get somewhat raised and the fluctuation has been mitigated on the lower elevations, the water regime on the higher elevations has not been changed significantly. This is probably due to the compromise made with forestry and finances. That is to say increased inundation on the higher grounds is likely detrimental for the forests growing there, furthermore such increase can only be achieved by erecting a summer dike on the cell boundary between Nyéki and the Danube, which would however cause a significant increase in investment costs.

The water regime of the Csörösz cell is in fact identical to that of Nyéki throughout the year except for the stork foraging period (Figure 9.9). This is because the sluice between these cells is kept open causing the two cells to merge into one single water body. During the foraging period however the two cells get disconnected by closing the sluice and the Csörösz gets emptied as much as possible with the help of its downstream sluice in order to make it wadable for the birds. Indeed the water level tends to stay below the maximum wadable depth during the foraging period as indicated by Figure 9.9.

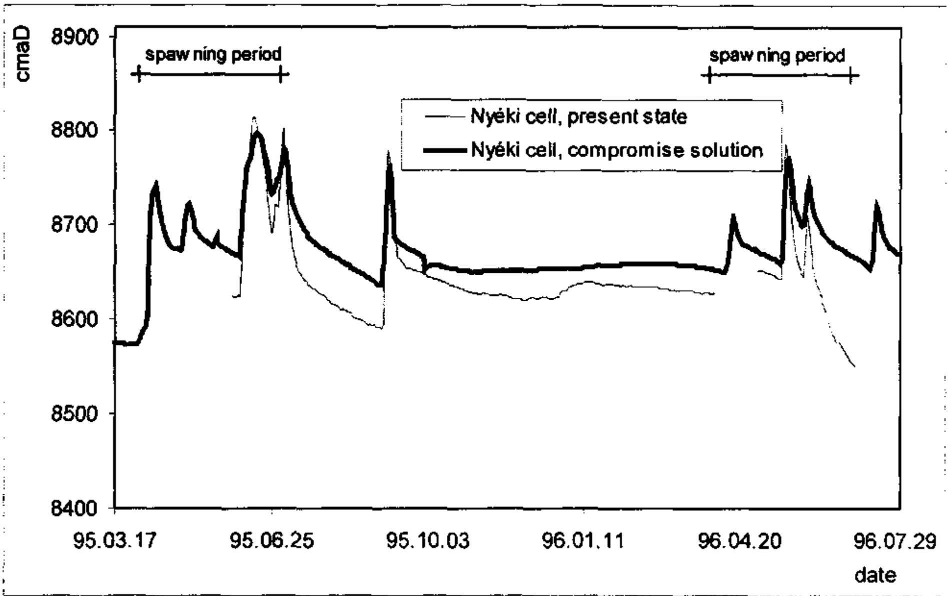

Figure 9.8 Effect of the compromise solution on the water levels of the Nyéki cell

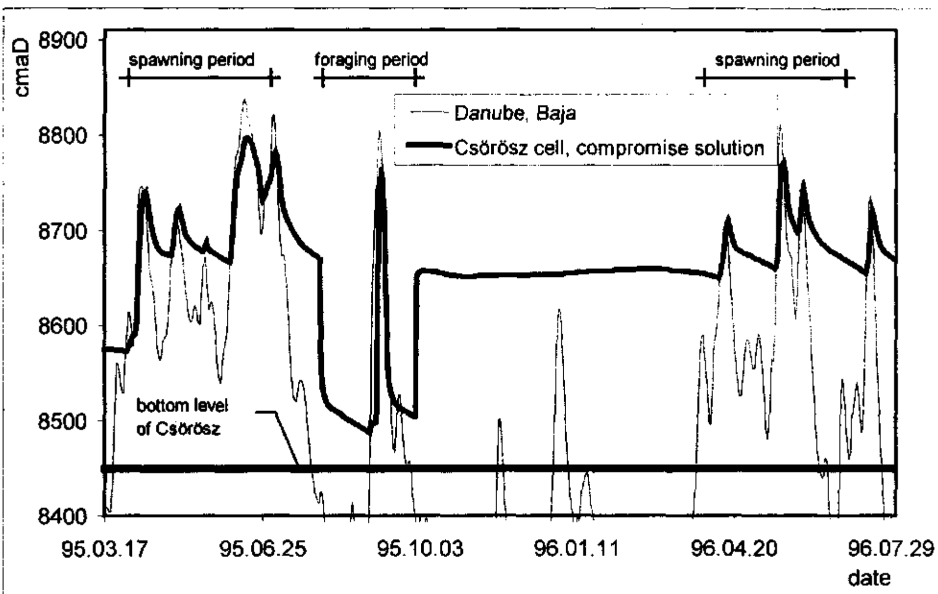

Figure 9.9 Effect of the compromise solution on the water levels of the Csörösz cell

9.6 Review of the decision making process

Figure 9.10 below shows the flowchart that summarizes the entire decision-making process as described in the previous sections of this chapter.

