A transdisciplinary approach for modelling macroinvertebrate habitats in lowland streams

JENS KIESEL[1], DANIEL HERING[2], BRITTA SCHMALZ[1] & NICOLA FOHRER[1]

[1] *Department of Hydrology and Water Resources Management, Ecology Centre, Christian-Albrechts-University Kiel, Olshausenstr. 75, 24118 Kiel, Germany*
jkiesel@hydrology.uni-kiel.de

[2] *Department of Applied Zoology/Hydrobiology, Institute of Biology, University Duisburg-Essen, Universitätsstr. 5, 45141 Essen, Germany*

Abstract Manifold anthropogenic influences are the main cause of river habitat degradation and extensive regeneration needs to be conducted to achieve the aims of the Water Framework Directive in Europe. As the outcome of river and stream rehabilitation measures is sometimes difficult to foresee, a GIS-based approach consisting of an eco-hydrologic, a hydraulic and a GIS mapping submodel is suggested for creating an integrated catchment and an in-stream modelling system to dynamically depict the influence of abiotic changes on the habitat quality. The Driver–Pressure–State–Impact–(Response) concept is utilised to depict the complex cause–effect chain of hydromorphological changes on macroinvertebrate habitats in lowland streams. A first application of the three submodels has been conducted in the North German Kielstau catchment and first results of modelling and mapping the impact on selected habitat parameters are displayed. Further work needs to be done in linking the submodels and in assessing the impact of the altered state on the macroinvertebrate fauna by parameter functions derived from a knowledge-based database and sampling schemes.
Key words DPSI; hydrological model; hydraulic model; GIS; parameter functions; hydromorphology; macroinvertebrate; lowland

INTRODUCTION

Dominant characteristics of flowing waters are the discharge regime, the currents and the interrelated sediment dynamics. Together with the properties of the ecoregion (Omernik, 2004) in which the catchment is located, and the anthropogenic influence, these parameters mainly define hydromorphology and stream biota (Frissell *et al.*, 1986; Lorenz *et al.*, 2004). Discharge regime, water quality and fine sediment input into the river are factors acting on the catchment scale. A variety of (eco-)hydrological models exist that are capable of depicting these processes (Abbott & Refsgaard, 1996; Singh & Woolhiser, 2002; Schmalz *et al.*, 2008). Current patterns and substrate dynamics in the stream are affected by catchment scale processes, but are also highly dependent on cross-sectional river features on the micro-scale. Nowadays these processes can be successfully depicted with hydraulic computer models (Zanke, 2002; Tate, 2006). This intertwined influence of catchment and stream properties on the aquatic habitat stresses the necessity for an integrated approach where a joint view on catchment and stream processes is indispensable.

Throughout history, cultural development induced continuous changes in attitude towards the environment. This had a decisive influence on how river management is carried out and is perceived in our society (Gregory, 2006). In the late 1980s for example, awareness was focused mainly on water quality while currently the river morphology is a major concern (Umweltbundesamt, 2007). The human influence on catchments and rivers is manifold (Surian & Rinaldi, 2002; James & Marcus, 2006) and can be well described by the Driver–Pressure–State–Impact–(Response) (DPSI(R))-concept (EEA, 1999). Applying the DPSI(R) conceptual model on flowing waters, the following cause–effect chain can be derived: the general drivers behind river degradation were, and still are, an increasing industrial and agricultural production caused by population and economic growth. The drivers induce numerous hydrological, water quality and hydromorphological pressures affecting physical conditions of the rivers. The resulting state defines the impact on the aquatic habitat. The response is an external feedback parameter from the society and only occurs if impacts lead to political responses (Kristensen, 2004) and it is thus not possible to consider it for a habitat modelling system. In Europe, a major political response to

water quality and habitat degradation resulted in the Water Framework Directive (WFD; EC, 2000) making the current approach on river management operational: the rehabilitation of aquatic habitats in order to restore good ecological status by 2015 (EC, 2000). As anthropogenic influence, which has driven the degradation of aquatic habitats, still puts a number of pressures on water bodies, failing of achieving the aims of the WFD within the considered time frame seems inevitable (Moss, 2008). It is thus necessary to optimize rehabilitation measures. Therefore, human constraints have to be discussed together with the ecological demands and aims in order to improve river ecological status. Both degradation and restoration of rivers cause a complex impact chain with positive and negative feedbacks (Wang *et al*., 2008). The overall impact can not always be directly foreseen (Reichert *et al*., 2007) as, for example, changing the drivers can reduce one pressure but increase another pressure, therefore unintentionally causing a degradation of the state (Nedeau *et al*., 2003) and thus negatively impacting habitat quality.

The following points are hence important for successfully modelling aquatic habitats and biota based on the DPSI(R) concept: (1) an integrated approach is needed for considering stream and catchment processes so that it is possible to depict the major drivers with the model input data; (2) the main pressures on the system need to be defined and be represented in the model algorithms; (3) based on the multiple pressures, it then has to be possible to dynamically assess the changes of the state of habitat parameters with the model output; (4) in the final step, the impact of the state on the aquatic habitat and biota needs to be evaluated, which closes the complex cause effect chain from the drivers to the impact.

The WFD generally defines fish, macroinvertebrates, macrophytes and phytoplankton as target organisms for improving the aquatic habitat. This study is restricted to macroinvertebrates, as they are considered the most appropriate organism group due to the generally good response to a multitude of stressors (Rawer-Jost *et al*., 2004; Sandin & Hering, 2004), and beyond that, lowland streams have a relatively species-poor fish and macrophyte community, which narrows the scope even more on macroinvertebrate species (Hering *et al*., 2006).

