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Research paper

Model-based design for restoration of a small urban river

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Abstract

A model-based design is presented for restoring the small urban river Panke located in Berlin, Germany. This new design process combines high resolution 2D hydraulic modeling with habitat modeling and river-ecological expert knowledge in a highly iterative way. Advances have been made for the habitat modeling: habitat suitability maps have been developed for fish and the habitat suitability for benthos has been assessed by including groups with different hydraulic preferences.

Using the model-based design we have developed preference variants for the Panke which include structures such as pools, riffles, river banks, dead wood as well as aquatic vegetation. To account for the very detailed geometry of some structures such as dead wood, high resolution grids with edge length up to one decimeter have been generated. Furthermore flood protection has been assured. The variants should be constructed in the Panke in 2015. We expect that the ecological conditions for fish and benthos will improve, however this has to be evaluated by further measurements. The model-based approach for the design of enhancement measures delivered valuable hints on current shortcomings in the river morphology, priorities for the creation of new habitats and quantitative information on the increase of suitable areas to be expected. In addition, relating the habitat changes to different flow rates helped to estimate the temporal availability of high quality habitats after the implementation of the measures.

Keywords: Urban river; High resolution modeling; Ecological expert knowledge; River restoration

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1. Introduction

Urban water bodies are facing numerous threats to their water quantity and quality. In the past especially small many urban rivers have been straightened, embanked and partially tubed, and often they are directly bordering or very closely located to buildings. Further, many urban rivers are stressed by various loads such as nutrients, heavy metals, personal care products or drugs resulting from combined sewer overflow, highly polluted surface runoff after heavy rainfall or their functioning as receiving waters. Consequently, the biodiversity and ecological state of many urban rivers is considerably impoverished compared to natural freshwater bodies (Meyer et al., 2005, Walsh et al., 2005; Fletcher et al., 2013). The aim of the European Water Framework Directive is to achieve a good ecological state for all water bodies (Bernhardt and Hardt, 2006) and corresponding criteria are defined, for example for different (natural) river types. However, achieving a good ecological state is hardly possible for many urban rivers. Therefore, the European Water Framework Directive

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has established a further classification, the Heavily Modified Water Bodies which are water bodies that have significantly changed their original appearance. These Heavily Modified Water Bodies have to achieve a good ecological potential rather than a good ecological status, i.e. they have to achieve less high aims which are not generally defined and case specific. In addition to often limited space in urban areas, further difficulties arise from restrictive administrative regulations when restoring a river.

The Panke, located in Berlin, Germany, is a small urban river or stream and it is such a Heavily Modified Water Body being faced by many of the above mentioned problems (see Fig. 1, left). Within a pilot project different preference variants have been developed to improve the structural quality of the channel in such a way that a good ecological potential can be expected in the future (Sieker and Peters, 2008; Brunke et al., 2012; Seidel and Mutz, 2012; Laub et al., 2012). One innovative aspect of this pilot project is the use of various modeling tools in combination with ecological expert knowledge to develop and optimize the channel design in an iterative procedure. The models cover hydrology, hydraulics, transport of substances and sediments, morphodynamcis as well as habitats (see Fig. 1, right). Especially the hydraulic modeling requires high resolution grids with a smallest edge length of one decimeter to resolve the geometric structures and optimize their design. Another important aspect in the pilot project is that the new channel design should not worsen the flood protection. Further, the habitat model had to be adapted and extended to meet the special conditions of fish and benthos in the Panke. This model-based design approach may also be interest for river restoration in Asia (e.g. Parish et al., 2004).

The objectives of this paper are the following: First we explain the scientific methods of the hydraulic and the habitat model, their extensions and their limitations. Then the current hydraulic, morphological and habitat conditions (fish, benthos) have been determined showing the highly degraded ecological status in the river Panke. In the following, preference variants are developed in a highly iterative way linking high resolution hydraulic and habitat modeling with river-ecological expert knowledge. Finally, the advantages and advancements in (practical) river restoration are discussed.

2. Modeling tools

2.1. Hydrological model

The rainfall-runoff simulation in the catchment is carried out with the model STORM (Sieker et al., 2006). STORM originally was developed for simulating water balances in urban areas (e.g. polluting loads, dimensioning of constructions for combined wastewater treatment). In recent years it has been extended to also simulate rainfall-runoff in natural catchments. In our pilot project rainfall-runoff in the Panke catchment is modelled with STORM which thus determines the inflow discharge of the river section under investigation.

2.2. Hydro-numerical model for hydraulics, transport and morphodynamics

If at all models are applied for river restoration, often 1D models are used. For our work we require a robust 2D model and this necessity is explained in the following. The 2D model numerically solves the vertically averaged shallow water equations. Thus in each node the water level as well as the horizontal flow components are computed. The computational domain includes the riverbed and the floodplains as well as bridges being special hydraulic structures and it is discretized by an unstructured mesh consisting of triangular and quadrilateral elements (see Figs. 2 and 3). The model must be robust to properly simulate the propagation of flood waves, flooding and drying as well as small water levels and flow transitions (Toro, 2001, Hervouet, 2007; Hou et al., 2013, Simons et al., 2014).

We need at least a 2D model to account for the flow diversity, i.e. at least the horizontal variability of the flow field which is significant, for example in areas with pools, banks and dead wood. Further, the geometric approximation of the structures mentioned before can be carried out much better with a 2D model compared to a 1D model and therefore the impacts of these structures on the flow, transport and the ecological state can be estimated much better. As some of structures such as dead wood are small, we need highly refined meshes with edge lengths in the range of one decimeter (see Figs. 2 and 9). This is much finer compared to classical 2D