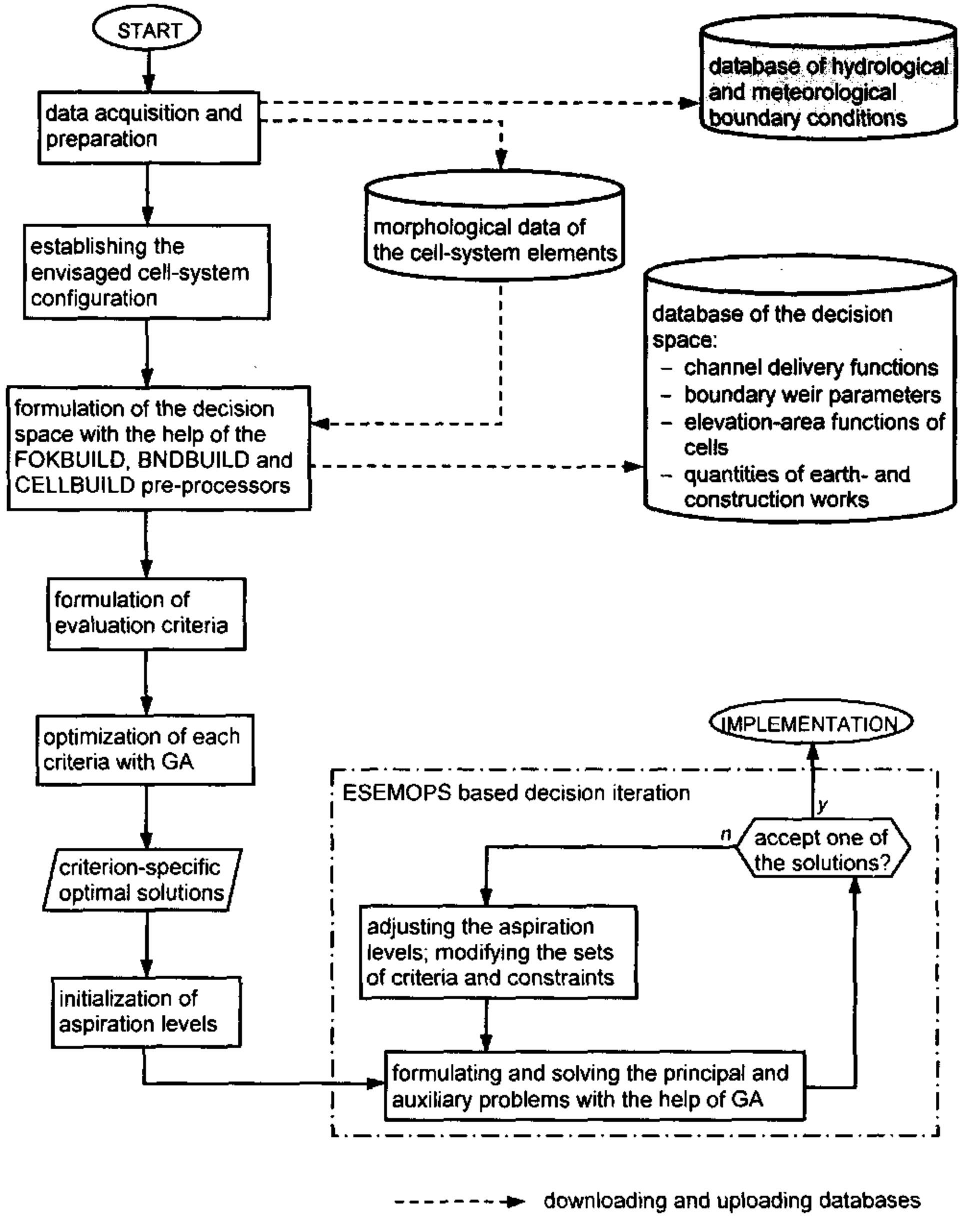

Figure 9.10 Flowchart of the decision making process for cell-system revitalization

The flow chart of the GA based kernel of the decision process is presented by Figure 6.5 in Chapter 6. Figure 9.11 below shows how the impact assessment step of GA was actually implemented within the DSS.

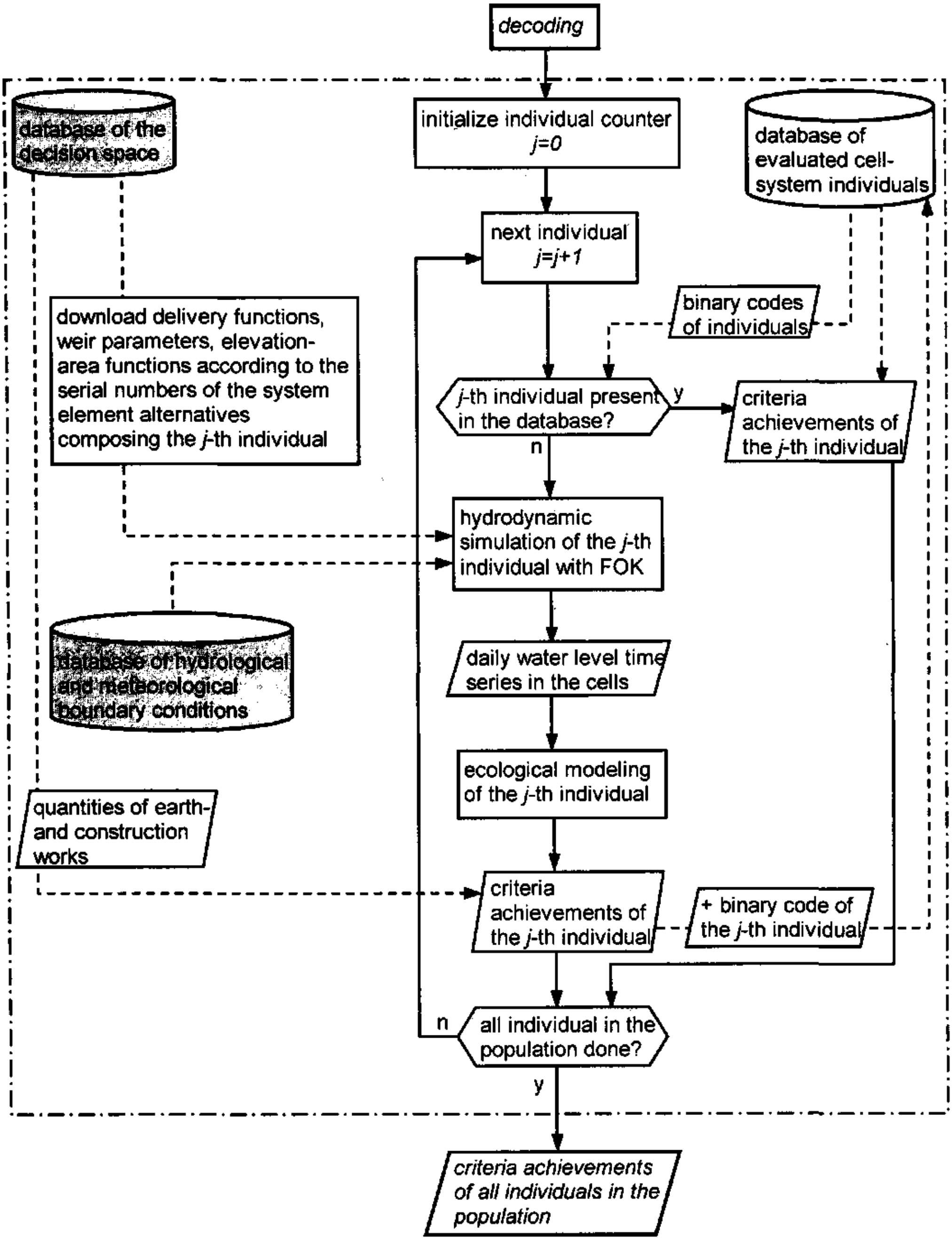

Figure 9.11 Flow chart of impact assessment (criteria evaluation) within GA

Besides the already-mentioned databases Figure 9.11 also presents an additional database, which contains information about cell-system solutions (or 'individuals' according to the GA terminology) that have already been evaluated by the actual GA search. As Figure 9.11 indicates this database enables to skip the evaluation of repeated individuals (in other words: 'clones'), and thus it results in significant savings of runtime. Such savings is essential for completing the decision iteration process within a feasible time interval. That is to say, in spite of the temporal and spatial adaptation abilities and of the application of channel delivery functions (which made the FOK model much faster than any other models as it is pointed out in Chapter 7) the speed of hydrodynamic simulation is still too slow for a DSS where several thousands of alternatives have to be evaluated during the subsequent GA searches. This database made possible to reduce the time of the GA runs to their thirds on average. For example the GA search that located the compromise solution processed altogether 5457 individuals, even though only 1910 of them were actually evaluated because the rest were simply the clones of these individuals.

10. CONCLUSIONS AND RECOMMENDATIONS

10.1 Conclusions

The purpose of this study was to create a Decision Support System (DSS) for ecological revitalisation of river floodplains. The scope of the DSS was restricted to the lentic cell-system of the floodplain, which is characterised by stagnant water bodies having fluctuating water level. Because of flood control, navigation and land uses, and also because of conflicts between the different ecological objectives, floodplain revitalisation is inevitably a constrained, multi-objective decision problem where the task is to identify the best compromise solution.

