MODELLING OF LONG-TERM FISH HABITAT CHANGES IN RESTORED SECONDARY FLOODPLAIN CHANNELS OF THE RIVER RHINE

FRANZ KERLE [a*], FRANK ZÖLLNER[a], MATTHIAS SCHNEIDER[b],
JÜRGEN BÖHMER[c], BERTHOLD KAPPUS[c] AND MARTIN J. BAPTIST[d,e]

[a] *Universität Stuttgart, Institute of Hydraulic Engineering, Prof. Dr. Ing.-habil Dr.-Ing. E.h. Jürgen Giesecke, Hydro Ecology Research Group Stuttgart, Pfaffenwaldring 61, D-70550 Stuttgart, Germany; phone +49 711 685 4774, E-mail: franz.kerle@iws.uni-stuttgart.de*

[b]*sje Schneider & Jorde Ecological Engineering GmbH, Viereichenweg 12, D-70569 Stuttgart, Germany*

[c] *Universität Hohenheim, Institut für Zoologie, Aquatische Ökologie, Garbenstraße 30, D-70593 Stuttgart,Germany*

[d] *Delft University of Technology, Faculty of Civil Engineering and Geosciences, Hydraulic and Offshore Engineering Section, P.O. Box 5048, 2600 GA Delft, Netherlands*

[e] *WL | Delft Hydraulics, P.O. Box 177, 2600 MH Delft, Netherlands*

ABSTRACT

In the Netherlands, large areas of the former floodplains of the river Rhine will probably be reconstructed the next decades to increase the discharge capacity and avoid uncontrolled flooding of the dykes. A major side effect of these measures is the chance to re-establish lost riverine fish habitats through the construction of shallow, slow flowing areas. However, it is expected that the habitat availability and quality in these newly created floodplain waters will change in time due to morphodynamic processes. According to this, three man-made secondary floodplain channels have been investigated in a computer modelling case study. The simulation was performed with a combination of the numerical model Delft3D and the fuzzy logic fish habitat module of CASIMIR. Seven fish species from different fish guilds have been investigated. The results show that primarily the rheophilous fish guild benefits from related kind of floodplain measures while the benefit for the limnophilous fish guild is only poor. During floods refuge habitats for some species are very scarce. The long-term morphodynamic alteration locally leads to significant shifts in habitat availability. Direction and amount of these shift differs and highly depends on the channel characteristics and the expected development of riparian and aquatic vegetation.

KEY WORDS: Rhine, river morphology, river restoration, floodplain channels, fish habitat, fuzzy logic, CASIMIR.

INTRODUCTION

The river Rhine is the blue artery of Western Europe. The spring brooks of the Rhine rise in the High Alps, the stream passes several regions and ends in the North Sea (see Figure 1). The river Rhine is 1,320 km long and its catchment area covers 185,000 km² shared by eight countries. Nowadays this great stream is Europe's most important waterway with the highest density of industry and power plants (nuclear, fossil, water) of all European rivers.

Naturally the Rhine was a wild untamed dynamic stream with braided and meandering sections. Depending on regional different geographical factors the floodplains of the Rhine have been up to several kilometres wide. Hydraulic engineering mainly river rectification, stabilization of riverbanks or construction of river dykes, has completely changed driving fluvial river and floodplain processes. The straightened riverbed started to deepen itself and floodplain waters were disconnected. The reduction of sand and gravel bars in the main stream as well as the loss of secondary channels, backwaters and oxbows caused a decrease of structural diversity and valuable Rhine-specific rheophilous and limnophilous fish habitats. According to Grift (2001) the fish community in the former meandering Dutch part of the Rhine has consequently changed into a less diverse, euryoecous community dominated nowadays by the four species Pikeperch *Stizostedion lucioperca*, Bream *Abramis brama*, White Bream *Abramis bjoerkna* and Roach *Rutilus rutilu*s.

Recent peak discharges and a potential increase of floods due to expected climate changes stressed the need for improved flood protection strategies. For different reasons raising the dykes is no longer acceptable. Therefore new concepts had to be developed during the last years. One of the favoured concepts is known under the popular keyword *Living Rivers,* which means restoration of secondary floodplain channels. *Living rivers* will increase discharge conveyance during extreme floods and enhance diversity of semi-terrestrial and riverine habitats. The last year's first secondary floodplain channels were created in the Netherlands and monitoring indicates that they provide in the present state valuable habitats for rheophilic macroinvertebrates and fish (Grift, 2001; Simons *et al.,* 2001).

