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Monitoring and Modelling of Sediment and Habitat at the Alluvial Zone National Park of the Austrian Danube

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Abstract

Within the scope of a large restoration project at the Alluvial Zone National Park, extensive monitoring was performed over four years. Innovative bed load transport measurement methods were applied, including an adapted basket sampler and a new methodology for coded radio acoustic tracer stones. Numerous bed load transport measurements were conducted by lowering a heavy-load basket sampler along a cross section to the river bed over the entire discharge spectrum, thereby covering low flows as well as a 15-year flood event. Additionally simulations were performed using a newly developed integrated numerical sediment transport and morphology model called iSed, which was specifically designed to suit the needs of large gravel bed rivers. Moreover, a new conceptual mesohabitat evaluation model MEM was developed and applied, using a functional linkage of three parameters (velocity, depth and bottom shear stress) to distinguish six different mesohabitat types (riffle, fast run, run, pool, backwater and shallow water) based on 2-D depth-averaged and 3-D hydrodynamic numerical modelling.

As result of the multi-discipline activities, substantial progress was achieved in describing sediment transport patterns at a large gravel bed river, thus facilitating the evaluation of a restoration project within a protected area. The linkage to biotic research was strengthened by validating the habitat model considering river morphodynamics on various scales.

Keywords

bed load, advanced field measurements, tracer stones, sediment transport modelling, habitat modelling, Danube River

Introduction

Rivers are the lifelines of our landscape and as such often subject to conflicting demands. They are serving mankind for basic needs such as water and food supply, transport ways, natural borders and recreation. Ecology is increasingly important not only because of the Water Framework Directive, requiring good ecological status for European Rivers by 2015 but also because of a paradigm shift in society cherishing nature and its treasures. The Danube to the East of Vienna additionally is part of the Alluvial Zone National Park and therefore particularly deserving protection. Hence River restoration is an issue there – but with the prerequisite of extremely well elaborated measures, gentle human impact and a comprehensive monitoring to evaluate the changes. Innovative measures – as planned within the National Park - demand an even better process understanding and thus sampled data, as they are planned on the limit of technical feasibility. Especially a new method called granulometric bed improvement (allowance of larger gravel sizes within the natural grain size spectrum) which is tested at the Austrian Danube (Habersack et al. 2008) has to be subject to extensive monitoring.

Regarding the restoration project at the National Park, a comprehensive monitoring concept was elaborated, connecting the parameters of numerous abiotic and biotic subjects. The integrative monitoring is performed by several work groups of different Austrian Universities. Within this broad field of investigations, this paper concentrates on computer-aided river monitoring and modelling of sediment and habitat which forms an essential basis for understanding river-related processes and predicting effects and impacts of river engineering measures (Habersack et al. 2012). As especially regarding sediment transport the need for accurate and applicable systems is still high (Hassan et al. 2009), a number of new methods were elaborated to gain insights to the transport processes of the gravel. Knowledge of distribution and dynamics of bedload transport is crucial for the understanding and prediction of morphological changes (Rennie & Millar 2004).

Measurements with a specially adapted basked sampler form the basis for determining the yearly load, additionally radio acoustic, active tracer stones were used for determining transport paths and lengths. Based on the results of river monitoring, numerical models solving the fundamental equations of fluid motion can be properly calibrated and validated. The application of these models allows for the prediction of water depths, the flow field and other corresponding flow properties such as bed shear stress or patterns of turbulence (Habersack et al. 2008). Furthermore the models allow for an upscaling of spatially limited measurements to a broader scale.Habitat modelling tools are designed for an integrated interpretation of abiotic and biotic monitoring results concerning river restoration and therefore are the linkage of the two. The applied Habitat-Evaluation-Model (HEM) allows quantitative analyses on different scales (micro / meso) based on various measured and/or modelled parameters.

This contribution aims for describing the innovative monitoring and modelling methods used at the Alluvial Zone National Park and some interesting results.