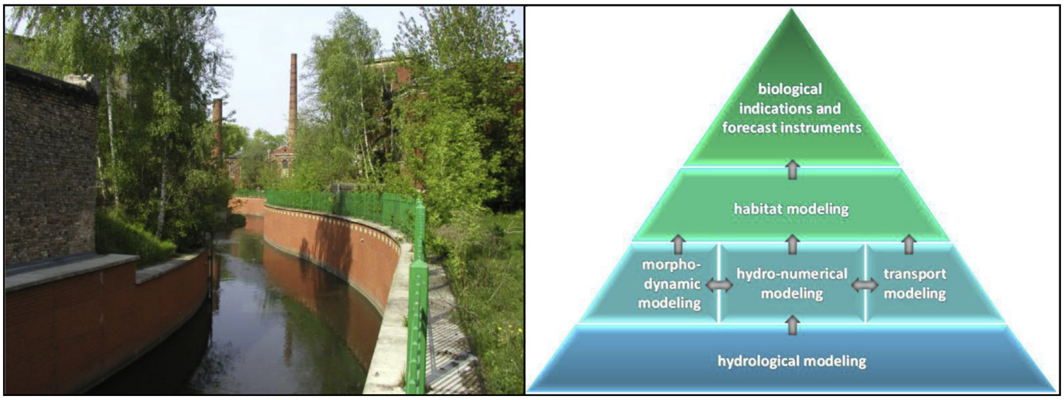

Fig. 1. River Panke in Berlin (left); pyramid of modeling and forecast tools (right).

Fig. 2. Current conditions in river Panke; lower reach near bridge (left), highly modified, urban morphology (right); uppermost reach with vegetated bank areas; arrows show current direction.

applications such as modeling floods or impacts of river engineering measures. Although these structures can geometrically be accounted for, we have to mention that we also have to make some geometrical simplifications. For example, we cannot exactly represent a round dead wood and have to make engineering simplifications and we cannot account for small branches. We are aware that also 3D flow effects might play a role, for example in pools or the near field of structures (e.g. Xie et al., 2013). However, this is very CPU time demanding and it is currently out of the scope of a practically oriented project. Finally, dense vegetation which occasionally occurs during the year requires special consideration.

For our investigations we have chosen the model HYDRO_AS-2D which is a robust shallow water solver based on the Finite-Volume Method (Nujić, 2006, Lange et al., 2014). Extensions of HYDRO_AS-2D enable modeling the transport of substances and sediments as well as morphological changes. Knowing the flow field, the bottom shear stresses can be easily computed. The spatial distributions of water levels, flow fields and bottom shear stresses for various discharge events are very important input parameters for the habitat modeling and the channel design.

2.3. Habitat model

Substrate properties obtained from field measurements were assumed constant in time. Target fish species have been selected based on historic information and recent surveys identifying river type specific species sensitive enough to detect improvements but also able to colonize an urban river stretch in a feasible time span. Two rheophilic cyprinids were selected as target species, gudgeon *Gobio gobio* and dace *Leuciscus leuciscus*. In the study area gudgeon is very rare but still present, while dace depends on connectivity improvements to approach. In addition three-spined stickleback and young of the year fish (YOY) in general were chosen as targets being the presently dominating species and the generally most sensitive life stage, respectively. For all target species a 2D fuzzy logic habitat model was set up using the software CASiMiR (Jorde, 1997; Schneider, 2001).

The standard modeling approach used by CASiMiR relates changes in the local hydraulic conditions and morphological properties such as substratum on the river bottom or cover types to the habitat requirements of fish (see model principle in Fig. 4). Via the intersection of this abiotic and biotic input using a fuzzy logic approach the habitat suitability for desired fish species and life stages can be determined and illustrated in terms of habitat suitability maps (see Fig. 3). Included in this project, however is the assessment of morphological variations which are used to test the viability of mitigation options before they are built. Thus the approach used in this paper provides an optimization tool which simultaneously accounts for hydraulic and ecological interactions.

Fuzzy rules and sets were created based on long-term regional field data on environmental requirements of the target species. Abiotic input parameters were the water depth and flow velocity, classified into ranges using sets such as “low”, “medium” and “high”. The definition of the sets

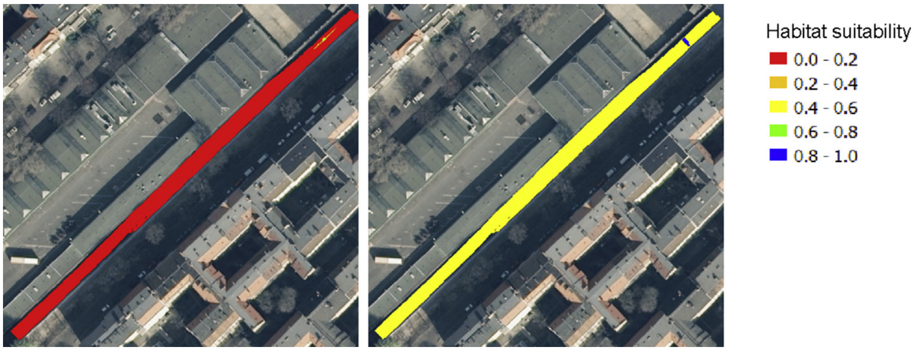

Fig. 3. Current conditions in Section 3; CASiMiR habitat model results for two life stages adult (left) and juvenile (right) of Gudgeon (*Gobio gobio*) for 310 l/s.