For future river plans, in which large parts of the floodplains of the river Rhine will be excavated and rehabilitated in order to decrease flood risks and enhance natural biodiversity, it is necessary to get more insight into the natural long-term behavior of these man-made secondary channels to elaborate floodplain management concepts.

THE STUDY APPROACH

As a part of a European research project a complex model tool, consisting of a morphodynamic model, a vegetation succession model and a fish habitat model, was developed and applied to three man-made secondary side channels in the Netherlands. The objective of the modelling procedure was to get more insight into the ranges of time scales and complex interrelations in floodplain dynamics in order to elaborate a new floodplain management strategy called Cyclic Floodplain Rejuvenation - CFR (Duel *et al.,2001*). This paper in particular addresses the methodology and results of the fish habitat simulation used within this tool to describe the present availability and expected long-term changes due to the morphological succession.

THE STUDY AREA

In the Netherlands the Rhine (firstly) splits into two major branches – in Dutch called the Nederrijn and the Waal. Along the river Waal the study area, the so-called Gamerensche Waard floodplain (see Figure 1), is situated between river kilometer 935 and 938, near the Dutch city of Zaltbommel. Discharge of the river Waal varies between 800 m^3/s and 6,000 m^3/s. Average summer discharge of the Waal is 1,500 m^3/s. The main river has an average width of approx. 500 m and is canalized for inland navigation. River embankments are stabilized with stones and groynes and a winter dyke protects settled former floodplains.

For dyke improvement after the extreme flood in 1995, large amounts of clay and sand were excavated at the left floodplain resulting in a deep sand pit and three river channels with different characteristics (see Table 1). The new created area is now a nature reserve of 144 hectares where river dynamics are given full play, as long as this does not lead to an increased safety hazard for the winter dykes. The aim is that these channels create the right conditions for characteristic, river-bound flora and fauna as part of nature development.

THE COUPLED MODELLING APPROACH

Fish habitat changes in the Gameren floodplain were simulated on the basis of coupled numerical hydrodynamic, morphodynamic and scenario rule based vegetation succession modelling. The study area including the three floodplain channels and the main river Rhine was spatially represented by a curvilinear two-dimensional grid with an average cell size of approx. 10 m x 30 m. Water levels and cell-averaged flow velocities were computed using a two-dimensional application of the Delft3D model (a numerical hydrodynamic finite element model). Hydraulic calculation supplied input data for sediment transport calculations performed with the Delft3D transport module. Hydraulic and morphodynamic output from these models was then fed into a rule based succession model for floodplain vegetation. After every 5th year, a new river geometry with corresponding spatial distribution of roughness defined by vegetation type and succession stage was obtained. New hydraulic calculations for 6 representative discharges, which cover the full range of hydrological dynamics in the study area, supplied the spatio-temporal input-data for physically based fish habitat modelling with CASIMIR. The investigation covered a time period of 30 years, whereas habitat modelling was performed after every 5th year.

For a more detailed description of the morphodynamic and the vegetation modelling reference is made to Baptist (2001), Baptist *et al.*, (2002) and Van der Lee *et al.* (2001).

THE FISH HABITAT MODEL

Habitat modelling was performed with CASIMIR (Computer Aided Simulation Model for Instream Flow Regulations). CASIMIR is a toolbox for habitat simulation in rivers, which comprises modules of individual computing programs. Development started in the early nineties at the University of Stuttgart, Institute of Hydraulic Engineering by Jorde (1996). For this study three CASIMIR modules were combined: (i) the flow regime module to describe hydrological variations (ii) the GIS based river-analyzing system and (iii) the fuzzy logic based simulation module developed by Schneider (2001).

The multivariate calculation procedure based on fuzzy logical principles shows several advantages compared with ‘classic’ univariate or other multivariate procedures in habitat modelling (Schneider 2001, Schneider *et al.* 2001) because,

- by the fuzzy rule-based approach usually qualitative knowledge about fish habitat demands can be numerically processed,
- fuzzy logical calculations consider multivariate effects but no independence of the input parameters is required,
- new parameters can be included easily,
- the calculation steps can be easily understood (no black box effect) and interactions within the system can be explained.