The motivation for this work is the lack of an integrated modelling system that is capable of optimizing catchment and in-stream rehabilitation measures in regard to their influence on the aquatic habitat. The aim of this paper is the description of a methodology to model macroinvertebrate habitats in lowland streams from driver through impact, based on the DPSI(R)-concept using a hydrological and a hydraulic model, GIS mapping techniques and the development of parameter functions for selected species.

MODEL DESCRIPTION

In order to model a dynamic DPSI-system from driver through impact it is important that the drivers are adequately accounted for by the model input data. Table 1 shows the representation of the drivers though the corresponding data and the submodels used.

The input data are necessary for applying the following submodels in the ArcGIS (ESRI, 1997) environment: an integrated *hydrologic* and *hydraulic model* and *GIS mapping* techniques. The 2005-version of the Soil and Water Assessment Tool (SWAT; Arnold *et al*., 1998) is used as the eco-hydrologic model. The physically-based model can simulate the water balance, nutrients and pesticides, erosion, plant growth cycles, management practices and water bodies on a daily time step for continuous simulations over long time periods (Neitsch *et al*., 2005). The SWAT model is applied on the catchment scale and is used to simulate the hydrological cycle and to assess the sediment input from fields and artificial drainages. As displayed in Table 1, the model requires spatially distributed data on GIS maps, climate data and physical information for a relational database. For calibration and validation, daily measured discharge, suspended sediment and water quality data is needed.

The ADaptive Hydraulics modelling system (ADH; Berger & Tate, 2007) is used as the hydraulic model. Model features are the automatic adaption of the numerical mesh to improve model accuracy and the rapid convergence of flows to steady state solutions. ADH's 2-D

Table 1 The drivers of the system, data to depict the drivers and corresponding submodel.

Driver	Data	Submodel
Agriculture	Climate data	Eco-hydrologic model SWAT
	Land use map	
	Soil map	
	Drainage map	
	Topography	
	Management information	
	Physical vegetation and soil parameters	
Urbanisation	Land use map	Eco-hydrologic model SWAT
	Soil sealing ratio	
	Point discharge data	
	Riverbed and bank material	Hydraulic model ADH GIS mapping
Flood control	Channel topography	Hydraulic model ADH
	Hydraulic structures	
	River course	
	Flow obstructions (stones, debris)	Hydraulic model ADH GIS mapping
	In-stream vegetation	Hydraulic model ADH GIS mapping

shallow water equations and the sediment transport module are applied for stream reaches up to 1 km length for regions of particular interest, e.g. rehabilitation measures. In order to solve the hydrodynamic equations, the model requires flow boundary conditions, surface roughness values and topographic data to construct a numerical mesh with triangular elements. The element size is chosen to be in the range of $< 1 \text{ m}^2$ within the stream to be capable of depicting boulders, dead wood and other flow obstructions, and $> 1 \text{ m}^2$ in the flood plains. As Light Detection and Radar (LiDAR), which is not penetrating the water surface, is used to depict the flood plain topography and the river course, the stream bathymetry needs to be refined with additional topographic data. For modelling sediment transport and substrate stability, the model requires information on substrate grain size and distribution.

GIS mapping techniques are used to refine the available structural river data that have been recorded on digital maps within the scope of the WFD status report (DAV-WBV/LAND SH, 2006). The river section of interest therefore has to be visited in order to capture substrate and small scale morphological features on digital GIS sketches.

METHODOLOGY

Figure 1 schematically explains the structure of the proposed modelling system which is being developed for lowland rivers. The *drivers* of the system are *agriculture*, *urbanisation* and *flood control*. Although *flood control* is necessary and somewhat caused by the needs of productive farming and to maintain the standard of living, it is listed here as an individual driver due to the unique pressures it causes. The three drivers need to be implemented in the modelling system by the input data (Table 1).

The *pressures* on the habitat are grouped according to the submodel which has to be capable of depicting the relevant processes. Important pressures on the macroinvertebrate habitat are: *hydrologic stress* (Li *et al*., 2008) defined as events exceeding a certain threshold in discharge and duration, *fine sediment intake* (Berry *et al*., 2003), *hydraulic stress* (Van Broekhoven *et al*., 2006), *profile alteration* and *straightening* (Horsák *et al*., 2008), *substrate stability* (Lorenz *et al*., 2004),

substrate degradation (Hering *et al*., 2004), *river cleaning* (Aldridge, 2000) and *bank and bed fixation* (Horsák *et al*., 2008). It is important to note that there has to be a connection between the submodels, emphasised by the wide black arrows in Fig. 1: the output hydrograph and sediment load graph of the hydrological model are used as input for the hydraulic model, thus linking catchment to in-stream processes. This is of particular importance for the sediment, as aquatic habitats are affected differently by the fine sediment input from fields and agricultural drains with high carbon content and the desired erosion of river banks which creates new flow patterns and increases river dynamics. The GIS mapping submodel needs to be connected with the hydraulic model as *substrate degradation, river cleaning* and *bank and bed fixation* influence the flow characteristics.