Ecological revitalisation of floodplains requires appropriate modifications in the water regime since this is the most influencing abiotic factor for floodplain ecosystems. Modifying the water regime of a cell-system can be implemented by modifying its water conveyance infrastructure. Revitalisation measures like narrowing or enlarging 'fok'-channels, erecting summer dikes along the cell boundaries, installing and operating sluices etc. have been identified. Based on these measures a discrete decision space have been set up for the case study system where each point stands for a particular cell-system alternative. Formulation of an explicit decision space enabled to use mathematical search techniques thus facilitating the identification of the best compromise solution. When establishing the decision space, it is possible to take into account certain constraints by confining the space in an appropriate manner. This improves the efficiency of the DSS since it has to search a smaller space. In the presented case study for example no summer dike alternatives were formulated for certain cell boundaries because such flow-obstacles would increase flood levels upstream thus causing flood control problems.

The mathematical search method embedded into the DSS is the ESEMOPS technique. One of the major advantages of ESEMOPS is that it enables the Decision Making Group (DMG) to articulate its preference structure in a perceptible way. That is to say, aspiration levels are much easier to grasp for the members of the DMG than e.g. criteria weights applied by other techniques. Aspiration levels also support better the process of 'bargaining' among the different interest groups of the DMG, since strengthening and relaxing aspiration levels indicate directly the gains and losses a certain sub-group books during the bargaining process.

Another advantage of ESEMOPS is that it supports progressive articulation of preferences. It enables the DMG to get acquainted with the hydrological and ecological responses of the subjected cell-system against the different restoration approaches. Based on the revealed trade-offs and inter-relationships, the DMG is enabled to modify its preference structure and adjust it to reality.

ESEMOPS actually forms mathematical optimisation problems by aggregating the criteria functions and the related aspiration levels into so-called 'surrogate objective functions'. The solutions of these optimisation problems are then used to adjust the preference structure and to proceed the search towards the best compromise solution. The technique applied in this study for optimising of the surrogate objective functions was Genetic Algorithms (GA). The major advantage of GA over other single objective search techniques is that it only needs the coding and the objective function values of alternative solutions for directing the search. It does not need derivatives or other sort of auxiliary information. Because of the complexity of the subjected cell-system revitalisation problem, deriving such information would be very problematic if not impossible. Another advantage of GA is that instead of searching from a single point, it searches the entire decision space all at once, thus reducing the chance of being trapped at local optima, which is likely to be a danger in case of such complex problems like revitalisation of floodplain cell-systems.

There is however a significant shortcoming of GA, which had to be faced in this study. It comes from the extremely high number of alternative evaluations the GA has to execute during one search. This may cause infeasible long runtimes even on the most powerful computers.

Calculation of criteria function values of alternative cell-system solutions, have been carried out with the help of hydrodynamic and ecological modelling. The applied hydrodynamic model was a cell type floodplain model developed by the author. Its role was to simulate the water regime of the cell-system. Because of the stochastic nature of the water regime, long-term simulations were needed in order to get time series long enough for subsequent statistical and ecological analyses. Accordingly, a 21 years-long water level time series of the river was selected as boundary conditions for simulations. This period has been judged homogeneous enough. Because of long-term simulations however, extremely high calculation speed was needed in order to cope with the aforementioned runtime problem of GA. The applied hydrodynamic model has proven to be very fast indeed, thanks to its special features, which are the adaptive time step and model-configuration control and the use of pre-determined delivery functions for flow calculations in the floodplain 'fok'-channels. In addition, the model is able to handle situations which usually cause troubles in hydrodynamic modelling but which frequently occur in the fok-channels of floodplain cell-systems. These situations are the transitions between sub- and supercritical flows and the discontinuities in the water surface.

Concerning ecological modelling it can be concluded that physiological vegetation models are much more suitable for analysing the consequences of different cell-system designs than conditional vegetation models. It is because physiological models are based on scientifically established equations describing real physiological processes, while conditional models work with simple regression equations only. That is to say, when establishing regression relationship between hydrological conditions on one hand and vegetation on the other hand, several characteristics of the water regime are implicitly accounted for, thus making conditional models specific to the actual water regime. The proposed cell-system revitalisation approach is however based just on the concept of modifying the actual water regime. Concerning fauna models the available fish habitat modelling approaches had to be modified in order to accommodate them to the unsteady water levels of floodplain water bodies. Namely, available habitat models basically assume steady-state hydrological conditions; only limited and inadequate attention was paid to the effects of unsteadiness. Carp, pike, bream and other fish species inhabiting floodplain lakes are however very much dependent on the temporal pattern of the water regime.

The presented case study has also proven that the proposed revitalisation method is able to satisfy many different preference structures. That is to say, the proposed flow control measures may create a wide range of different hydrological conditions in the respective cell system. In addition, the costs of this revitalisation method have proven to be quite low with respect to the size of the influenced area, namely it is possible to achieve significant improvements in ecological conditions on waste areas by means of small scale, local earth- and construction works.

The proposed floodplain revitalisation method may also have culture historical importance. That is to say, restored and maintained cell-systems enable to restore the ancient 'fok' management, which was the basis for life on the floodplains of the Danube in the middle ages (see also Chapter 4). Especially renewal of 'fok'-system based fisheries seems to be very promising because the very high productivity and the efficient harvesting method provided by such cell-systems make fisheries economically feasible.

Nevertheless, cell-systems need continuous maintenance. First of all because of the wooden debris, which tend to accumulate in the fok-channels. These accumulations may significantly change the discharge capacities of the channels, thus they have to be removed in order to ensure the desired water regime in the cell-system.

10.2 Recommendations for further research

This study has been intended to be the pioneering step towards a new approach for floodplain revitalisation. Accordingly, it was necessary to deal with the problem as a whole. This however made the study quite interdisciplinary. Because of this interdisciplinarity, the study could only lay down the bases of the proposed DSS. It is the task of further research to improve and extend it.

As a first step, the performance of the present DSS has to be improved. One of the most important improvements would be to speed up further the GA search as it still takes a lot of time in spite of the several accelerator measures applied. The illustrative decision iteration presented in Chapter 9 for example took 5 days to be completed on a computer equipped with a Celeron 366 processor. Members of the DMG sitting around the negotiation table would not wait several hours to get the results of the principal and auxiliary problems related to their actual preference structure. Acceleration of the GA search should concentrate first of all on the hydrodynamic modelling because this is still the most time consuming module of the DSS. A promising way of acceleration might be to build in a sort of pattern recognition algorithm, which, after a learning period, recognises characteristic hydrographs patterns and thus enables to skip the time-consuming numerical integrations. Another promising way is to create short 'synthetic' water level time series at the boundary cells giving similar achievement figures as the long term (> 20 years) simulations.

Nevertheless, the runtime problems of the DSS are being gradually eliminated also by the rapidly increasing capacity and calculation speed of computers.