For a detailed description and discussion of this rather new methodology in fish habitat modelling, reference is made to Schneider (2001). Basic component of the fuzzy-logical approach are membership functions called fuzzy sets (Bardossy & Duckstein, 1995), by which variables can be defined in a linguistic way, i.e. low, medium or high. According to the project requirements CASIMIR has been adapted to four abiotic variables: (i) water depth, (ii) flow velocity, (iii) type of substrate and (iv) aquatic vegetation cover. The selected four parameters are expressed in fuzzy sets as membership functions. Their ranges are defined with respect to the typology of a large lowland river. Substrate was expressed in the terms gravel, sand, silt. Figure 2 shows the used membership functions for water depth, flow velocity and aquatic vegetation cover.

Sets of fuzzy rules are used to define the habitat suitability of a certain combination of input parameters for a life stage of a fish species. The rules are formulated in following way:

IF *flow velocity* is *high* AND *water depth* is *high* AND *substratum* is *gravel* AND *vegetation cover* is *high* THEN *habitat suitability* is *medium*.

IF *flow velocity* is *medium* AND …

Habitat suitability is subdivided in four linguistic classes labeled low, medium, good and very good. Modelling is processed as follows: With crisp input numbers from the hydraulic model (water depth, flow velocity) the fuzzy model first calculates the degrees of membership of these parameters to the membership functions. In a next step the degree of fulfilment (DOF) of each fuzzy rule is analysed. Then, the fuzzy sets of the output variable (HSI = habitat suitability index) are weighted with these DOF’s and combined to a final fuzzy set. In a last step called defuzzification the final fuzzy set is transformed back into a standardized crisp number to describe the habitat suitability index (HSI) defined between 0 (unsuitable) and 1 (suitable).

Coloured habitat maps generated by the GIS based river-analyzing system within CASIMIR explain the spatial distribution of the calculated habitat suitability index HSI.

By the two indeces *Weighted Usable Area* (WUA) and *Hydraulic Habitat Suitability* (HHS) habitat suitability is integrated over the whole area under investigation.

$$\mathrm{WUA} = \sum_{i=1}^{n} \mathrm{HSI}_i \cdot \mathrm{A}_i \ \ [\mathrm{m}^2]$$

where

n	total number of grid cells	[-]
HSI	habitat suitability index of a single grid cell	[-]
A	area of the single grid cell	[m²]

The index HHS is computed by dividing WUA with the wetted area of the study site.

$$\mathrm{HHS} = \frac{\mathrm{WUA}}{\mathrm{Wetted\ Area}} \ \ [-]$$

For an area with best habitat qualities the HHS is theoretically up to 1.0. If a river section provides no suitable habitats at all HHS can in theory be 0.0.

FISH SPECIES, LIFE-STAGES AND FUZZY RULES

According to Glasbergen (2001) 42 fish species are actually present in the Dutch part of the river Rhine. For habitat modelling seven indicator species from different guilds of the endemic Rhine fish-fauna were investigated (see Figure 3). River Lamprey *Lampetra fluviatilis* was selected since it is recorded in the Red List of Endangered Fish Species and as a species, which uses different habitats during its life cycle. Bullhead *Cottus gobio*, Dace *Leuciscus leuciscus* and Gudgeon *Gobio gobio* were selected from the rheophilous fish guild. The first two species have specific needs for water quality as well as gaps between bottom substrates like stones or gravel for reproduction. The Gudgeon does not have this clear demand to a specific substrate. The Pike *Esox lucius*, which belongs to the euryoecous guild, has a strong dependency on aquatic or flooded vegetation especially when spawning. Thus Pike was selected as an indicator species for the ecological functionality of floodplains. Rudd *Scardinius erythrophthalmus* and Tench *Tinca tinca* represent the limnophilous fish guild. Both species have in rivers a strong dependency on backwaters, oxbows and on the occurrence of aquatic vegetation - typical features of a river floodplain ecosystem.

For the investigation the life cycle of each fish species was subdivided into following five life-stages:

- spawning adults/eggs
- fry (small and weak juvenile fish up to 3 cm body-length)
- juvenile (young-of-the-year, fish reach an age of one summer)
- subadult (young fish which survived its first winter)
- adult (fish that have attained sexual maturity)

According to the combinations of the abiotic variables fish biologists (Kappus *et al.*, 2001) generated multivariate fuzzy rules for above species according their habitat requirements during different life-stages (see following section). For sets of these fuzzy rules reference is made to Kerle *et al.* (2001).