   The *state* is the actual condition of the habitat parameters and represented by the output from the submodels. The output time series of the hydrological model is analysed and the *duration of extreme events*, like minimum and maximum discharge periods, are recorded. The hydraulic habitat parameters *velocity*, *water depth* and information about the substrate *silt and clay*, *sand* and
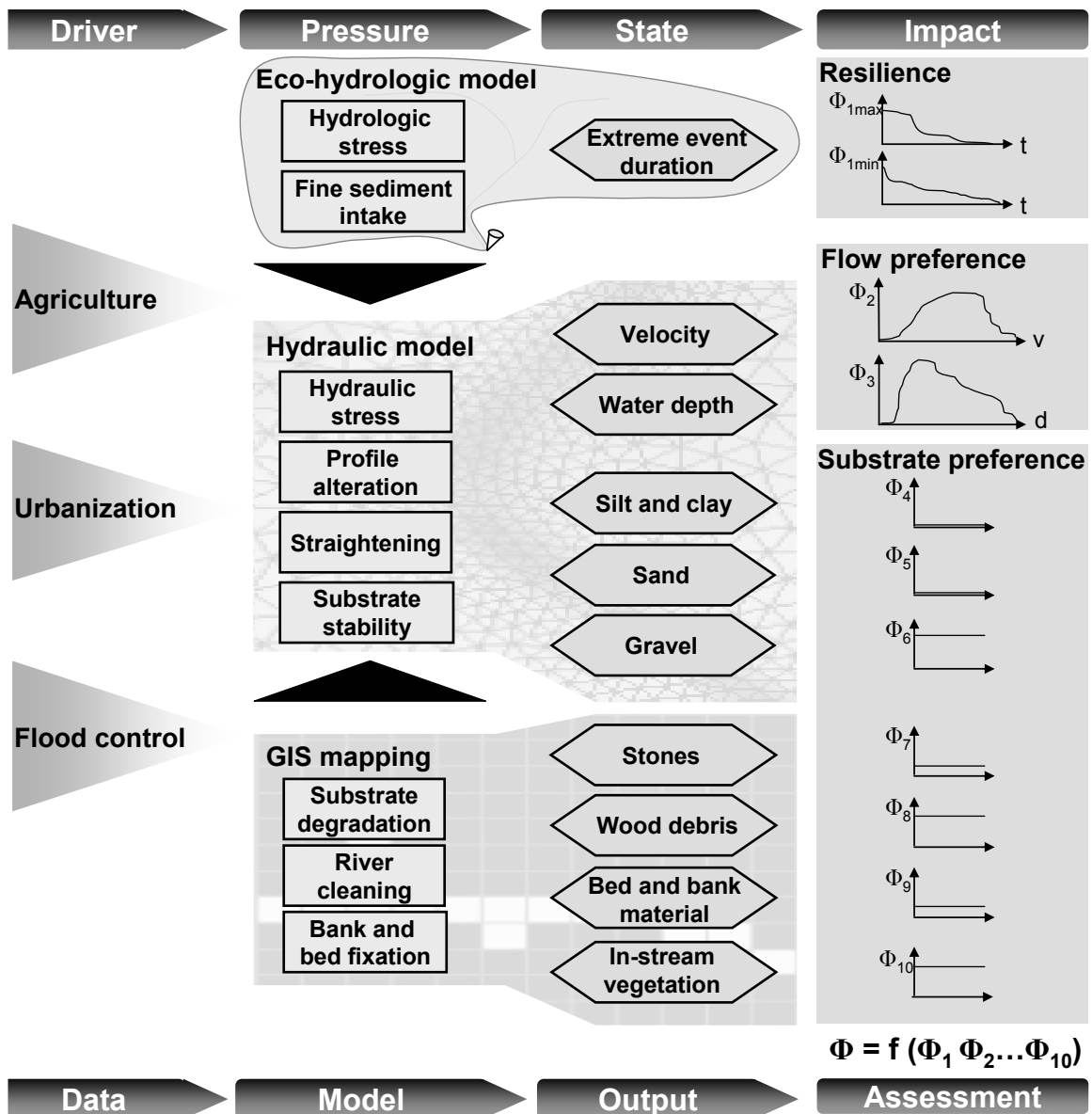

Fig. 1 Implementing the DPSI concept in the habitat modelling system.

gravel calculated by the hydraulic model are recorded on maps. These maps are dynamic over time, meaning that depending on the hydrological and hydraulic regime the parameters change over time, resulting in one map for one time step. Changes of catchment properties and stream structure are thus causing an alteration in the hydraulic habitat parameters. Depending on the time period of interest and the type of the rehabilitation project, the output time step can be daily up to yearly. The state of *stones, wood debris, bed and bank material* and *in-stream vegetation* is directly derived from the GIS maps, thus allowing an easy implementation of potential in-stream rehabilitation scenarios.

The term *impact* describes the consequences of the altered state, in particular changes in substrate and flow properties on the macroinvertebrate fauna. In order to depict the current state of the macroinvertebrate fauna with the modelling system, parameter functions have to be derived (Van Broekhoven *et al.*, 2006; Li *et al.*, 2008) for species regularly occurring in the stream. Two data sets of macroinvertebrate samples are available (Brinkmann, 2002; LANU, 2006) listing several species occurring in the study stream. *Parameter functions* ($\Phi_1 - \Phi_{10}$) between resilience to extreme discharge events, current patterns, substrate composition and species abundance are derived from a knowledge based database (Euro-Limpacs, 2009) and from data collected in comparable lowland streams (Kramm, 2002; Wenikajtys, 2004). The parameter functions define the suitability for certain substrates and current velocity classes for each species. The functions will be weighed and interconnected by a decision tree diagram for each species. Each decision tree is then implemented in the GIS and applied on each time step map. The result of each decision tree is the *habitat suitability* (Φ), which leads to a dynamic habitat description for each species.

A validation of the knowledge-based parameter functions and the overall model results is necessary. Based on substrate and flow specific macroinvertebrate samples, the model performance will be evaluated by assessing how well the model is capable of reproducing the status quo of the aquatic habitat.