Beyond improving the performance it is also important to upgrade DSS by adding new modules that account for the effect of factors that have not been considered yet, but may be of significant influence. The most important of these factors are sedimentation and erosion. Especially sedimentation needs further investigation since such cell-systems work in fact as sediment traps. Erosion may also influence the system especially at the narrow fast flowing sections of fok-channel. Investigation of these morphological processes can be carried out with the help of sediment transport and other morphological models. These models would make possible to plan the measures, with which the negative effects of erosion and sedimentation can be counteracted. These measures would be for example armouring the fok-channels (with stone lining) and constructing sedimentation basins.

Upgrading the DSS should also concern the ecological modelling module of the DSS. First of all it has to be supplemented with physiological models that simulates the dynamism of all the important vegetation species and groups of species inhabiting the floodplain. For the simplest plant species, the phytoplankton, already existing models like the DELWAQ [Delft Hydraulics, 1995] would be a convenient choice. In case of terrestrial species however, model developments are still going on in several research centres. The most unexplored area of ecological modelling is the habitat modelling. The models presented in this study can only be considered as concepts based on information from the relevant literature. Improving the correctness and the accuracy of these models needs field observations as well as lab experiments in order to reveal the dependence of the different activities of fish on the water regime.

Finally the scope of the proposed DSS may also be extended towards the entire river-floodplain system. As a start one may choose a representation, decision variables, modelling and evaluation tools similar to the ones applied by Nieuwkamer [1995] (see Figure 3.3) and integrate them into the ESEMOPS-GA based DSS. The so-modified DSS would enable the DMG to search for compromise ecological revitalisation solutions for the river-channel system too.

APPENDIX I. DETAILS ABOUT THE HYDRODYNAMIC MODEL

I.1 Fifth order Runge-Kutta scheme with adaptive stepsize control

Runge-Kutta methods are applied for numerical integration of first order ordinary differential equations or equation systems:

$$\frac{dy_j}{dx} = f_j(x, y_1, y_2 .... y_m) \qquad j = 1,....m \tag{I.1}$$

A special kind of Runge-Kutta methods is the fifth order Runge-Kutta scheme with adaptive stepsize control [Press *et al.*, 1992]. One step of this method advances the solution from x_n to $x_{n+1} \equiv x_n + \Delta x$ where Δx is the actual stepsize. The step equation is as follows:

$$y_{n+1} = y_n + c_1 \cdot k_1 + c_2 \cdot k_2 + c_3 \cdot k_3 + c_4 \cdot k_4 + c_5 \cdot k_5 + c_6 \cdot k_6 + O(\Delta x^6) \tag{I.2}$$

Where:

$$k_1 = \Delta x \cdot f(x_n, y_n)$$
$$k_2 = \Delta x \cdot f(x_n + a_2 \cdot \Delta x, y_n + b_{21} \cdot k_1)$$
$$\cdot \quad \cdot$$
$$k_6 = \Delta x \cdot f(x_n + a_6 \cdot \Delta x, y_n + b_{61} \cdot k_1 + ... + b_{65} \cdot k_5)$$

$O(\Delta x^6)$: error term; a power series of order Δx^6 and higher.

An other combination of the $k_1 ... k_6$ terms gives a fourth order Runge-Kutta formula:

$$y^*_{n+1} = y_n + c^*_1 \cdot k_1 + c^*_2 \cdot k_2 + c^*_3 \cdot k_3 + c^*_4 \cdot k_4 + c^*_5 \cdot k_5 + c^*_6 \cdot k_6 + O(\Delta x^5) \tag{I.3}$$

The particular values of the various constants that Press *et al.* [1992] favoured are those found by Cash & Karp [1990] and given in Table I.1.

Table I.1 Parameters for the fifth order Runge-Kutta method with adaptive stepsize control [Cash & Karp, 1990]

i	a_i	$b_{i,j}$					c_i	c_i^*
1							$\frac{37}{378}$	$\frac{2825}{27648}$
2	$\frac{1}{5}$	$\frac{1}{5}$					0	0
3	$\frac{3}{10}$	$\frac{3}{40}$	$\frac{9}{40}$				$\frac{250}{621}$	$\frac{18575}{48384}$
4	$\frac{3}{5}$	$\frac{3}{10}$	$-\frac{9}{10}$	$\frac{6}{5}$			$\frac{125}{594}$	$\frac{13525}{55296}$
5	1	$-\frac{11}{54}$	$\frac{5}{2}$	$-\frac{70}{27}$	$\frac{35}{27}$		0	$\frac{277}{14336}$
6	$\frac{7}{8}$	$\frac{1631}{55296}$	$\frac{175}{512}$	$\frac{575}{13824}$	$\frac{44275}{110592}$	$\frac{253}{4096}$	$\frac{512}{1771}$	$\frac{1}{4}$
$j=$		1	2	3	4	5		

The difference between the fifth and the fourth order Runge-Kutta estimates of $y(x+\Delta x)$ gives a good estimate about the error of the step [Press *et al.*, 1992]:

$$\Phi \equiv y_{n+1} - y^*_{n+1} = \sum_{i=1}^{6} \left(c_i - c_i^*\right) \cdot k_i \tag{I.4}$$

In case of an equation system, the standard step error is obviously the maximum of errors obtained at the individual equations:

$$\Phi = \max_{j=1}^{m}\left(\phi_j\right) \tag{I.5}$$

According to equations I.2, I.3 and I.4, Φ is also equal to the differences of the error terms. Because the terms of order Δx^6 and higher are practically of the same magnitude, Φ scales as Δx^5. This means that if a step Δx_1 produces an error Φ_1 the step Δx_0 that would have given the error Φ_0 is readily estimated as follows [Press et. al., 1992]:

$$\Delta x_0 = \Delta x_1 \cdot \left|\frac{\Phi_0}{\Phi_1}\right|^{0.2} \tag{I.6}$$

Now if Φ_0 is the desired accuracy, then this equation is used in two ways:

1. If $\Phi_1 > \Phi_0$ then Δx_0 is the stepsize with which the present (failed) step should be retried.
2. If $\Phi_1 \leq \Phi_0$ then Δx_0 is the recommended increased stepsize for the next step.

This dynamic stepsize adjustment satisfies the desired accuracy on one hand, on the other hand it reduces the computational efforts by increasing the stepsize at the smooth sections of the function where even high stepsizes satisfy the desired accuracy.

How the Φ_0 desired accuracy should be specified in case of the FOK model?

