Impact study of physical habitat restoration on aquatic macroinvertebrates in rivers by means of neural networks and migration models: case study of the mayfly *Baetis* (Insecta – Ephemeroptera)

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ABSTRACT: This research illustrates the use of predictive models to assess the effect of physical habitat deterioration on the habitat suitability and migration behaviour of macroinvertebrates in the Zwalm river basin. The effect of impounded river sections and weirs was studied using Artificial Neural Networks for the habitat suitability modelling of *Baetis*. These models were extended with a quantitative description of the migration by means of a multi-layer approach in a geographical information system (GIS). Applications of the models show that not only the migration behaviour is affected by the weirs, but also that the change in the physical habitat can be (un)favourable for particular macroinvertebrates. This type of research can thus help to support decision making about integrated ecological issues related to flood control in river management.

1 INTRODUCTION

Ecosystem models can function as interesting tools to support decision-making in river restoration management. In particular models which are able to predict the habitat requirements of organisms are of considerable importance to guarantee that the planned actions have the desired effects on the aquatic ecosystem. To this end, Artificial Neural Network (ANN) models were applied for the prediction of the habitat suitability of the mayfly *Baetis*, an important indicator taxon in water quality assessment. In recent years, ANN models have increasingly been used to predict macroinvertebrate communities (Walley & Fontama 1998, Schleiter et al. 1999, Wagner et al. 2000, Obach et al. 2001, Dedecker et al. 2002, Brosse et al. 2003, Céréghino et al. 2003, Dedecker et al. 2004). In general, these ANN models are quite robust with a rather high predictive reliability. Because ANN models are considered being empirical (Guisan & Zimmermann 2000), they generally make the assumption that all points in space are freely and equally accessible. In this way, a direct relationship between presence and preference or habitat suitability can be assumed. However, when the accessibility is restricted, it is necessary to control for the effects of it before conclusions about preference and habitat suitability can be drawn because variations in spatial distribution of a species can no longer be attributed entirely to its preference (Matthiopoulos 2003). For this reason, the model performance had to be increased with regard to simulations of river restoration options. In particular, species migration kinetics (upstream and downstream migration) and migration barriers along the river (weirs, impounded river sections, etc) can deliver important additional information on the effectiveness of the restoration plans.

The aim of this study was to assess the effect of physical habitat deterioration on the habitat suitability and migration behaviour of *Baetis* in the Zwalm river basin. To this end, ANN models were applied for the habitat suitability modeling, and a migration model based on a multi-layer approach in a geographical information system (GIS) was developed.

2 MATERIAL AND METHODS

The Zwalm river basin which is part of the hydrographical basin of the Upper-Scheldt was selected as study area (Fig. 1). The basin has a total surface of 11,650 ha, the Zwalm river itself has a length of 22 km. Although, in the unpolluted headwaters a sensitive and vulnerable fauna can be found, several parts of the river are still polluted by untreated urban wastewater and by diffuse pollution originating from agricultural activities (Goethals & De Pauw 2001). Besides, numerous structural and morphological disturbances still exist (e.g. weirs for water quantity control) which can hinder free migration of fishes and macroinvertebrates.

Figure 1. Location of the Zwalm river basin in Flanders, Belgium. Position of the selected sampling sites.

To develop the ANN models, data were used from 60 sampling sites evenly distributed across the Zwalm river basin. Each site was examined on a yearly basis during the period 2000-2003. Each year, monitoring was carried out in summer to minimize seasonal variability. At each site, 26 environmental variables were recorded: temperature (°C), dissolved oxygen (mg l^{-1}), pH, conductivity (µS cm^{-1}), suspended solids (mg l^{-1}), nitrate (mg NO_3^- l^{-1}), phosphate (mg PO_4^{3-} l^{-1}), ammonium (mg NH_4^+ l^{-1}), COD (mg l^{-1} COD), total phosphorus (mg P l^{-1}) and total nitrogen (mg N l^{-1}), flow velocity (m s^{-1}), water level (cm), width (cm), shade (%), macrophytes (present/absent), the degree of meandering, hollow river banks, deep/shallow variation and artificial embankment structures, the fractions of boulders, pebbles, sand, loam and clay (%) and the distance to mouth (m). Macroinvertebrates were collected by means of a standard handnet (NBN 1984) and by *in situ* exposure of artificial substrates (De Pauw et al. 1994). The ANN model setup was based on the backpropagation algorithm (Rumelhart et al. 1986) and is described by Dedecker et al. (2004). The ANN models were implemented with the neural network extension of the software package MATLAB 6.1 for MS Windows™.