STUDY AREA AND DATA

The modelling system will be tested in the 50 km^2 Kielstau catchment. The catchment is located in Northern Germany in the state of Schleswig-Holstein as part of a lowland area (Fig. 2(a)). The mean annual precipitation and temperature are 893 mm and 8.3°C, respectively (DWD, 2007). Land use is dominated by arable land and pasture. There are only few small villages and detached farms (Fig. 2(b)). From the source to the catchment outlet, the Kielstau has a total length of 16.2 km and a mean gradient of 1.2‰. The topography in the catchment ranges from 78 m to 27 m a.m.s.l., is flat but relatively uneven with rolling hills and numerous depressions (Fig. 2(c)). The prevailing soils are Haplic and Stagnic Luvisols, while the river valleys are characterised by peat soils (Fig. 2(d)). About 5 km downstream of its origin, the Kielstau flows through Lake Winderatt, which has a surface area of 0.24 km^2. Downstream of Lake Winderatt two large tributaries, the Moorau and the Hennebach, and various drainage pipes and open ditches discharge into the Kielstau. The location and extent of drained areas within the catchment has been estimated by Fohrer *et al.* (2007) using a GIS-based methodology. The fraction of drained area in the catchment is estimated to be approx. 38% (Fohrer *et al.*, 2007; Fig. 2(d)). Close to the catchment outlet the gauging station Soltfeld is located, which is part of the official gauging network of the Federal State Schleswig-Holstein.

The hydrology is characterised by agricultural drainage, near surface groundwater, low hydraulic gradients and thus a high interaction between groundwater and surface water. Many parts of the Kielstau have been changed markedly during the reallocation of land from its natural course. In these areas, the river has been straightened, incised and thus disconnected from its flood plains. Here, hydromorphological variety and value is relatively low, while near-natural river sections still exist and can act as reference points (DAV-WBV/LAND SH, 2006). The overall morphological state of the stream is assessed as "poor" to "moderate" (Olbert *et al.*, 2006) according to the standard hydromorphological river survey method in Germany (LAWA, 2000)
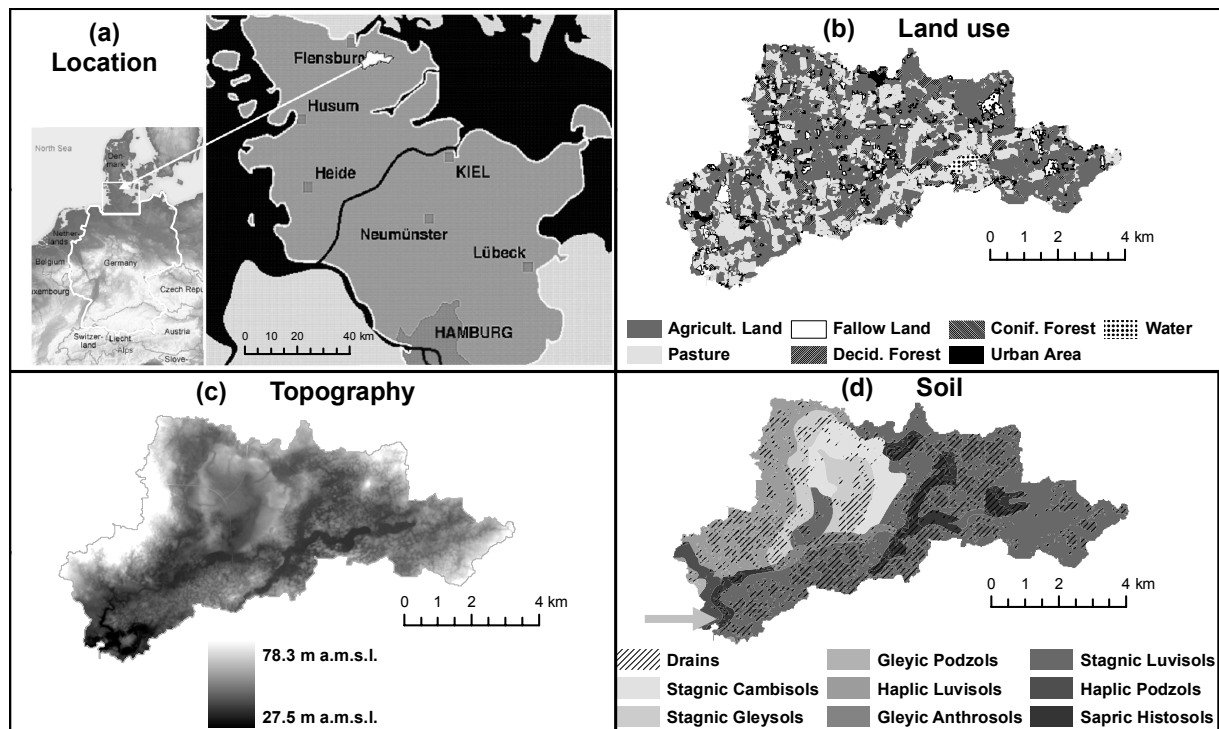
Fig. 2 (a) Location of the Kielstau catchment in Germany (Jose, 2006; LVA); (b) land use (DLR, 1995); (c) topography (LVA); (d) soil (BGR, 1999) with drained areas (Fohrer *et al.*, 2007), the grey arrow marks the location of the hotspot.

and is typical for many streams in northern Germany. Nevertheless, the Kielstau is part of the flora fauna habitat protection area (FFH-directive; EC, 1992) and 175 ha of land along the river and around Lake Winderatt are owned by two nature conservation foundations, which increases the potential for river rehabilitation measures within and beyond the scope of the WFD.

The macroinvertebrate assemblage of the Kielstau was assessed by Brinkmann (2002) and LANU (2006); further data have been generated in the framework of the present study. The macroinvertebrate community is mainly composed of generalists inhabiting lakes and lentic zones of streams, in particular snails (Gastropoda), mayfly larvae (Ephemeroptera), beetles (Coleoptera), caddis larvae (Trichoptera) and midges (Chironomidae). Dominant feeding types are grazers (mayfly larvae and snails), filter feeders (several caddis larvae and mussels) and shredders (Amphipoda). More specialised species include various caddis larvae feeding on dead wood (e.g. *Lype reducta*).