Recall that the above Runge-Kutta scheme is applied for two types of calculations: integration of the cell continuity equations and flow profile calculation in the fok-channels. In both cases the accumulation of step errors may severely influence the accuracy. In the worst case, when all errors have the same sign, this final error could be quite high, especially in case of high number of steps. Thus, in order to keep the accumulated final error low, Φ_0 is scaled as Δx so that the desired accuracy per step is strengthened if the stepsize is reduced. Accordingly, Φ_0 is defined as follows:

$$\Phi_0 = \varepsilon \cdot \Delta x \tag{I.7}$$

Where ε is the dimensionless fractional accuracy. Because of the implicit scaling of Φ_0 with Δx, equation I.6 no longer holds in the above form. Namely, using equation I.6 may result that after a failed step the reduced stepsize is still too big, as the Φ_0 has also been reduced in the meantime according to equation I.7. This may result time-consuming repetitions of stepsize reduction. To avoid such situations Press *et al.* [1992] suggested to reduce the stepsize more after a failed step by increasing the exponent from 0.20 to 0.25. Thus, the actual equations applied for stepsize adjustments are as follows:

$$\Delta x_0 = \Psi \cdot \Delta x_1 \cdot \left|\frac{\Phi_0}{\Phi_1}\right|^{0.2} \qquad \text{if} \quad \Phi_0 \geq \Phi_1 \tag{I.8}$$

$$\Delta x_0 = \Psi \cdot \Delta x_1 \cdot \left|\frac{\Phi_0}{\Phi_1}\right|^{0.25} \qquad \text{if} \quad \Phi_0 < \Phi_1 \tag{I.9}$$

Where Ψ is a safety factor.

I.2 Calculation of the section factor and conveyance functions of the cross-sections

A pre-processor module of the FOKBUILD program calculates conveyance (K) and section factor (sf) values at each input cross section on discrete Δz elevations.

Calculation of K and sf requires the computation of width of water surface (T), wetted area (A) and wetted perimeter (P) in the sections. Given the width of the sections at discrete elevations, the T, A and P variables are interpolated as follows [Rátky, 1989] (see also Figure I.1):

$$T = T_0 + m \cdot (z - z_0) \tag{I.10}$$

$$A = A_0 + (z - z_0) \cdot \frac{T_0 + T}{2} \tag{I.11}$$

$$P = P_0 + (z - z_0) \cdot \sqrt{4 + m^2} \tag{I.12}$$

Where:

$m = \dfrac{T_1 - T_0}{z_1 - z_0}$: section enlargement factor (-)

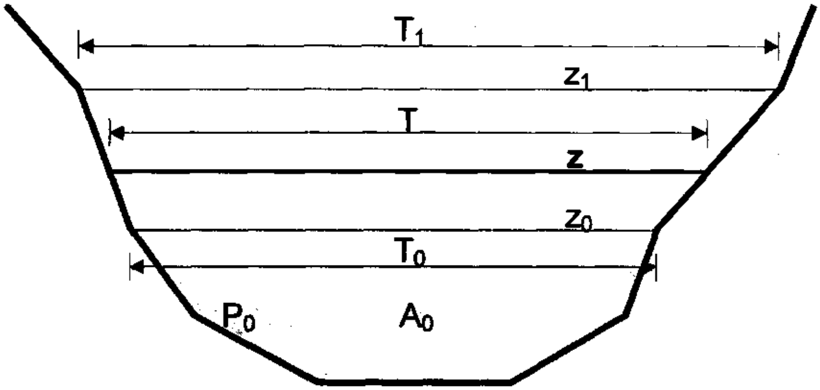

Figure I.1 Section geometrical parameters for calculating A and P at an arbitrary z elevation

As Figure I.2 indicates, certain channel sections may have sudden enlargements in their width. As soon as the water level reaches such enlargement zone, the flow is not uniform any more, meaning that the standard uniform flow calculation cannot be applied. It is possible for example that the uniform conveyance starts to decrease while the water level increases, due to the sudden increase in P. This would mean that at constant friction slope the same discharge can be conveyed on two different water levels, which is a contradiction.

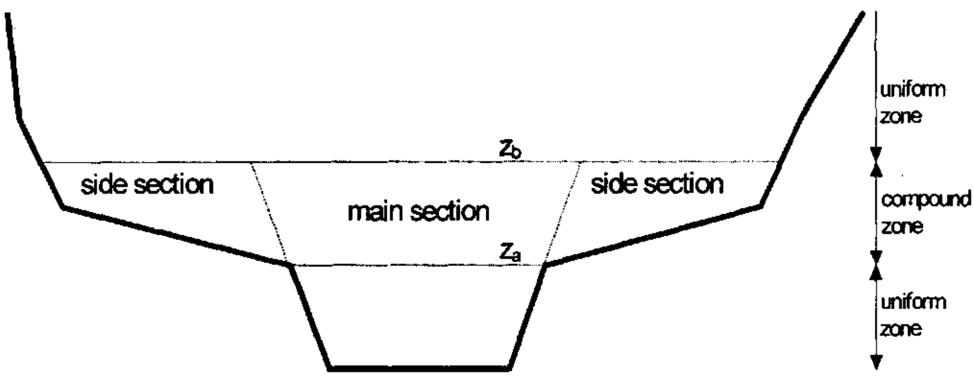

Figure I.2 Typical cross section with uniform and compound zones

In these situations the flow can be considered as compound, that is to say the flow section can be divided into main section and side section(s) (Figure I.2). The bulk of the water is discharged in the main section while only secondary flow develops in the side sections with mean velocity much less than in the main section. Considering these sections as separate channels, the Manning formula becomes applicable for each of them [Chow, 1959; Weiss, 1976]:

$$Q_{main} = K_{main} \cdot \sqrt{S_f}\ ;\ \ Q_{side1} = K_{side1} \cdot \sqrt{S_f}\ ;\ \ Q_{side2} = K_{side2} \cdot \sqrt{S_f}\ ;\ \ . \ . \ . \qquad (I.13)$$

Based on the hypothesis that the friction slope S_f is constant across the channel width, the total channel discharge is:

$$Q = \sum Q = \left(\sum K\right) \cdot \sqrt{S_f} = K_{comp} \cdot \sqrt{S_f} \tag{I.14}$$

where K_{comp} is the compound conveyance of the channel section.

To determine whether the section is uniform or compound at a certain water level, the following practical rule is applied: the section is uniform if $K_{comp} \le K_{uniform}$, while it is compound if $K_{comp} \ge K_{uniform}$.

As the water level on Figure I.2 rises above z_a the channel width suddenly increases which results a significant drop in the rate of increase of uniform conveyance, indicating that the flow section may have turned to compound. Now, if the compound conveyance, calculated from the conveyances of the indicated component channels, is higher than the uniform one, then it becomes the determining conveyance and the channel has to be considered as compound in this section. As the water level rises further, the flow distribution among the main and side sections starts to even up, so the flow section becomes uniform again. This transition takes place at level z_b above which the $K_{comp} < K_{uniform}$ relation holds.

Compound flow sections make the flow profile calculation complicated, because the flow is distributed among parallel beds. Calculation of flow profile in each of these beds is a difficult task because the total discharge should be distributed among the component channels on a way that the flow profile calculations result the same level in each of these channels at each step. This would require an iteration algorithm where at each step the discharge distribution is adjusted until the calculated water levels becomes practically equal.