MODEL APPLICATION AND BOUNDARY CONDITIONS

For all 7 fish species and their different life-stages habitat availability was calculated for the time steps 0, 5, 10, 15, 20, 25, 30 years. For each long-term time step 6 different discharges were simulated (1000, 1500, 2000, 3000, 4000, 5000 m^3/s). All simulations were based on a sandy substrate because monitoring showed that sand is the far dominant substrate in the Gamerensche Waard. Development of aquatic vegetation was not modeled yet. All habitat simulations were therefore based on a most probably and most realistic scenario, which assumes only low aquatic vegetation cover. To demonstrate the effect of vegetation development on the rate of fish habitat changes, a second scenario, which assumes the development of a very high vegetation cover, was calculated.

RESULTS

Model results showed that habitat availability in the present state is very different for the rheophilous and the limnophilous fish species in the three investigated channels. In the long-term view according to the characteristics of the channels increases and decreases of habitat qualities exist in parallel for the different species (see Figure 4 and Figure 5). Rheophilous fish benefit most from the three man-made channels.

Simulated present habitat quality

Results show that the lateral side channels provide good habitats for different life-stages of rheophilic fish. The simulated situation for spawning habitats of rheophilic fish is indifferent. Bullhead and Dace prefer gaps between bottom substrates like pebbles or gravel for reproduction. The calculated spawning habitat for the sandy Gameren floodplain is therefore only moderate for these two species. The Gudgeon finds much better habitat conditions for spawning. For the larvae of the River Lamprey large areas with good to moderate habitat qualities were calculated for all flow situations. More variations in simulated habitat quality would have to be expected, if better data with the spatial variation of substratum (silt, sand) were available. Results for the adult and subadult life-stages of the Pike show good habitat qualities. For the younger life-stages of the Pike and for spawning fish only poor habitat qualities have been calculated. Calculated habitat qualities for adult and subadult limnophilous fish is more or less moderate. The qualities for life-stage fry and spawning fish as well as for the juvenile life-stage of the Tench are very poor though small patches of moderate quality should still allow reproduction. Limnophilic species do not seasonally migrate among different habitats (Grift, 2001). Considering the whole life cycle of Tench and Rudd, which is normally, completed within one floodplain lake or oxbow, habitat quality of the three channels is very poor.

Long-term changes (30 years)

The long-term simulation showed that fish habitat availability spatially shift due to side-by-side erosion and sedimentation of the three channels. Increases and decreases of habitat quality exist in parallel for the different species. In average only a slightly shift within the 30 years period was calculated. Figure 4 shows the calculated habitat quality.

Large channel: According to the morphodynamic simulations (see Baptist *et al.* 2002), the eastern part of this channel deepens by erosion starting at the entrance from the main river. After 30 years of simulation the sand pit is filled up with sediment. The channel develops to a moderate or fast flowing river. Due to the simulated faster flow rheophilic fish slightly benefit whereas the habitats for limnophilic species further decreases.

East and West Channel: The situation for the other two channels is different. According to the simulation one of the smaller channels develops to an oxbow by silting, which has only flow during floods. Habitat quality for limnophiloc fish therefore increases over time. Results show that during floods slow flowing refuge habitats are very scarce (see Figure 5).

Comparison with calculated scenarios, which assume the development of rich vegetation cover, show much better habitat qualities for some species, especially for the early life-stages and for spawning habitats of Tench, Rudd and Pike.

DISCUSSION

The calculated fish habitat qualities are not validated yet with real world fish data. However, this is difficult, because presence and abundance of fish species in a water body depend not only depend on habitat availability but also on food supply, inter-specific competition, seasonal and day-night moving activities etc.

The results of the simulation highly depend on the generated fuzzy rules, which are static average values. They are based on experience attained during fish studies in potamal large rivers; mostly in the Neckar (Kappus *et al.,* 2001) and accompanied by expert knowledge from literature. This approach stipulates uncertainties. For other applications in the Netherlands we recommend to review and further develop these rules in cooperation with Dutch fish experts. The fuzzy rules therefore have to be seen as a starting point for further discussions and development. The set of rules yet neglect seasonal and hydrological variations. E.g. during floods, fish can have other habitat preferences (refuge) as during mean and low flow situations. However, the rules are used to simulate the full range of hydrological dynamic. Other very limiting habitat parameters like temperature and oxygen were not investigated. But if data is available the multivariate fuzzy approach offers best opportunities to incorporate these additional factors.