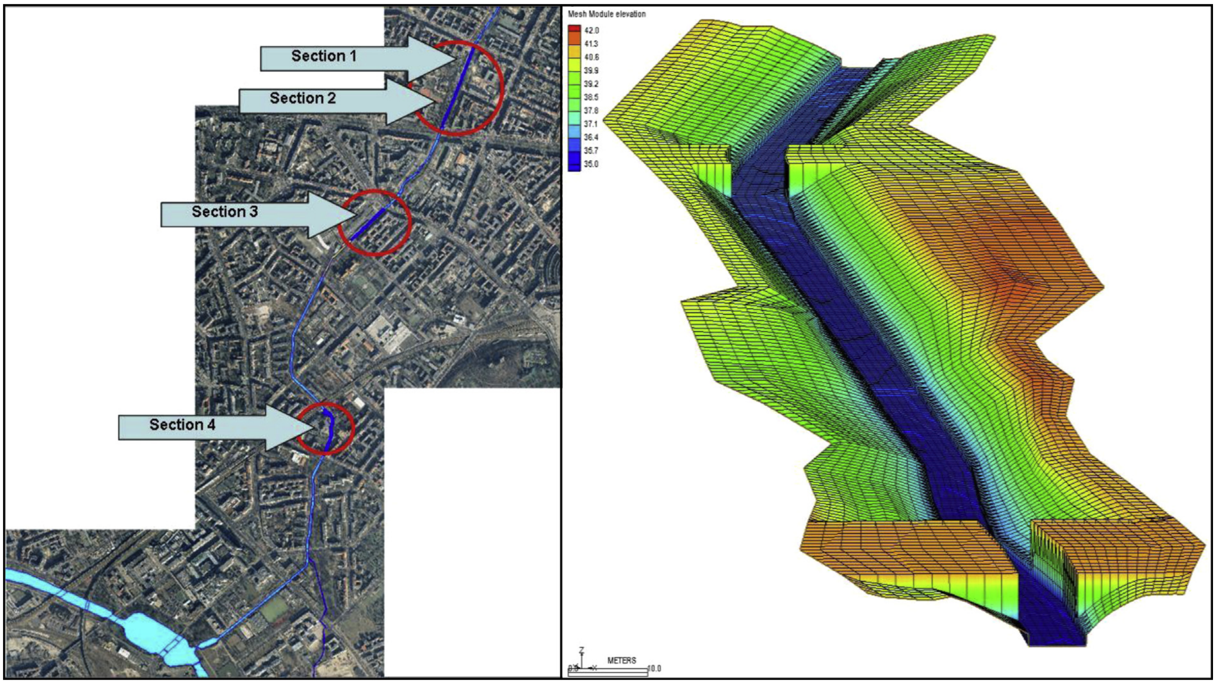

Fig. 4. Reach of river Panke within the city of Berlin including the 4 sections (left); detail of the grid showing the current state of Section 1 including 2 bridges, ground level (dark red 42.0, dark blue 35.0 m above sea level) (right).

depends on the considered species. The "medium" flow velocity range is higher for rheophilic species adapted to fast flowing environments as opposed to limnophilic species with affinity for slow flowing and stillwater. Substrate properties were assumed constant in time. Examples for the definition of habitat requirements by fuzzy rules are listed in Fig. 3.

The habitat suitability results are calculated in terms of a Habitat Suitability Index (HSI) having scalar values between 0 and 1, where 1 represents the most suitable habitat at a given mesh element and 0 represents unsuitable habitat.

Another advancement in this work was the inclusion of the Perlodes methodology for the assessment of benthic habitat suitability. The Perlodes system assumes specific distributions of benthos taxa to river types based on the assumption of 'matching' species to the typical hydraulic characteristics of the rivers they inhabit. The hydraulic preferences of the benthos taxa are determined from a large number of field investigations relating the FST hemisphere measurements (Statzner and Müller, 1989; the FST hemisphere number is indicator for the near bottom flow force) and are mathematically defined as preference functions. In the current investigations a new approach has been applied. Preference functions were not defined for single taxa but for different hydraulic preference groups (limnobiotic, limnophilic, rheophilic and rheobiotic, see above) as part of the Perlodes system. The functions for these different groups were derived by the analysis of available preference functions for single taxa belonging to a group and their integration. That way each function relates the habitat suitability of a particular benthos group to FST values (see Fig. 5).

3. Current results

3.1. Preparatory work and current conditions

A reach of the Panke with a length of about 2.2 km has been investigated (see Fig. 4, left). For the bathymetry about 80 profiles of cross sections were available having a distance of about 25 m. The computational domain also includes forelands which are of course small due to closely located buildings and urban infrastructure. The 2D grid consists of about 220.000 triangular and quadrilateral elements (see Fig. 4, right). The bottom friction has been chosen to a Strickler value of 40 $m^{1/3}/s$ which has been determined in a preparatory project (Sieker and Peters, 2008). Within the considered reach four sections have been defined where different structures should be built (see Section. 3.2). Preparatory work has been carried out by Lange et al., 2012, 2013.

First we have modeled the Panke under current conditions. For different purposes we had to consider mean as well as extreme low and high discharge conditions: extreme low flow conditions 0.050 m^3/s, median discharge 0.150 m^3/s, mean discharge 0.310 m^3/s, bankfull discharge 0.900 m^3/s and flood discharges with different frequencies of occurrence, annual: 2.550 m^3/s, 50 years: 7.250 m^3/s, 100 years: 8.380 m^3/s. For dimensioning the height of dead wood and sandbanks we have chosen a discharge of 0.900 m^3/s to ensure that the upper parts of the structures still remain dry, are a few centimetres above the water table and are not overflown (see Fig. 9).

The uppermost region has currently the 'best' morphological characteristics, despite its placement within the highly urbanized landscape. Dominant substrate for this reach