Thus, for the sake of simplicity, the applied flow profile calculation algorithm considers always one single channel bed and only the variables in the governing equation are calculated on a different way in case of compound sections. This means that not only K_{comp} should be applied instead of $K_{uniform}$ but also the section factor should be calculated in another way since the $sf = \sqrt{\frac{A^3}{T}}$ equation corresponds only to uniform sections.[1]

Since it is not possible to derive a kind of compound section factor like in case of conveyance, the sf values in the compound zone are calculated by interpolation.

Spline interpolation technique is applied because it maintains the continuity of derivatives at the boundaries of the interpolation zone resulting a smooth sf function, which characterises better natural channels than for example a function with linearly interpolated intervals. The following cubic spline interpolation formula was applied:

$$sf = B \cdot sf_a + C \cdot sf_b + \left(B^3 - B\right) \cdot \alpha + \left(C^3 - C\right) \cdot \beta \tag{I.15}$$

Where:

sf_a : uniform section factor at z_a (see Figure I.2)

sf_b : uniform section factor at z_b

[1] It may happen again that due to the great increase of T, the calculated uniform sf starts to decrease with the increase in depth, which is not possible because that would mean that there exists a discharge, which could be conveyed on two critical levels.

$$B \equiv \frac{z_b - z}{z_b - z_a}$$

$$C \equiv \frac{z - z_a}{z_b - z_a}$$

The unknown parameters of α and β are derived from the condition of continuity of derivatives at z_b and z_a.

The derivative of the interpolation function takes the following forms at z_b and z_a :

$$sf_a' = \frac{sf_b - sf_a}{z_b - z_a} - \frac{2 \cdot \alpha}{z_b - z_a} - \frac{\beta}{z_b - z_a} \tag{I.16}$$

$$sf_b' = \frac{sf_b - sf_a}{z_b - z_a} + \frac{2 \cdot \beta}{z_b - z_a} + \frac{\alpha}{z_b - z_a} \tag{I.17}$$

By arranging these equations, α and β can be expressed as follows:

$$\alpha = (sf_b - sf_a) - \frac{1}{3} \cdot (z_b - z_a) \cdot (2 \cdot sf_a' + sf_b') \tag{I.18}$$

$$\beta = \frac{1}{3} \cdot (z_b - z_a) \cdot (sf_a' + 2 \cdot sf_b') - (sf_b - sf_a) \tag{I.19}$$

Where sf_a' and sf_b' are calculated from the derivative function of the uniform section factor function:

$$sf' = \frac{1.5 \cdot \sqrt{A} \cdot T^{1.5} - 0.5 \cdot T^{-0.5} \cdot m \cdot A^{1.5}}{T} \tag{I.20}$$

Note that the $A'(z)=T$ and $T'(z)=m$ relations are included into the above equation.

I.3 Outlet and entrance conditions

Flow profile calculation in the FOKBUILD program ends at the last section of the channel. Thus, it is still necessary to find the transition relations between the standing lake level and the level of the flowing channel at its upstream end, in order get the desired 'discharge - lake levels' relation.

At the outlet of the channel the kinetic energy of the flowing water is usually dissipated entirely in eddies and whirls [Chow, 1959]. Therefore if the level of the downstream lake is higher then the critical level in the first section (subcritical outflow), then the water level in the first section is considered equal to that of the lake.

At the entrance of the channel however, head loss occurs resulted by transformation of potential energy to kinetic energy. For subcritical transition, this head loss may be expressed in terms of velocity head at the entrance section [Chow, 1959]:

$$h_e = C_e \cdot \frac{v_1^2}{2 \cdot g}$$

C_e : head loss coefficient [-] (for a rounded entrance it is 1.25 [Chow, 1959])

v_1 : mean velocity at the entrance section of the channel [m/s].

Thus, after that the flow profile integration arrives to the last section (which is the entrance section), the value of h_e should be calculated and added to the integrated level in order to get the level of the upstream lake.

APPENDIX II. PREPARATION OF HYDROLOGICAL DATA BY STATISTICAL HOMOGENEITY ANALYSIS

As Figures 4.4, 4.5, 4.6 and 4.7 in Chapter 4 have already indicated, the full water level time series of the Danube at Baja is likely to be inhomogeneous. To get a more accurate picture, the homogeneity of time series of different annual statistical parameters (extracted from the daily water level time series) was tested with the help of the Technical Hydrology (TH) program package [Goda, 1998]. The testing techniques applied by TH are based on the *Smirnov-Kolmogorov method.*

The original Smirnov-Kolmogorov method tests the homogeneity by cutting the data series and checking whether the resulted sub-series are from the same statistical domain. Figure II.1 for example shows the results of the test executed on the mean water levels of the growing season. The cutting site is the turn of 1948/49. Based on this test the hypothesis that the whole time series is homogeneous has to be rejected since the *1-L(z)* value, which indicates the probability that the sub-series are from the same statistical domain, is below the 0.3 significance level [Zsuffa sr., 1994].

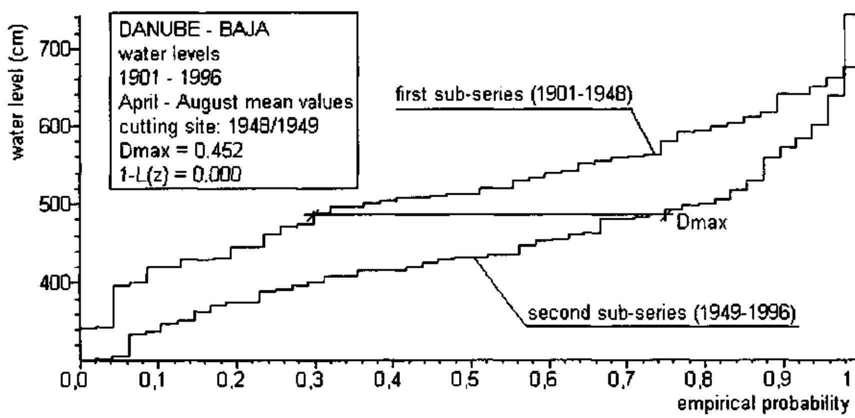

Figure II.1 Smirnov-Kolmogorov homogeneity test of mean water levels of the growing season

One can implement the above test with different cutting sites too. The only thing that has to be taken into account is that none of the sub-series may be shorter than 10 years. Thus, by stepping the cutting site along the time series, one can derive an array of *1-L(z)* values. The final result of this *stepping Smirnov-Kolmogorov test* [Goda, 1998] is the lowest of these values. In the above case this values is obviously 0.00.

As the homogeneity of the full time series had to be rejected, it was necessary to select out a sub-series, which is homogeneous and represents the actual hydrological conditions. This sub-series can than be applied as boundary conditions for hydrodynamic simulations within the Decision Support System (DSS). Selecting out such sub-series is implemented with the help of the *combined Smirnov-Kolmogorov test* [Goda, 1998]. This method gradually truncates the time series from below, and after each truncation it tests the homogeneity of the time series with the help of the stepping method.

Figure II.2 shows the results of the combined test executed on the growing season mean water levels. It can be concluded that only the last 20-35 years show some probability of homogeneity, even though these probabilities still tend to stay below the 0.3 significance level.