The data described above are available for the whole catchment. A 300-m stream section was chosen where in-stream measures to improve the aquatic habitat will be tested. For this hotspot, additional data has been gathered in order to apply the modelling system (grey arrow in Fig. 2(d)). Here, channel topography data has been surveyed (soilAQUA, 2009), discharge rating curves have been established and a morphological river mapping campaign including a sediment analysis has been conducted (Thiemann, 2008). The following 10 substrates have been recorded and their distribution has been digitised on GIS maps: fascines, alder trees, water plants, dead wood, coarse particulate organic matter, clay, sand, gravel, cobbles and stones.

To evaluate model performance, macroinvertebrate sampling was carried out in spring 2008 and spring 2009. Within the first sample campaign, each substrate has been sampled eight times, resulting in 80 sampling sites. Additionally, actual flow velocity and water depth has been measured on all sites. Oxygen concentration, water temperature, electrical conductivity and pH have been recorded on all sampling days and daily continuous measurements of the nitrogen and phosphorous fractions were conducted at the stream section since 2006.

RESULTS

The data representing the drivers has been gathered and implemented in ArcGIS and the submodels (Table 1). The hydrological model SWAT has been applied to depict the pressures *hydrologic stress* and *fine sediment intake* on the catchment scale. The modelled and measured daily discharge hydrographs for the 5-year calibration period show a very good fit. Moriasi *et al.* (2007) suggested performance tests which are all passed by the model: Nash Sutcliffe efficiency of 0.80, Percent bias of 6.34 and a Root Mean Square Error of 0.19 (Fig. 3(a)). In order to achieve a good model performance it was of particular importance to consider the two lowland characteristics landscape depressions and agricultural tile drains. Therefore, the surface water storage potential has been derived from high quality topographic data and has been implemented in the model together with the distributed drainage map. The tile drain parameters have been used within plausible ranges for model calibration.
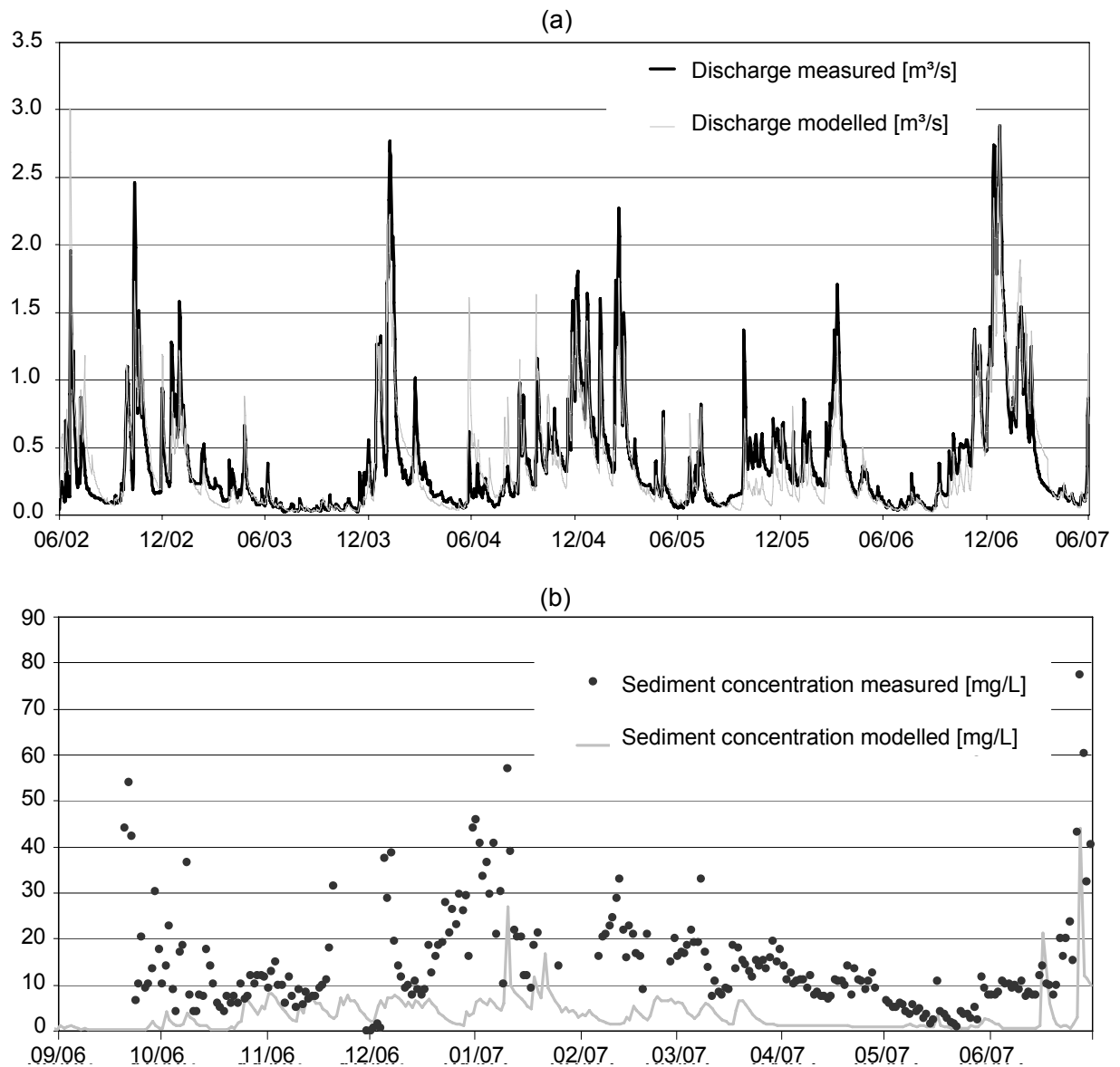

Fig. 3 Discharge (a), and suspended sediment (b), calibration of the SWAT model; please note the different time scale.