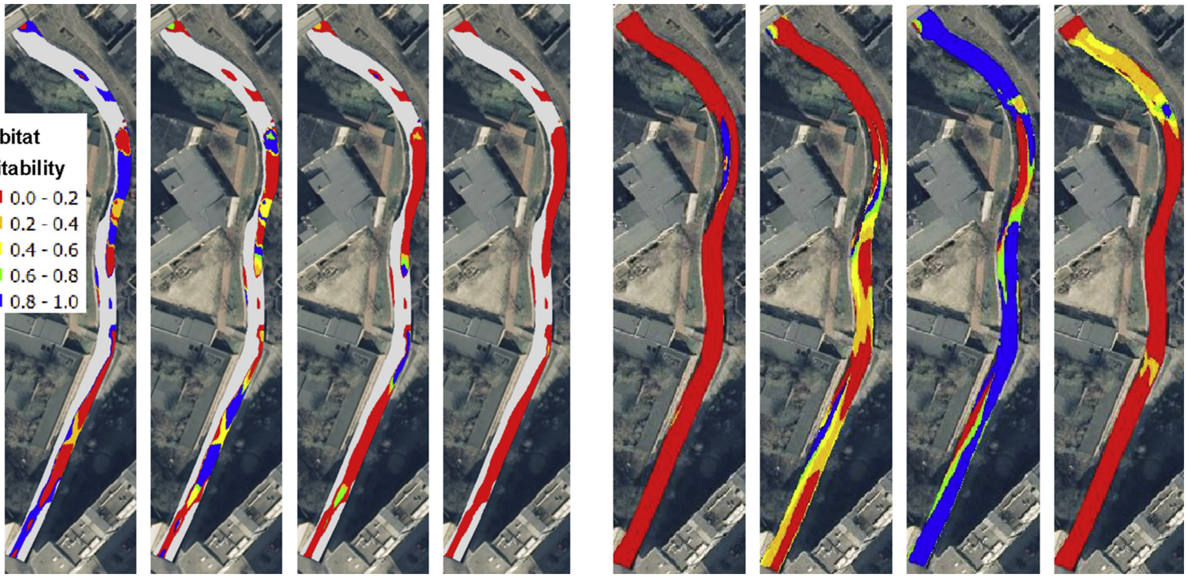

Fig. 5. Current conditions in Section 4; Habitat suitability for the benthos groups (left to right) “limnobiotic”, “limnophilic”, “rheophilic”, and “rheobiotic” for a discharge of 0.05 m^3/s (left) and 0.31 m^3/s (right).

consists of large stones, with alternating subdominant regions of small stones (6–12 cm) and sand (see Fig. 2).

Due to the poor morphological conditions, a low hydraulic variability exists within the reach which effectively leads to a homogenization of the flow field. Since fish across species and life stages are rheoactive across a wide spectrum of local flow conditions, a homogeneous flow field acts effectively as a physical sorting mechanism for fish species diversity. The results of the habitat model showing the poor suitability conditions for life stages of gudgeon (Gobio gobio) for a discharge of 0.310 m^3/s are given in Fig. 3. Adults do not find any areas with good conditions in the current situation. This is mainly because of the very low flow velocities in conjunction with very shallow water. For juveniles the situation is better since water depth and flow velocity is low in the whole stretch. However, the most preferred shallow areas with low flow velocities and small substratum are missing.

Results of habitat modeling for the four benthos groups with different hydraulic preferences are shown in Fig. 5 for a flow rate of 0.05 m^3/s (not exceeded 45 days per year, left) and a flow rate of 0.31 m^3/s (not exceeded 145 days per year, right). The four groups are classified based on their preferences for the environmental flow characteristics: limnobiotic = requires slow flowing or stillwater, limnophilic = affinity for slow flowing and stillwater, rheophilic = affinity for flowing water and rheobiotic = requires flowing water. It can be seen that in the current situation habitats for limnobiotic and limnophilic species are only found in larger portions for the low flow situation while for the higher flow they are severely reduced. In contrast the rheophilic group has access to a wide expanse of high quality habitats for the higher flow whereas for the low flow situation these habitats virtually disappear. This becomes most pronounced in the low flow period during summer when large quantities of macrophytes (not considered in the hydraulic model) further reduce the flow velocity. Habitats for rheobiotic organisms are found only in single spots for the higher flow and are not present in the low flow situation which is however not atypical for the river type considered.

The change of habitat distribution over the whole investigated flow range can be read from the suitability distribution diagrams shown in Fig. 6. High quality habitats (Habitat suitability > 0.6) are hardly found during low flow for all groups, for the limnobiotic and limnophilic they almost disappear for high flow situations above 0.9 m^3/s. Rheobiotic organisms find virtually no highly suitable areas for all flow rates.

In the current situation this is a particular problem that locally hydraulic habitats change completely with river flow. For that reason only indifferent benthos species can settle, who get along well with this flow dependent changes.

In parallel to the modeling work an assessment scheme for sampling fish was set up following a BACI (before-after-control-impact) approach. Immediately upstream of each of the four sections (Fig. 4), a control section of similar length was established. Both all stretches with rehabilitation planned and all controls have been sampled for fish three times prior the rehabilitation work started, in spring (April), summer (August) and autumn (October) 2012.

Fish sampling comprised wading single run electric fishing without stop nets using two portable battery-powered DC electric fishing gears (EFGI 650, 1.2 kW, Brettschneider-Spezialelektronik, Chemnitz) with a towed ring anode of 0.4 m diameter each. Both banks were simultaneously fished by two operators. All fish stunned were collected immediately and stored in an aerated tank until the site was completely sampled. The site length was determined by the rehabilitation planning. Control sites were of similar length as the corresponding rehabilitation sites. Because rehabilitation Sections 2 and 1 were connected (Fig. 4), a common control site was

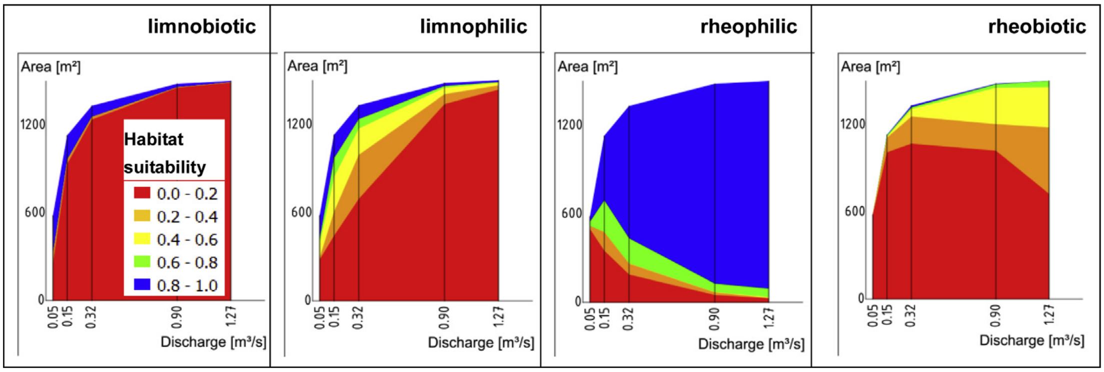

Fig. 6. Current conditions in river Panke; distributions of the areas for different habitat classes as a function of the discharge for the benthos groups (left to right) "limnobiotic", "limnophilic", "rheophilic", and "rheobiotic".

sampled upstream corresponding to the length of both together. Site length were measured using a laser rangefinder (LEICA LRF 800 Rangemaster) and the coordinates of starting and ending points were recorded with a hand-held GPS (Garmin GPSmap 60CS). All fish were identified to species, measured (nearest mm) and released. Catch per site was standardised to number of fish caught per 100 m fished. Catch was pooled for sites over seasons to assess the current conditions of the fish assemblage of the Panke.