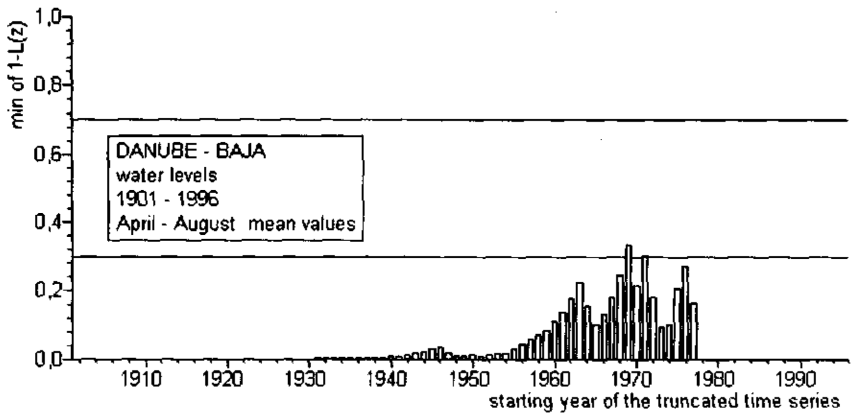

Figure II.2 Combined homogeneity test of mean water levels of the growing season

The combined test has also been executed on the maximum water levels of the growing season (Figure II.3). This shows better results although none of the minimum *1-L(z)* values of the truncated series reached the 0.7 significance level where the hypothesis of homogeneity are accepted according to the hydrological convention [Zsuffa sr., 1994].[1]

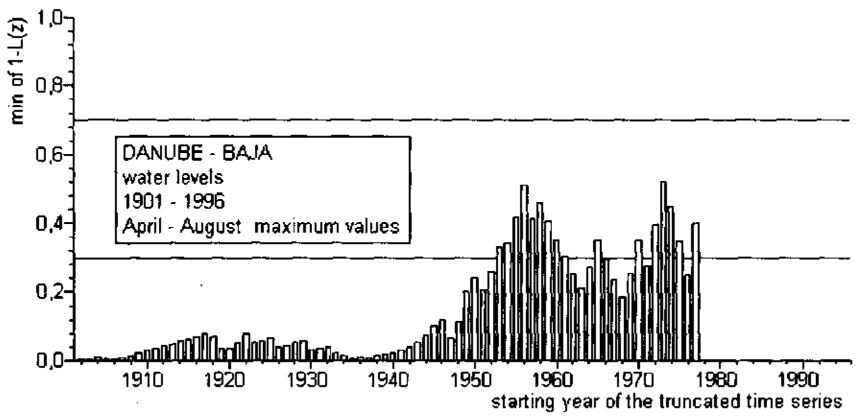

Figure II.3 Combined homogeneity test of maximum water levels of the growing season

[1] Within the 0.3 and 0.7 significance levels the homogeneity is considered to be uncertain [Zsuffa sr., 1994].

Beside maximum and mean water levels, the extremes of the temporal gradients of water levels are also very important parameters characterising the water regime. Thus their homogeneity is worth to be tested if one wants to get a clearer picture about the homogeneity of the subjected water level time series. The results of the combined test executed on the maximum daily water level decreases and increases during the growing season are presented on Figures II.4 and II.5. Accordingly, the probabilities of homogeneity of the maximum decreases and increases stay above the 0.3 significance level only after 1970 and 1975 respectively, while the 0.7 level (where the homogeneity can be accepted) is exceeded only in 1974 and 1977.

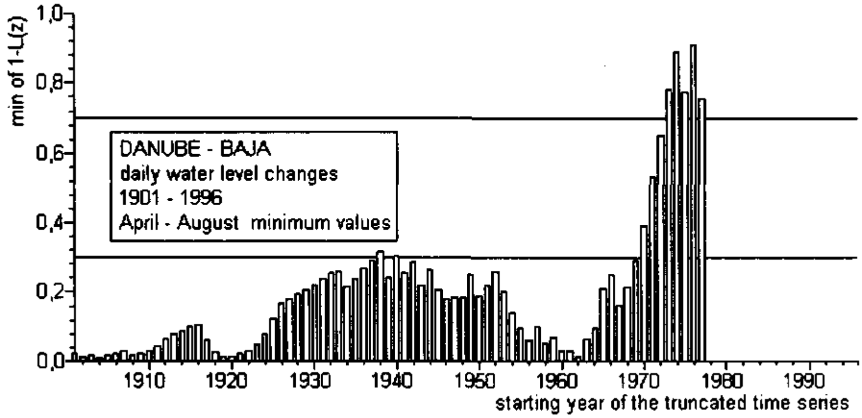

Figure II.4 Combined homogeneity test of maximum daily water level decreases of the growing season

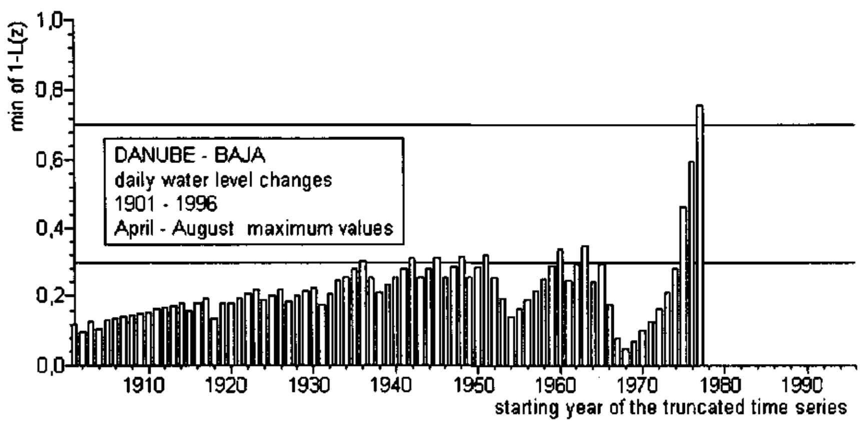

Figure II.5 Combined homogeneity test of maximum daily water level increases of the growing season

It can thus be concluded that the homogeneity of the water level time series *tends* to improve as its length decreases. This is clearly the result if river training and barrage construction. River training resulted bed degradation, which has led to tendentious decrease of water levels. Meander shortcuts, dike and barrage constructions have increased the speed of flood wave propagation, which resulted in increased rate of water level changes. The decreasing tendency in water levels is clearly indicated by Figure II.1 too, where the empirical distribution function from the first half of the Century is far above that of the second half.

Considering these facts, as well as the results of the homogeneity tests, it has been decided to single out daily water levels from the period 1976-96 as boundary conditions for hydrodynamic simulations within the DSS. On the one hand, this period is longer than 20 years, which is the shortest period of time that can be applied for hydrological (and ecological) statistical analysis according to the hydrological convention [Zsuffa sr., 1994]; on the other hand, large scale river training works had already been finished far before the start of this period, and most of the barrages in the Austrian and German reach of the Danube had already been put into operation, even though new ones have been constructed in the eighties and even in the nineties too.