The habitat simulation is based on the results of the linked vegetation succession and hydromorphological modelling. Therefore it has to be considered that the results fully reflect uncertainties, which arise from the other models supporting the input data. Especially the long-term scenario has to be interpreted carefully with respect to these uncertainties. Only cover from aquatic vegetation was expected to be relevant. In 30 years development it can be expected that woody debris and overhanging riparian vegetation will play a more significant role. Important aspects like temporal connectivity or flood events and droughts during the spawning period etc. have not been investigated yet.

CONCLUSIONS

The study showed that many additional fish habitats for growing and reproduction of Rhine specific rheophilic fish species will sustainably be created by flood protection measures like secondary bypasses. Therefore restoring or creation of side arms is highly recommended and supported by the findings of this study.

A clear conclusion of the model simulations of the Gamerensche Waard is that rheophilous fish benefit most from the suggested kind of floodplain restoration while the benefits for limnophilous fish are only moderate. In parallel existing erosion and sedimentation processes locally lead to shifts in habitat availability for different species, silting-up creates oxbows that enhance scarce habitats for limnophilous species. Enough space along the rivers is the key to make these natural dynamic acceptable for river managers. For future river plans, in which large parts of the floodplains of the Rhine river will be excavated and restored, it is recommended to guarantee that refuge habitats during floods, scarce oxbows or oxbow lakes are included to increase habitat diversity even though they have no real function for flood protection.

The complex linked modelling approach developed within the framework of the CFR project is able to approximately estimate hydro-ecological developments over different time scales. Interactions of hydrological variations with hydraulics, sedimentation and erosion processes, vegetation succession and the quality and extension of fish habitats were simulated – a kick-off and a small step forwards to build an integrated hydro-ecological modelling tool.

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Table 1. Channel characteristics.

	East	West	Large
Length (km)	0.5	1.0	2.0
Design flow frequency (d/y)	100	265	365
Min. discharge for flow (m^3/s)	1511	821	--
Completion year	1996	1996	1999