During the assessment of the current fish ecological status of the Panke within the study area a total of 8401 fish was caught representing 9 species. The fish assemblage was completely dominated by three-spined stickleback contributing more than 99% to the total catch. All other species were rare. In addition, most of the other species were caught in the control sites (Table 1). Fish densities did not significantly differ between rehabilitation and control sites.

The catch was fully dominated by eurytopic, environmentally tolerant, generalist species (99.58%) and a few stillwater preferring limnophils (sunbleak, tench and rudd with a total share of 0.29%). In the Panke the only riverine fish species remaining was gudgeon (0.13%). This species has to be considered the most sensitive with regard to its requirements for both water quality and hydromorphologic habitats (e.g. Wolter, 2010; Scharf et al., 2011; Wolter and Schomaker, 2013).

Summing up, the fish assemblage is in a highly degraded ecological status with only one species dominating and many of the historically present species disappeared. It is hypothesized that implementing the planned measures and structures in the rehabilitation sites will significantly increase the numbers of species therein, the species diversity and especially the abundance of gudgeon and pike. The dominance of three-spined stickleback will most probably persist; however, at a substantially lower proportion. In the controls in contrast, low changes are expected except a slight increase of fish other than sticklebacks due to dispersal effects from the rehabilitation sites. The fish ecological benefits of the control sites from nearby rehabilitation measures will increase with time after implementing the measures.

3.2. Preference variants

Preference variants have been developed in a highly iterative procedure between the different modelers and the ecologists to improve the potential ecological benefits step by step. Several aspects have been considered:

Table 1
Number of specimens caught and fish densities obtained during the baseline sampling in 2012 at all sites pooled over season. RS = rehabilitation site, CS = control site; numbers refer to sections in Fig. 2.

Fisch Species	RS 4	CS 4	RS 3	CS 3	RS 2	RS 1	CS 2,1	Total
Gudgeon				10		1		**11**
Silver bream	1							**1**
Pike		2				2	1	**5**
Sunbleak				1				**1**
Roach		2	2			1		**5**
Rudd	2	1	2			1		**6**
Tench	1	5	3	4	1	1	2	**17**
3sp. stickleback	1528	1836	912	844	738	1362	1121	**8341**
10 sp. stickleback	1	4	3	3		1	2	**14**
Cumulative length fished (m)	610	840	550	435	540	515	620	**4110**
# Species	5	6	5	5	2	7	4	**9**
# Individuals	1533	1850	922	862	739	1369	1126	**8401**
Fish per 100 m	251.31	220.24	167.64	198.16	136.85	265.83	181.61	**204.40**

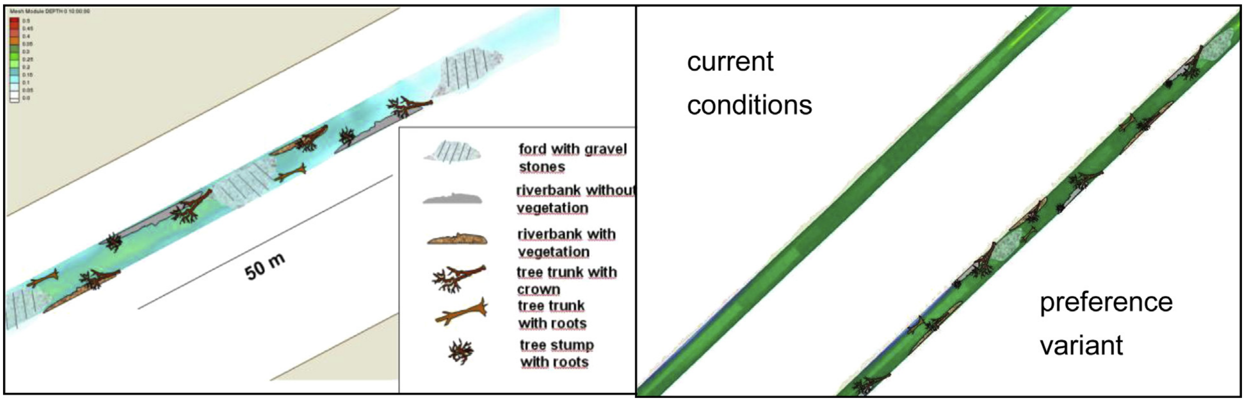

Fig. 7. Preference variant in Section 3; diverse structures (left); elevation of river bed (green = high; blue = deep) for current conditions and a preference variant (right).

- Fish habitat: Fish need pools and wooden refuges for shelter and resting; riffles provideshallow nursing areas for juveniles and suitable spawning gravel for lithophilic fish.
- Benthos habitats: Benthic species have most different demands related to flow forces, water depth, drift initiating currents, bottom substratum (e.g. sandbanks) and light availability.
- Macrophyte habitats: The macrophytes typical for the considered river type have an affinity to high velocities and shadowed areas.

We put a main focus on fish and benthos as there were for example restrictions constructing shadowed areas. Finally we have designed diverse structures consisting of spools cours (with several decimetres depth), riffles (with several decimetres height), dead wood and river banks shown in Fig. 7. The dead wood structures are also important for the morphology of the river bed as they enhance the development of natural pools. Fig. 7, right compares the current conditions with a preference variant in Section 3.

Most of the structures such as riffles, dead wood, river banks and pools are taken into account by geometric modifications of the grid, i.e. rising or lowering the river bed, as can be seen in Fig. 8, left and 9. In addition the friction has been increased as these structures are more rough compared to the river bed. Further the friction has been increased in areas with vegetation to take this effect at least qualitatively into account. In Fig. 8, right the positive effect of the structures on the flow field in Section 3 can be seen for the design flow of 0.900 m^3/s. The white areas are dry and the blue and green colors show the drifting current around the structures. Further the light blue color indicates low velocities and thus possible rest areas for fish in the pools.