To allow for development of the migration model, a second monitoring campaign was set up because this type of model required a different and more intensive monitoring approach (Dedecker et al. 2004). To this end, the selected river parts (the brooks Verrebeek, Dorenbosbeek and the upstream part of the Zwalm river, Fig. 1) were split up into stretches of 50 m. To develop the migration model, a Geographical Information System (ArcView 8.3) was used.

3 RESULTS

3.1 *Development of a migration model for Baetis*

To know the possibility of dispersal of the mayfly *Baetis* from one site to another, a resistance model has been constructed. This dispersal model consists of three layers, each representing one resistance map. These three maps characterize the migration resistance of *Baetis* respectively upstream (R_{up}) and downstream (R_{down}) through the water column and through the air (R_{air}) (Fig. 2). The attribution of the resistance for the active upstream ($R_{up(active)}$) and downstream ($R_{down(active)}$) dispersal was based on Elliott (2003). This author concluded that the maximum distances *Baetis* was moving upstream and downstream were respectively 5.5 and 1.5m. Based on this and taking into account the factors affecting the active dispersal (e.g. presence of boulders) a resistance value was attributed to each 50 m stretch for the upstream and downstream migration. The calculation of the passive downstream dispersal (= drift) resistance ($R_{down(passive)}$) was based on the flow velocity (Equation 1) and the fact that the drift distance is divided by two if macrophytes are present (Elliott 2002):

$$D = 8.97 \times V + 0.11 \tag{1}$$

where D = drift distance downstream (m) and V = flow velocity (m s^{-1}).

Also the migration barriers such as weirs and impounded river sections along the river are considered to determine the total upstream and downstream migration resistance through the water column (Table 1).

Table 1. Attribution of the resistance for the upstream (R_{up}) and downstream (R_{down}) migration of *Baetis* through the water column based on the determining parameters. (n.a. = not applicable).

Determining parameters	$R_{up(active)}$	$R_{down(active)}$	$R_{down(passive)}$
• Boulders			
- Presence	2	7	n.a.
- Absence	4	13	n.a.
• Flow velocity	n.a.	n.a.	1-50
• Macrophytes			
- Present	n.a.	n.a.	1-50
- Absent	n.a.	n.a.	1-50
• Impounded river section	50	50	30
• Weir	200	100	100

Since *Baetis* as a nymph has an aerial phase, dispersal through the air means an important part of the migration dynamics of this organism. To this end, a resistance value was given to the surrounding environment according to the land use (urban, agricultural, industrial or forest region) and the presence/absence and width of buffer strips along the river (Table 2).

Table 2. Attribution of the resistance (R_{air}) for migration of *Baetis* through the air in relation to the surrounding environment.

Surrounding environment	R_{air}
• Water surface	1
• Buffer strip (if present)	1
• Land use	
- Urban region	20
- Industrial area	20
- Forest	1
- Meadow	1
- Arable land	1
- Nature reserve	1
• Impounded river section	10-20
• Weir	2

Then, an overlay of the resistance maps was made to obtain an overall resistance for the area. The total resistance to migrate in the downstream ($R_{tot(down)}$) and the upstream ($R_{tot(up)}$) direction is given by Equation 2 and 3 respectively. Because the migration through the water column (larva) and the air (nymph) can act at the same time, both resistances are connected in parallel.

$$\frac{1}{R_{tot(down)}} = \frac{1}{R_{down(active)}} + \frac{1}{R_{down(passive)}} + \frac{1}{R_{air}} \tag{2}$$

$$\frac{1}{R_{tot(up)}} = \frac{1}{R_{up}} + \frac{1}{R_{air}} \tag{3}$$

At the end, the 'Cost weighted distance' function in ArcView 8.3 was applied to find the least accumulative cost from each point in the river to the nearest source population of *Baetis* (Fig. 2). The functions that perform 'Cost weighted distance' mapping compute the accumulative cost of traveling from each cell to the nearest source, based on the cell's distance from each source and the cost to travel through it.