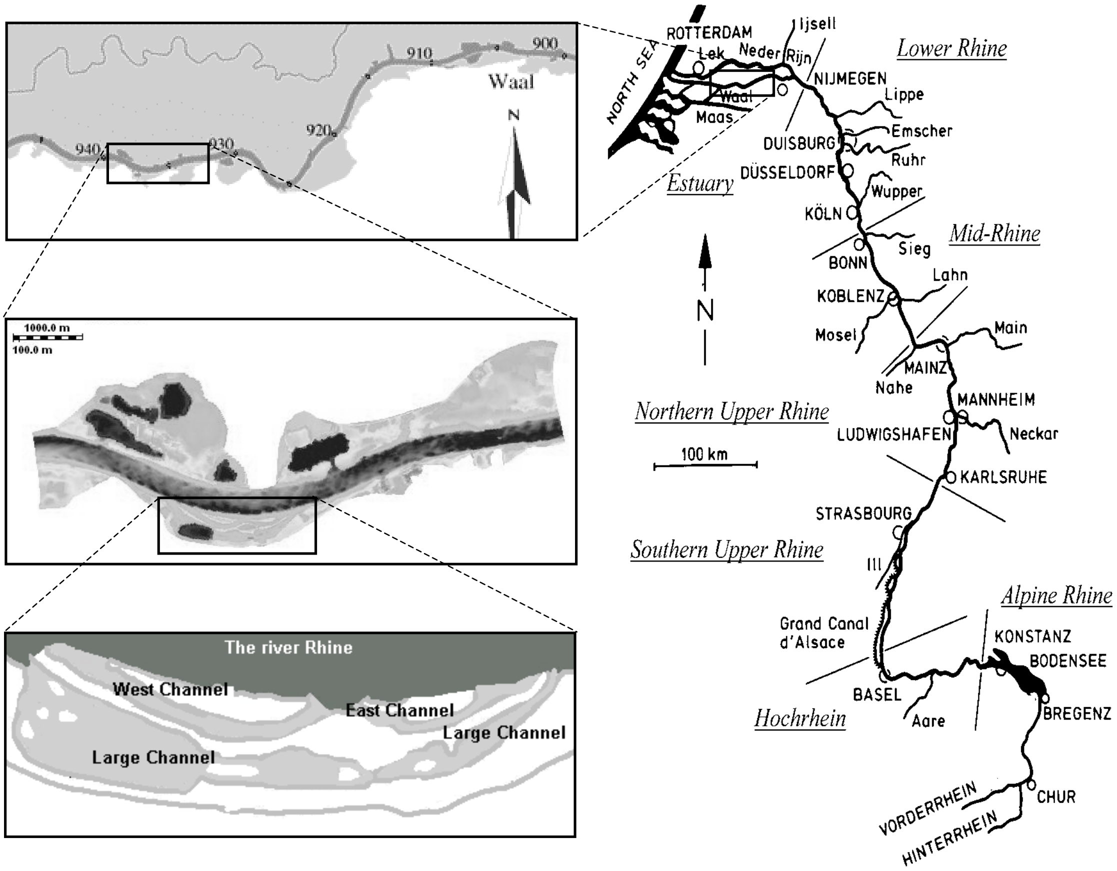


Figure 1.

The river Rhine, the location of the Gameren floodplain, and the three secondary floodplain channels.

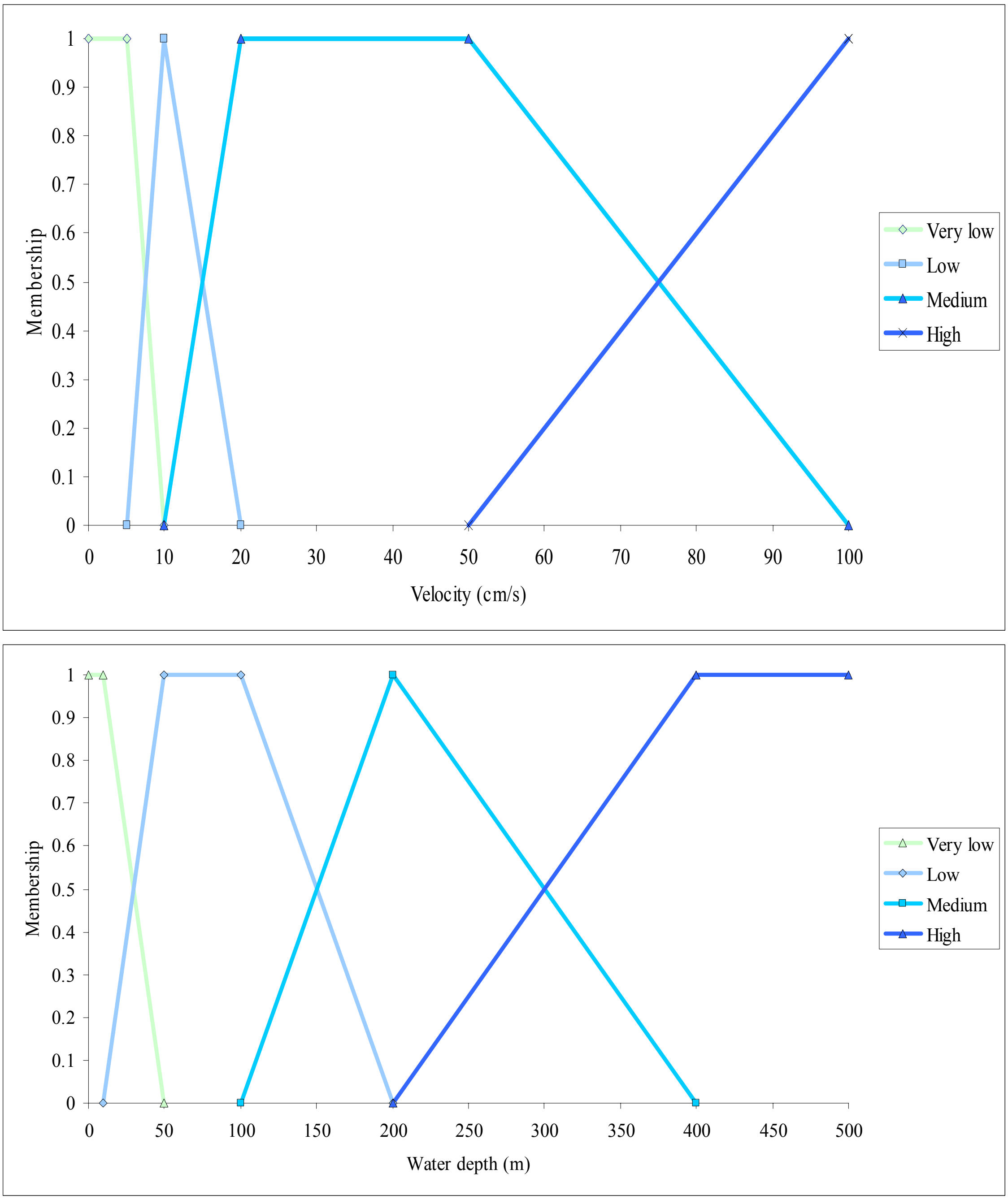


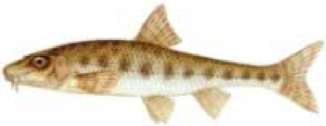
Figure 2.