Fig. 9 presents the distribution of the water depth for the design flow of 0.900 m^3/s. Again the white areas which represent the upper part of structures are dry (as they should be following the design suggestion) and the drifting current can be seen. We find shallow (light blue) and deep areas (dark blue), the latter being the pools and possible rest areas. The high resolution of the grid enables a very detailed and precise dimensioning of the height of emerged structures like the river banks, dead wood and riffles as well as of the depth of submerged structures like the pools. We would like to point out that the grid resolution is such fine that even big branches of

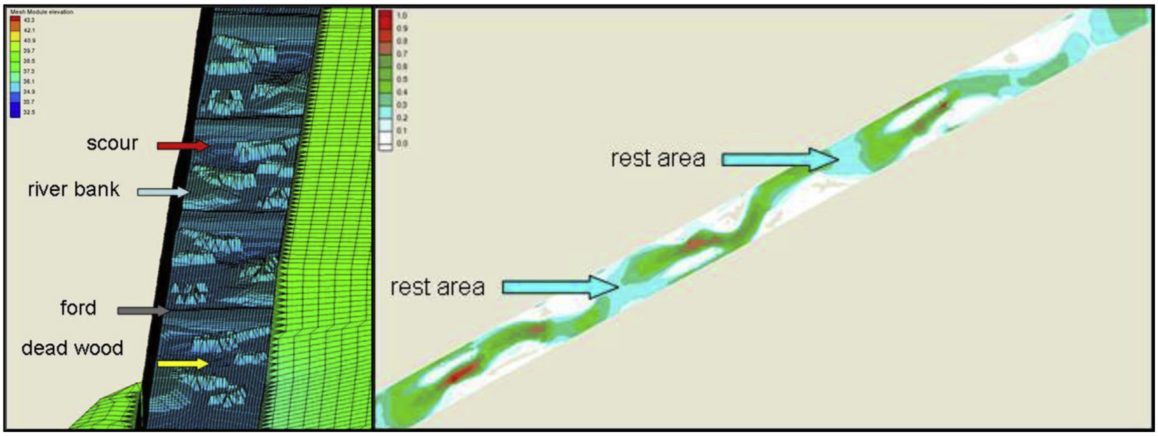

Fig. 8. Preference variant in Section 3; high resolution grid including geometric modifications for structures (elevation in [m]) (left); flow velocity for design flow of 0.9 m^3/s (flow velocity in [m/s]) (right).

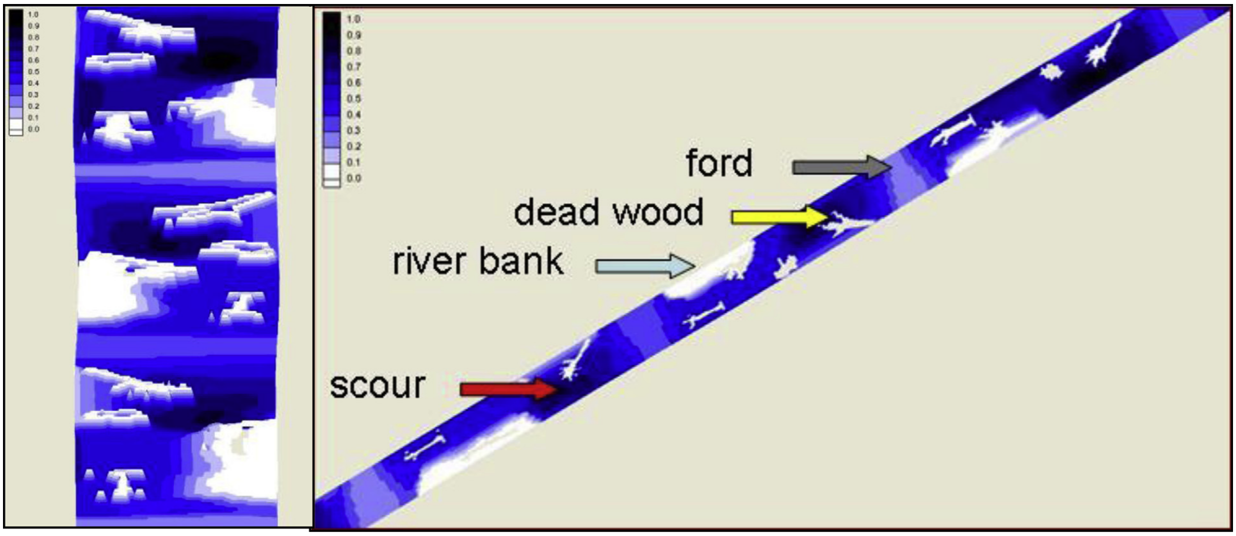

Fig. 9. Preference variant in section 3; water depth for design flow of 0.9 m^3/s (in [m]) (left); 3D view (left); top view (right).

dead wood are resolved. The preference variants locally have an impact on the flood water level and discharge, however they were placed in areas such that the flood protection was assured. As mentioned before, the high resolution hydraulic results (water level, velocity field, bed shear stress) are important input parameters for the habitat modeling.

The CASiMiR results of a preference variant including morphological enhancements are shown for the gudgeon in Fig. 10. Here it can clearly be seen that a marked improvement over the current conditions (see Fig. 3) for both the adult and juvenile gudgeon can be expected. The proposed morphological enhancements do not only change the local hydraulic characteristics of the investigation reach, but also provide new types of cover and a new substrate dynamic which further acts to reinforce the heterogeneity, effectively establishing new ecological niches. The habitat conditions improve significantly (see Figs. 3 and 10). For adult gudgeon spots with medium suitability are provided due to the increased water depth. The amount and quality of sites with good conditions increase with flow. For young fish the effects