Sediment input in the lowlands mainly consists of three sources: fields, agricultural drains and the river banks. It is possible to depict sediment input from agricultural fields, but so far no model can account for sediment input from tile drains. Due to this, a GIS-based methodology has been developed to estimate the sediment entry pathway share in the Kielstau catchment resulting in sediment input of 15% from fields, 15% from drains and 70% from river banks (Kiesel *et al.*, 2009). Based on this estimation, a drainage flow sediment concentration has been derived and implemented in SWAT. Suspended sediment data are available since September 2006 and thus the model has been applied to the time period displayed in Fig. 3(b). The graph shows an underestimation of modelled sediment concentration to measured sediment concentration (Fig. 3(b)) because the model considers sediment input from fields and drainages only, while the samples are conducted with the total sediment concentration of the stream which comprises the bank entry pathway. Including the separated depiction of the bank erosion processes with the hydraulic model will improve the result.

The GIS mapping took place at a 300 m section of the Kielstau where the *substrate degradation* and *bank and bed fixation* have been mapped (Thiemann, 2008). *River cleaning* is not occurring within that stream reach. The resulting digital map shows the distribution of 10 different substrates (Fig. 4(a)).

The hydraulic model ADH has been applied on this stream section. Figure 4(b) and (c) show the resulting depth and velocity distribution of a steady state run for a high discharge value. As the stream reach bathymetry needs to be further refined with the aid of the digital GIS map, and the SWAT hydrograph and sediment load graph has not yet been linked, these are only preliminary results. Especially for the time-dependent simulation of the current patterns and the substrate, it is necessary that the hydrological discharge regime is linked to ADH.

The parameters descriptively shown in Fig. 4 form the base for the proposed simulation of the macroinvertebrate habitat on the micro scale.
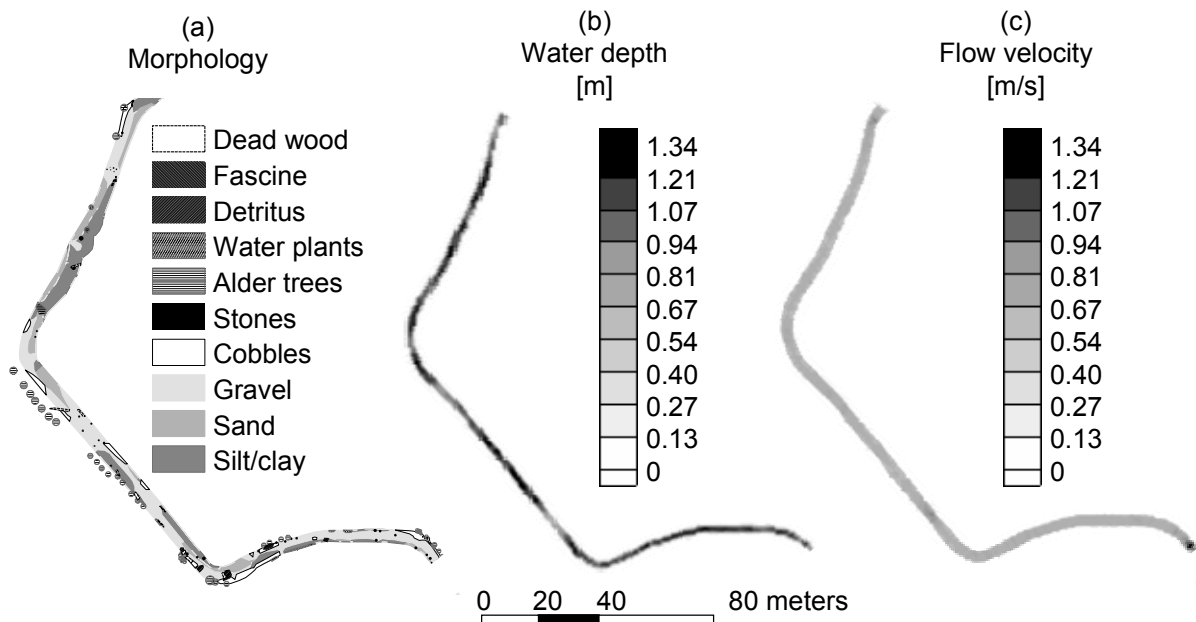

Fig. 4 GIS mapping of observed morphology and substrates (a); ADH model results (from October 2008): water depth (b) and flow velocity (c) distribution.

DISCUSSION

A methodology has been introduced on how the impact of anthropogenic changes of catchment and river properties on the macroinvertebrate habitat can be assessed. The first step is the depiction

of the *status quo*, while the strength of the modelling system is the capability of assessing the influence of changes on the catchment scale and also the effect of in-stream measures on potential indicator species. Therefore, the DPSI concept (EEA, 1999) is utilised within a GIS-based modelling system on the example of a 300 m river section located in a German lowland catchment. Three submodels are used to depict the current state of necessary habitat parameters by incorporating the drivers into a hydrological and a hydraulic model, and GIS maps. The results show that the hydrological discharge simulation performs well in comparison to the measured data and is capable of depicting the scale and duration of extreme events that can cause hydrological stress. Considering, that the fine sediment input from fields and agricultural drainages accounts for about 30% of the total sediment contribution, the model results show a reasonable depiction of fine sediment intake. The preliminary results of the steady state hydraulic model application emphasize the need for a dynamic link of catchment and in-stream processes so that the change in flow characteristics and substrate is based on the hydrological regime. In order to depict the current status of the stream, field mapping of the morphology is necessary. The natural seasonal variation of stream properties, especially the vegetation, can be considered, and is the only possibility to include important small scale habitats like wood debris, water plants, stones and artificial structures into the modelling system. Furthermore, the influence of habitat upgrading measures can be conveniently assessed by modifying the digital morphological GIS maps.