Fuzzy sets for *flow velocity* and *water depth*.

Rheophilous: River Lamprey *Lampetra fluviatilis*

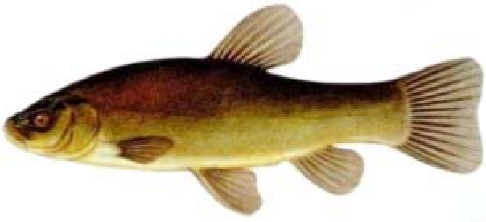
Rheophilous: Dace *Leuciscus leuciscus*

Rheophilous: Bullhead *Cottus gobio*

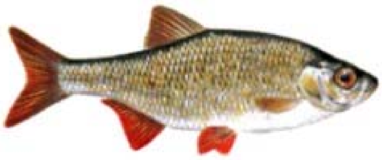


Rheophilous: Gudgeon *Gobio gobio*

Euryoecus: Pike *Esox lucius*



Limnophilous: Tench *Tinca tinca*



Limnophilous: Rudd *Scardinus erythrophtalmus*

Figure 3.

The selected fish species.

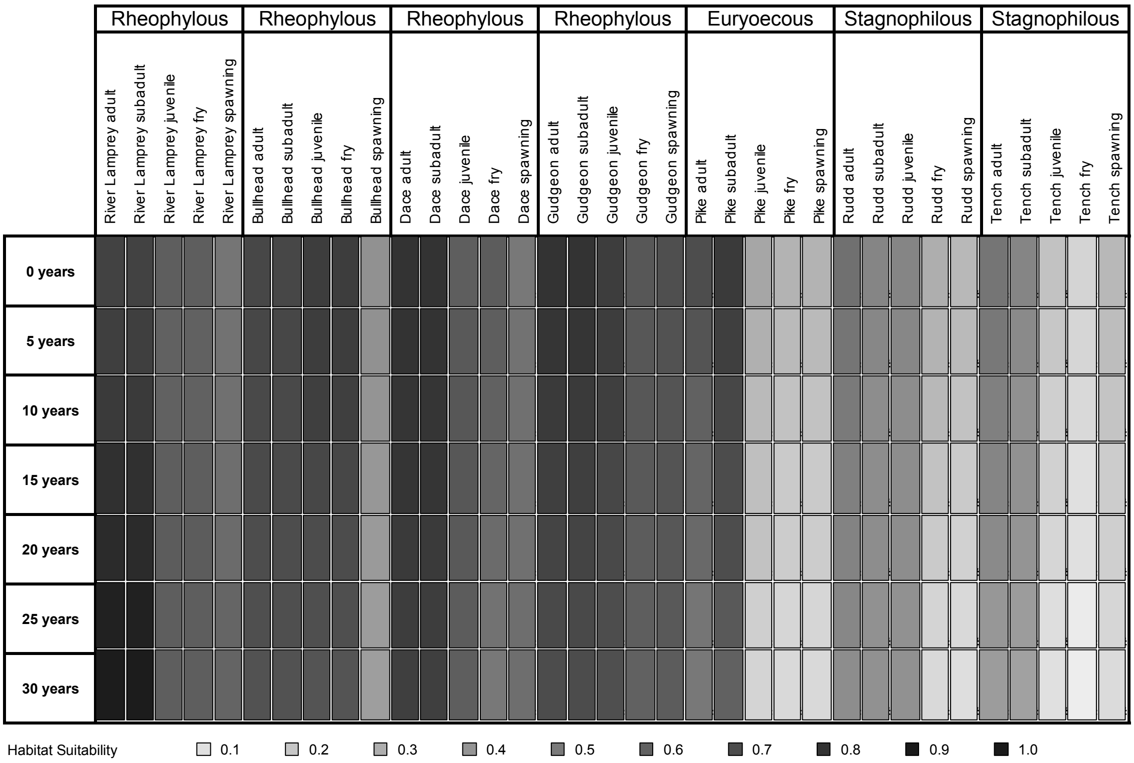


Figure 4.