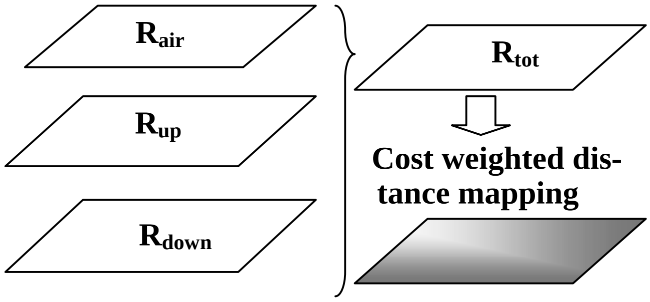

Figure 2. Resistance model for *Baetis* including three layers, each representing one migration resistance map respectively through the air (R_{air}) and upstream (R_{up}) and downstream (R_{down}) through the water column. An overlay results in a map representing the total migration resistance (R_{tot}). Applying the 'Cost weighted distance' function in a GIS environment, the least accumulative cost from each point in the river to the nearest source population can be found.

3.2 *Model simulation of practical river restoration scenarios*

Several migration barriers exist along the selected river parts (the brooks Verrebeek, Dorenbosbeek and the upstream part of the Zwalm river). The major bottlenecks are the impounded river sections and weir for water quantity control, as shown in Figure 3. As known, impounded river sections and weirs in particular obstruct the migration of fish and other water organisms, including macroinvertebrates. In addition, weirs create an almost stagnant water body immediately upstream of the weir resulting in conditions which are totally different compared to the rest of the Zwalm river (Belconsulting, 2003). Therefore, solving these problems has priority in the Zwalm river basin.

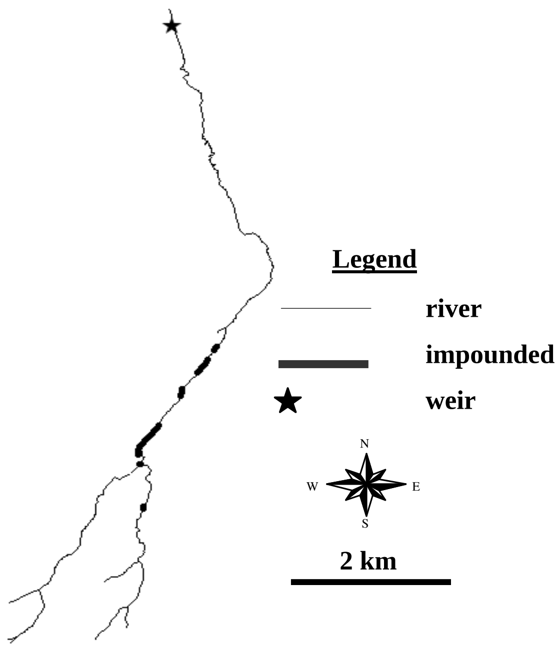

Figure 3. Situation of the major migration barriers along the selected part of the Zwalm river basin.

The simulation of river restoration scenarios implied two parts. First, ANN models are used to predict the habitat suitability of *Baetis*. As output for the ANN models, abundances were applied indicating how 'suitable' the habitat is. The higher the predicted abundance was after implementing the restoration options, the better the restored habitat would be suited for *Baetis*. However, additionally it was necessary to control for the effects of accessibility. To this end, the developed migration model for *Baetis* could be used. In this way, decision makers could have an idea if a selected restoration option would have the desired effect.

4 DISCUSSION AND CONCLUSIONS

In simulations of river restoration scenarios, the impact on the different structural components of the river have to be taken into account. When removing a weir for example, in the upstream section of the removed weir, flow velocity will increase while width and depth will decrease. Also the quality of the channel morphology will evolve positively. In contrast to species which have an aerial phase, such as *Baetis*, in-stream migration barriers can completely block the migration of organisms which have a completely aquatic life cycle. Dedecker et al. (2004) for example developed a migration model for the Crustacean *Gammarus pulex*, which does not have an aerial phase and for which flow velocity was the driving force for upstream and downstream migration. The authors demonstrated that after weir removal the restored river section could be recolonized within about 2 months.

In the future, migration models for other aquatic macroinvertebrates will be developed. Indicator species for good water quality such as the EPT taxa (e.g. Limnephilidae, *Heptagenia*, *Ephemera*) will receive particular attention. To this end, the factors affecting the upstream and downstream dispersal have to be assessed in advance. Also, the scale of the developed models will be extended to the whole Zwalm river basin.

To conclude, it can be stated that the combination of both a migration model for *Baetis* and the ANN models to predict its habitat suitability allow for a more rational selection among different restoration scenarios. The extension of these migration models to other taxa including nearly extinct as well as invasive exotic species will hopefully also prove to be of major importance in river management.

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