Concerning the evaluation of the parameter functions, different demands of a species during its life cycle have to be extracted from the database and have to be considered in the decision tree for each particular species. The emphasis on constructing the GIS-based modelling system lies: (1) on a smooth data handling between the hydrological and the hydraulic model; (2) the direct usability of the GIS maps for the hydraulic model by linking roughness values to the surface type; and (3) to keep the data transfer within a manageable size by simplifying long-term daily hydrographs to time-dependent flow classes for computing quasi-steady model runs.

REFERENCES

Abbott, M. B. & Refsgaard, J. C. (1996) *Distributed Hydrological Modelling*. Kluwer Academic Publishers, The Netherlands.

Aldridge, D. C. (2000) The impacts of dredging and weed cutting on a population of freshwater mussels (Bivalvia: Unionidae). *Biological Conservation* **95**, 247–257.

Arnold, J. G., Srinivasan, R., Muttiah, R. S. & Williams J. R. (1998) Large area hydrologic modeling and assessment part I: model development. *J. Am. Water Resour. Assoc.* **34**(1), 73–89.

Berger, R. C. & Tate, J. N. (2007) Guidelines for solving 2D shallow water problems with the Adaptive Hydraulics (ADH) Modeling System. *Coastal and Hydraulics Laboratory, ERDC, USACE.*

Berry, W., Rubinstein, N. & Melzian, B. (2003) The biological effects of Suspended and Bedded Sediment (SABS) in aquatic systems: a review. Internal Report, USEPA.

BGR (1999) Bundesanstalt für Geowissenschaften und Rohstoffe, Bodenübersichtskarte 1:200 000 CC.1518 Flensburg, Hannover, Germany.

Brinkmann, R. (2002) Pflege- und Entwicklungsplan für das Naturschutzgroßprojekt Obere Treenelandschaft, Ergebnisse der faunistischen Untersuchungen, Limnische Wirbellose. Auftraggeber: *Naturschutzverein Obere Treenelandschaft*, 1–83.

DAV-WBV/LAND SH (2006) Digitales Anlagenverzeichnis Schleswig-Holstein. *Wasser- und Bodenverbände des Landes Schleswig-Holstein und Land Schleswig-Holstein.*

DLR (1995) *Landsat TM5-Scene. 25 × 25 m resolution*. German Aerospace Center, Köln, Germany.

DWD (2007) Weather and climate data from the German Weather Service, Offenbach, Station Flensburg 1957–2006.

EC (1992) Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora. FFH Directive. European Council, Consolidated Version 01-01-2007.

EC (2000) Directive 2000/60/EC of the European Parliament and of the Council. Water Framework Directive, European Council.

EEA (1999) Environmental indicators: Typology and overview. European Environment Agency, Technical report no. 25, 1–19.

ESRI (1997) *Understanding GIS – The ARC/INFO Method, Self-Study Workbook*. Environmental Systems Research Institute, Redlands, California, USA.

Euro-Limpacs (2009) Euro-limpacs Consortium: freshwaterecology.info – the taxa and autecology database for freshwater organisms. Available from www.freshwaterecology.info (Version 3.2, 08/08).

Fohrer, N., Schmalz, B., Tavares, F. & Golon J. (2007) Modelling the landscape water balance of mesoscale lowland catchments considering agricultural drainage systems. *Hydrol. Wasserbewirtsch.* **51**(4), 164–169. (in German).

Frissel, C. A., Williams, J. L., Warren, C. E. & Hurley M. D. (1986) A hierarchical framework for stream habitat classification: viewing streams in a watershed context. *Environ. Manage.* **10**, 199–214.

Gregory, K. J. (2006) The human role in changing river channels. *Geomorphology* **79**, 172–191.

Hering, D., Meier, C., Rawer-Jost, C., Feld, C. K., Biss, R., Zenker, A., Sundermann, A., Lohse, S. & Bohmer J. (2004) Assessing streams in Germany with benthic invertebrates: selection of candidate metrics. *Limnologica* **34**, 398–415.

Hering, D., Johnson, R. K., Kramm, S., Schmutz, S., Szoszkiewicz, K. & Verdonschot P. F. M. (2006) Assessment of European streams with diatoms, macrophytes, macroinvertebrates and fish: a comparative metric-based analysis of organism response to stress. *Freshwater Biol.* **51**, 1757–1785.

Horsák, M., Bojková, J., Zahrádková, S., Omesová, M. & Helesic, J. (2008) Impact of reservoirs and channelization on lowland river macroinvertebrates: A case study from Central Europe. *Limnologica 2008*, doi:10.1016/j.limno.2008.03.004, 1–11.

James, L. A. & Marcus, W. A. (2006) The human role in changing fluvial systems: retrospect, inventory and prospect. *Geomorphology* **79**, 152–171.

Jose (2006) Relief map of Europe. Wikimedia Commons. http://commons.wikimedia.org.

Kiesel, J., Schmalz, B. & Fohrer, N. (2009) SEPAL – a simple GIS-based tool to estimate sediment pathways in lowland catchments. In: *Advances in Geosciences, Special Issue: Transdisciplinary Concepts and Modelling Strategies for the Assessment of Complex Environmental Systems* (accepted).