HHS – time – species - life-stage matrix of the three channels of the Gameren floodplain for an average Rhine discharge of 1500 m³/s. Dark shading indicates very good habitat qualities, bright shading indicates only poor habitat quality.

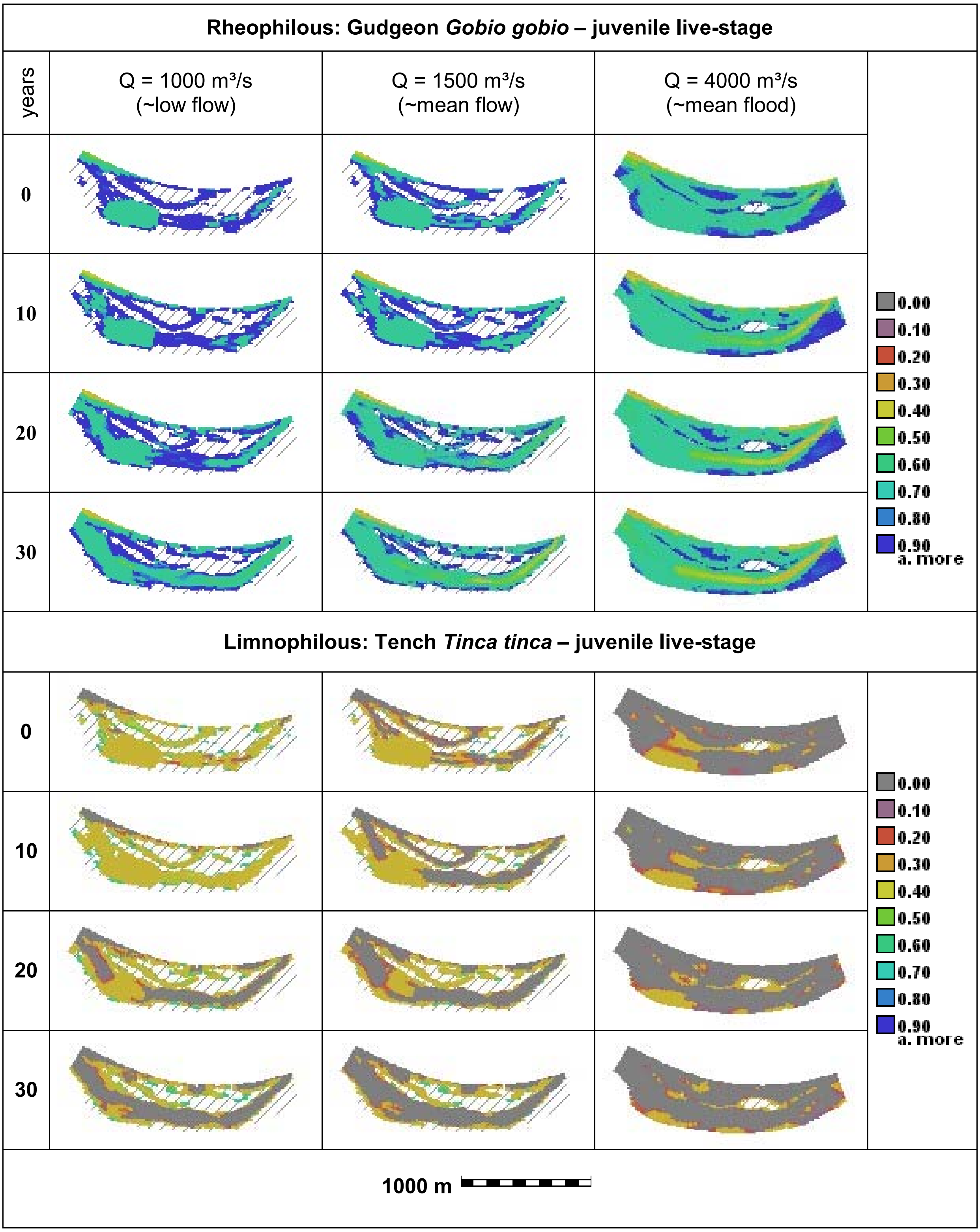


Figure 5.

Time-discharge-habitat maps for the juvenile life-stage of Gudgeon and Tench.