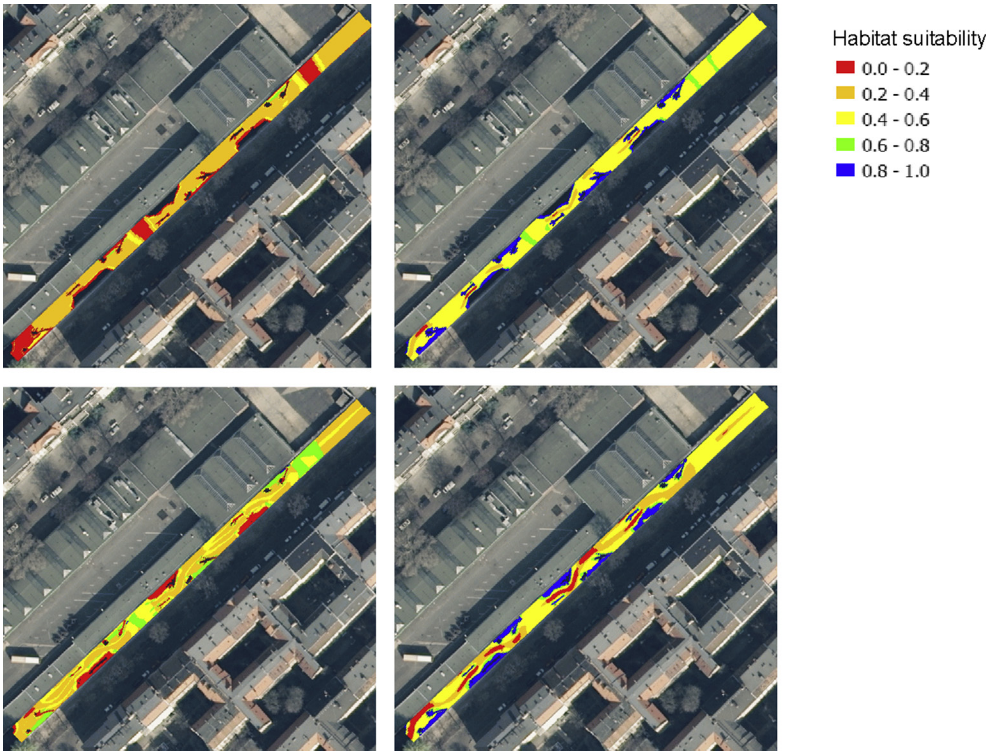

Fig. 10. Preference variant in section 3; CASiMiR habitat model results for the gudgeon (*Gobio gobio*) adult (left) and juvenile (right) after restoration in Section 3; the morphologically enhanced situation offers significantly improved habitat conditions for both life stages.

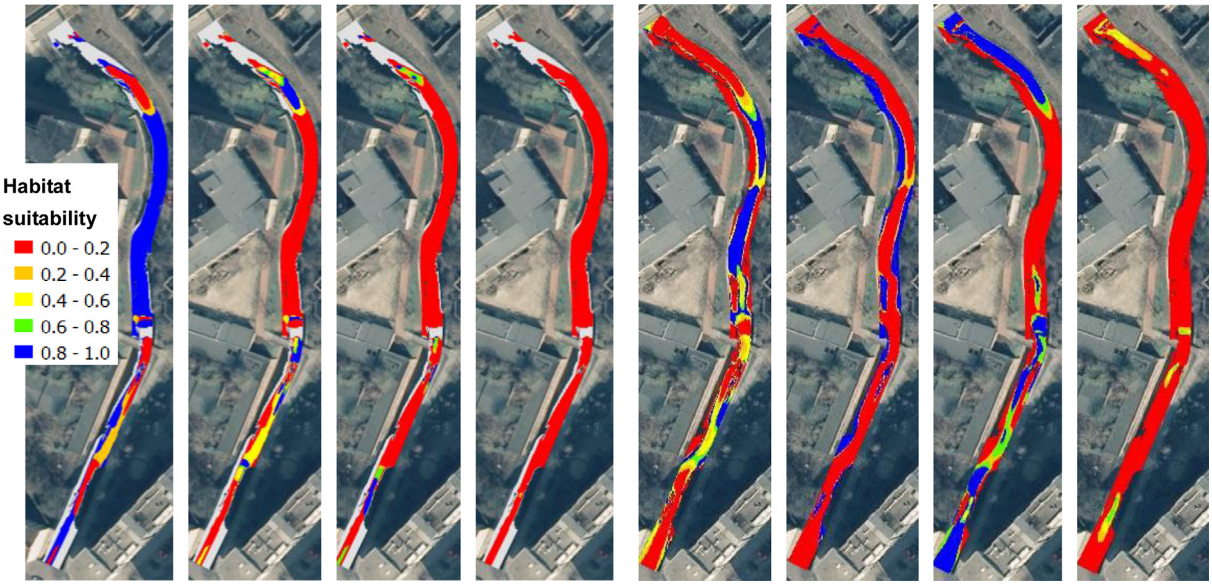

Fig. 11. Preference variant in section 4; habitat suitability for the benthos groups (left to right) “limnobiotic”, “limnophilic”, “rheophilic”, and “rheobiotic” for a discharge of 0.05 m^3/s (left) and 0.31 m^3/s (right) in Section 4, future situation.

are even stronger. A lot of optimum hydraulic habitats are present, particularly in the very shallow stillwater regions around the installed large dead wood. With increasing flow velocity they are still available (Fig. 3, bottom right) and assumably provide rest areas for young fish even during smaller flood events.

For the benthic groups habitat conditions in the future situation change significantly as well (see Fig. 11). Locations with high habitat suitability for limnobiotic and limnophilic species are much more frequent and can be found along the entire investigation reach. Areas with high suitability are reduced for rheophilic species but are still available in high portions during the higher flow 0.31 m^3/s, in small portions for the low flow 0.05 m^3/s as well. A reduction in very good habitat for higher flow situations is expected for rheobiotics, which under current conditions have a small, localized region of very good habitat but only for the 0.31 m^3/s. For the low flow rate 0.05 m^3/s hydraulic conditions are not suitable for this group, which thrive on very intense currents. However, for higher flows also in the new situation regions with middle to good habitats are expected to persist. It is also worth noting that these species are not expected to occur in high abundance, since regions with very high flow velocities are not characteristic of the Panke.