Kramm, S. (2002) Vergleichende Untersuchung der Besiedlung von Hartsubstraten durch Makroinvertebraten in Sandbächen. Diploma Thesis, University of Essen, Germany.

Kristensen, P. (2004) The DPSIR Framework, European Topic Centre on Water. European Environment Agency. In: *UNEP Workshop 27–29 September 2004* (Nairobi, Kenya), 1–10.

LANU (2006) Ökologischer Bewertungsrahmen Fließgewässer (Bäche), Kielstau, Kennzahl 95222. Landesamt für Natur und Umwelt des Landes Schleswig-Holstein.

LAWA (2000) Gewässerstrukturgütekartierung in der Bundesrepublik Deutschland – Verfahren für kleine und mittelgroße Fließgewässer. Länderarbeitsgemeinschaft Wasser, 1–164.

Li, F. Q., Cai, Q. H., Fu, X. C. & Liu, J. K. (2008) Construction of habitat suitability models (HSMs) for benthic macroinvertebrate and their applications to instream environmental flows: A case study in Xiangxi River of Three Gorges Reservoir region, China. *Progr. Natural Sci. 2008*, doi:10.1016/j.pnsc.2008.07.011, 1–9.

Lorenz, A., Feld, C. K. & Hering, D. (2004) Typology of streams in Germany based on benthic invertebrates: ecoregions, zonation, geology and substrate. *Limnologica* **34**, 379–389.

LVA (1992–2004) Digital Elevation Model for Schleswig-Holstein and map of Schleswig-Holstein, 5m cell size. Land Survey Office, Kiel, Germany.

Nedeau, E. J., Merritt, R. W. & Kaufmann, M. G. (2003) The effect of an industrial effluent on an urban stream benthic community: water quality vs. habitat quality. *Environ. Pollut.* **123**, 1–13.

Neitsch, S. L., Arnold, J. G., Kiniry, J. R. & Williams, J. R. (2005) Soil and Water Assessment Tool, Theoretical Documentation. Version 2005, Grassland, Soil and Water Research Laboratory, Blackland Research Center, Temple, Texas, USA.

Moriasi, D. N., Arnold, J. G., Van Liew, M. W., Bingner, R. L., Harmel, R. D. & Veith, T. L. (2007) Model evaluation guidelines for systematic Quantification of accuracy in watershed simulations. *Trans. ASABE* **50**(3), 885–900.

Moss, B. (2008) The Water Framework Directive: Total environment or political compromise? *Sci. Total Environ.* **400**, 32–41.

Olbert, C., Fell, F., Ahrens, H., Beurton, D., Wetzel, H. & Hnida, D. (2006) Structural river mapping 2005 in the Eider watershed. Informus GmbH, Water- and Soil Association Schleswig-Holstein, Germany.

Omernik, J. M. (2004) Perspectives on the Nature and Definition of Ecological Regions. *Environ. Manage.* **34**, Suppl.(1), S27–S38.

Rawer-Jost, C., Zenker, A. & Böhmer, J. (2004) Reference conditions of German stream types analysed and revised with macroinvertebrate fauna. *Limnologica* **34**, 390–397.

Reichert, R., Borsuk, M., Hostmann, M., Schweizer, S., Spörri, C., Rockner, K. & Truffer, B. (2007) Concepts of decision support for river rehabilitation. *Environmental Modelling & Software* **22**, 188–201.

Sandin, L. & Hering, D. (2004) Comparing macroinvertebrate indices to detect organic pollution across Europe: a contribution to the EC Water Framework Directive intercalibration. *Hydrobiologia* **516**, 55–68.

Schmalz, B., Bieger, K. & Fohrer, N. (2008) A method to assess instream water quality – the role of nitrogen entries in a North German rural lowland catchment. *Adv. Geosci.* **18**, 37–41.

Singh, V. P. & Woolhiser, D. A. (2002) Mathematical Modelling of Watershed Hydrology. *J. Hydraul. Engng* **7**(4), 270–292.

soilAQUA (2009) Cross sectional measurements in the Kielstau River. Engineering Company soilAQUA, Sterup.

Surian, N. & Rinaldi, M. (2002) Morphological response to river engineering and management in alluvial channels in Italy. *Geomorphology* **50**, 307–326.

Tate, J. N. (2006) Implementation and testing of a non-cohesive sediment library in the 2-D shallow water equations of adaptive hydraulics (ADH). In: *7th ICHE* (Philadelphia, USA).

Thiemann, K. (2008) Morphological Assessment of a German Lowland Stream as a Basis for Management Recommendations. Master Thesis University of Kiel, Department of Hydrology & Water Resources Management, Kiel, Germany.

Umweltbundesamt (2007) Umweltdaten Deutschland Online, Binnengewässer, Fließgewässer, www.env-it.de (accessed 02/09).

Van Broekhoven, E., Adriannssens, V., De Baets, B. & Verdonschot P. F. M. (2006) Fuzzy rule-based macroinvertebrate habitat suitability models for running waters. *Ecol. Modelling* **198**, 71–84.

Wang, Z. Y., Lee, J. H. W., Cheng, D. H. & Duan, X. H. (2008) Benthic invertebrates investigation in the East River and habitat restoration strategies. *J. Hydro-environment Res.* **2**, 19–27.

Wenikajtys, M. (2004) Test verschiedener Sortierungsmethoden für Makrozoobenthosproben in Tieflandflüssen Deutschlands und Polens. Diploma Thesis, University of Essen, Germany.

Zanke, U. C. E. (2002) *Hydromechanik der Gerinne und Küstengewässer – Für Bauingenieure, Umwelt- und Geowissenschaftler*. Parey Buchverlag, Berlin, Germany.