The reason why only the growing season was analysed and not the entire year is that all hydro-ecological evaluation criteria applied in the DSS correspond to this period. Also the ice jamming that occurred in the past quite frequently would significantly distort the results of homogeneity analyses. For example if the entire year had been subjected to the analyses then it would have turned out that the extremes of the rates of water level change have been decreased during the last hundred years. This is due to the sudden formations and collapses of ice-jams, which resulted extremely quick water level increases and decreases in the past.

Longer and more homogeneous water level time series can be obtained by means of data generation. Hydrodynamic river runoff model based on the actual configuration of the Danube can be applied for this purpose. Input for this model would be historical and/or synthetic discharge time series from the basin of the river. Synthetic discharges would be generated by means of rainfall-runoff and/or Monte Carlo models. Such work however could not be fitted into the frame of this study.

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GLOSSARY

Ecology

action	the effect of *biotope* upon *biocenosis*
allelopathy	inhibitory and stimulatory biochemical interactions among water plants (including algae)
biocenosis	the totality of living communities (plants, animals, micro-organisms) which live in a *biotope*
biotope	spatial unit which offers similar conditions for living and which possesses sufficient resources for the survival of particular living communities
centrarchidae	family of sunfishes and basses within the order Perciformes
coaction	effect of an element of the *biocenosis* upon an other one
ecosystem	*biotope* + *biocenosis*
ecotone	transition zone between two *ecosystems*
ecotope	a specific vegetation community whose survival depends on the specific abiotic conditions of the hosting *biotope*; thus *ecotope* is a subset of the *biocenosis*; an *ecotope* is defined by its vegetation composition and measured by its area
epiphyte algae	algae growing on the leaves of water plants
ethology	behaviour of animals in their normal environment
heterotrophic	feeding from external sources
homeotypical coaction	mutual influence of individuals within the population
lentic	standing water
lotic	running water
periphyton	everything that can be found on substratum like stones, roots and water plants
phenology	recurring phenomena in faunal life, such as migration

phytophil fish	open substratum spawner, eggs adhere to submerged plants
phytolithophil fish	open substratum spawner, eggs adhere to submerged plants, but other substrata are utilised if suitable plants are absent
reaction	the effect of *biocenosis* upon *biotope*
rheophilic	preferring flowing water as habitat
stagnophilic	preferring standing water as habitat
stolon	a slender horizontal stem that grows along or beneath the surface of the soil and propagates by producing roots and shoots at the nodes or tip
stoma, stomata	a pore, present in large numbers in plant leaves, that controls the passage of gases in and out of a plant

Hydrology and Hydraulics

critical flow	flow conditions under which a certain discharge is conveyed in a certain channel section with the smallest possible specific energy
gradually varied flow	steady or unsteady flow where hydrostatic pressure distribution can be assumed as the streamlines are practically parallel
hydraulic drop	transition from *subcritical* to *supercritical* flow in a channel; the flow profile is continuous and the flow is critical
hydraulic jump	transition from *supercritical* to *subcritical* flow in a channel, which takes place in the form of a complex, swirling hydraulic phenomenon; the flow profile is discontinuous
hydrograph	a graph showing the temporal variation in the level of a body of water
normal depth	a depth in a certain section of the channel at a certain discharge; it equals to the steady-state, uniform flow depth that develops at the same discharge in a prismatic channel whose cross-section geometry and bed slope are the same as that of the section in question (normal depth is infinite in case of zero slope, while it is not defined for reverse bed slopes)
subcritical flow	the flow depth is higher and the flow velocity is smaller than that of the critical flow
supercritical flow	the flow depth is smaller and the flow velocity is higher than that of the critical flow

Operations research

aspiration levels	levels of *criteria* achievements the decision maker desires to exceed, stay below, stay within or stay outside
cardinal number	a number denoting quantity (or value) but not order on a scale
criteria space	a space determined by the value sets of the *criterion* functions in such a way that each dimension of the space stands for a particular criterion function
criterion	provides a mean for evaluating the level of the related objective; a measurable aspect of judgement by which alternative solutions of the given problem can be characterised
decision space	the domain space of the criteria functions; each point in the decision space stands for a particular solution of the given problem
ideal point	the point in the *criteria space* having the criterion-specific optimal scores; criterion-specific optimal scores are determined by optimising each criteria function without regard to the other criteria
ordinal number	a number denoting relative position on a scale

Statistics

exceeding probability	the probability that the random variable takes a value, which is higher than a certain number
non-exceeding probability	the probability that the random variable takes a value, which is lower than, or equal to a certain number
return time	long-term average time intervals between occurrences of a certain outcome of an experiment, provided that the experiment is executed on a regular basis and the subsequent executions are independent from each other (e.g. annual runoffs in a river channel)

LIST OF ABBREVIATIONS

AL	Aspiration Level
ATTZ	Aquatic / Terrestrial Transition Zone
BOD	Biological Oxygen Demand
CPT	Cutting Plane Technique
DEM	Digital Elevation Model
DMG	Decision Making Group
DO	Dissolved Oxygen
DSS	Decision Support System
EA	Evolutionary Algorithms
EGEM	Everglades Ecological Model
EGHM	Everglades Hydrological Model
EGVM	Everglades Vegetation Model
ESEMOPS	Evolutionary Sequential Multi-Objective Problem Solving (method)
GA	Genetic Algorithms
GIS	Geographical Information Systems
GMM	Gemenc Matrix Model
GF	Growing Season
HSI	Habitat Suitability Index
HUF	HUngarian Forint
IFIM	Instream Flow Incremental Methodology
maD	meter above Datum
MCDS	Multi-Criteria Decision Support
OVM	Ottawa Vegetation Model
PG	Planning Group
RMM	Rhine Matrix Model
SEMOPS	Sequential Multi-Objective Problem Solving (method)
SI	Suitability Index (of a habitat)
TH	Technical Hydrology (software)
WA	Weighted Average (method)
WUA	Weighted Usable Area

CURRICULUM VITAE

István János Zsuffa was born on 11 June 1966 in Budapest, Hungary. In 1991 he received his graduate degree as a civil engineer (with hydraulic engineering orientation) from the Faculty of Civil Engineering of the Technical University of Budapest, Hungary. In 1992 he joined the Department of Water Resources of the Wageningen Agricultural University, the Netherlands, where he started his activities by following courses and taking exams on computer science and operations research. In the meantime he also followed classes and took exams on numerical methods, mathematical modelling, river and channel systems and ecosystem analysis at the International Institute for Infrastructure Hydraulic and Environmental Engineering (IHE) in Delft, the Netherlands. In 1993, after completing the aforementioned study program, I.J. Zsuffa was officially admitted to the PhD programme of the Wageningen Agricultural University under the supervision of Prof. Dr. –Ing. J.J. Bogardi and Prof. Dr. Ir. J. Leentvaar. In 1998, after a five-years-long research period, he moved back to Hungary where he was given a job at the Eötvös József College, Baja, where he is still employed as a teacher of fluid mechanics and hydrology. While teaching, he has completed his PhD research and has written the hereby-presented dissertation.