More importantly, it can be recognized that the future situation with improved morphology is expected to provide a broader range of habitat types, with considerable improvements anticipated for limnobiotic and limnophilic species and large portions of highly suitable areas for rheophilic species as well. The higher diversity of river bottom substratum and hydraulic conditions comes along with an overall higher biodiversity. It is particularly important that favourable conditions for these different benthos groups do not occur only in a limited flow spectrum, as in the current situation, but they can be found over a very wide discharge range. This means that even with changing flow conditions, good habitats are not completely displaced or disappear but remain usable.

The suitability distributions for the benthic groups in Fig. 12 indicate the significantly improved situation compared to the current status (see Fig. 6). This is expressed in a much less flow dependent class distribution. After mitigation three groups find a significant amount of highly suitable areas for all investigated flow rates and the reduction for higher flows is much less drastic. Only the rheobiotics find no habitats for low flow and only a small amount of good habitats for increased flows. However, this is not surprising since rheobiotics are expected with higher abundancies in the investigated river type.

3.3. Discussion

Developing the design for the structural improvement of the Panke took several iterations of modeling, expert-generated scenarios, and expert-based evaluations. This step wise model-based adaptive approach had several advantages. First, the modeling of water depth, flow velocity and bed shear stress for the current conditions of the Panke enabled the positioning of key structural elements such as pools, riffles and river banks at sites where the Panke showed already the tendency towards developing the respective element. Since the slope of the Panke was low and the bed fairly uniform, this tendency was not visible in the field. Hence, modeling firstly provided the base for the primary rule in restoration ‘work with the river’. Second, the design aimed at near natural interaction among key structures. Therefore size and relative orientation of the structural elements had to be adapted to the local hydraulic situation, e.g. the distance of pools and riffles and the relative orientation of river banks and pools in the cross section. This was done in a trial and error procedure shifting the position and changing the size of individual structures in the model,

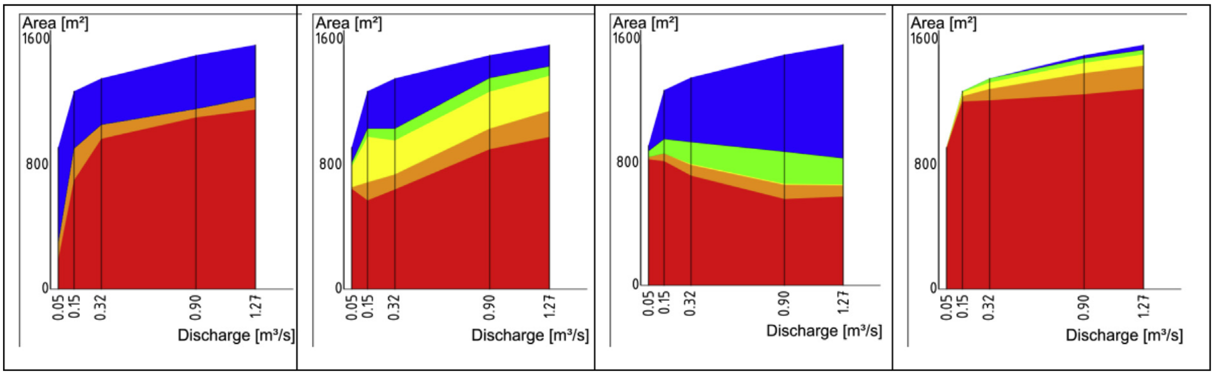

Fig. 12. Future conditions in the river Panke; distributions of the areas for different habitat classes as a function of the discharge for the benthos groups (left to right) “limnobiotic”, “limnophilic”, “rheophilic”, and “rheobiotic”, future situation.

e.g. the height of vegetated river banks. Third, the design aimed at increasing the habitats for target species among fish, benthos and aquatic macrophytes. This aim was accomplished in further iterations of modeling and expert evaluation that enabled fine tuning in the orientation and size of single structural elements. In this fine tuning process ecologists could compare the computed depth, velocity and shear stress at the stream bed with habitat requirements of the target species for these major environmental factors. By modifying the level of riffles and river banks and the size and orientation of large wood structures, the patches of best habitat suitability for single species were optimised. The overlay of the best habitat suitability for single species, finally enabled the partitioning of habitats among the different target species to achieve a balanced habitat availability for the entire community in the restored reaches.

In summary the modeling translated the ecologist's ideas in quantitative data at several levels of the process and by this enabled control and maximizing of target conditions. Since modeling was done for variable discharges, assumed bottlenecks for the target species at high and low flow could be avoided or reduced. The resulting restoration design hence has much more certainty than standard restoration designs that mimic natural references, which are mostly not appropriate for urban rivers with unalterable unnatural constraints.

The complex decisions rely on the accuracy of the hydraulic model. The high spatial resolution of the model matched the extent of meso- and microhabitats for fish and even benthic invertebrates. However, for complex secondary currents and patterns of local pools and fill, like the pools or dead wood structures, it remains unclear whether the near bed hydraulics as a crucial factor for benthic invertebrates was sufficiently approximated by the 2D model. Here further field measurements or high resolution 3D simulations are required.

Finally the assessment of the current status of the fish and benthic invertebrates' assemblages indicated highly degraded urban ecological conditions and no differences between rehabilitation and control sites. By that a main prerequisite for the success evaluation has been set up. In future work modeling of transport and water quality (e.g. combined sewer overflow, contaminants, heat) should be included into the model-based design process.

4. Conclusions

The model-based design applied here to a small urban river is an advancement in river restoration as it improves the design process, i.e. it enables a better prediction of impacts of engineering and ecological measures and it better enables a fine tuning or an optimization of measures when compared to classical procedures. The model-based design combines high resolution 2D hydraulic modeling with habitat modeling in close interaction with river-ecological expert knowledge being an overall highly iterative process. For the habitat modeling, habitat suitability maps have been developed for fish and the habitat suitability for benthos has been assessed by including the Perlodes methodology and FST hemisphere measurements.

We have applied the model-based design to develop preference variants which should be constructed in the Panke in 2015. We expect that the preference variants will improve the ecological conditions for fish and benthos.

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