Study reach

The Austrian Danube River is affected by several severe, conflicting processes and influences. Caused by the retention of bedload in the catchment (e.g. torrent control) and reservoirs of hydropower plants almost no bedload is entering the reach downstream of Vienna, leading to a deficit of bedload and consequently - in combination with prevented side erosion - to river bed degradation amounting to about 2.5 cm per year (DONAUCONSULT 2006; HABERSACK et al. 2008). Furthermore during low flow periods the constraint of minimum water depth for navigation is not met, especially in specific areas of fords. Additionally, the free flowing Danube downstream of Vienna is part of a National Park, which in the long term is endangered by the lowering of the groundwater table in the Aue area. Due to channelization and bank protection measures the former morphodynamics have been prohibited and entail ecological deficits. These problems led to arestoration project which intends to solve them by implementing a mix of measures including the allowance of larger gravel sizes within the natural grain size spectrum (granulometric bed improvement). It is planned to reduce sediment discharge to about 10% of the current amount by superimposing a layer of 25 cm width, but not to stop it entirely. It is expected for the added material to mix with the normal load subsequently (DONAUCONSULT 2006; HABERSACK et al. 2012). Furthermore seven huge sidearm systems will be reconnected and about 30% of the bank protection will be removed in order to improve the ecological situation.

Within a 3 km long test reach (river-km 1884.50 to 1887.50) near the municipality of Bad Deutsch Altenburg(Figure 1; flow direction is from left to right), the described measures are currently tested and monitored.

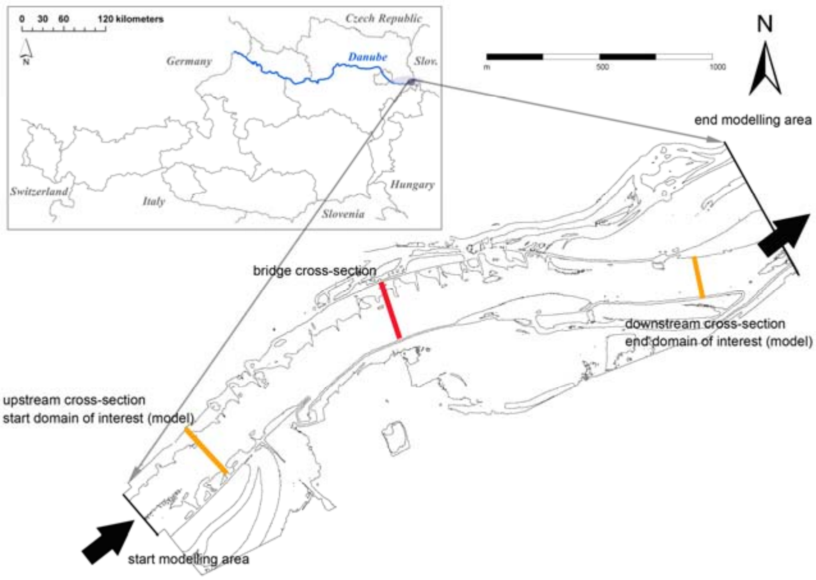

Figure 1: Map of the study reach near Bad Deutsch Altenburg; cross-sections with bedload transport measurements; upstream and downstream boundary of the model and of the domain of interest.

Regulated low flow (RNQ; 94% duration of exceedance) lies at 915 m^3s^{-1}, the annual mean flow (MQ) at 1930 m^3s^{-1}, bankfull discharge (1% duration of exceedance, approximately equal to a 1-year flood event) at 5060 m^3s^{-1} and a 15-years flood at 8000 m^3s^{-1}. The Danube east of Vienna is classified as gravel bed river with an average bed slope of about 0.0004. The average arithmetic mean sediment diameter is found at d_m = 27.5 mm. Other characteristic values are: d_{50} = 21.2 mm, d_{90} = 59.9 mm.

Methodology

<u>Tracer Stones</u>

For sediment transport characterisation, a new methodology of the tracer stone assembly had to be developed - in order to be applicable at a large river - and a tracer study was performed at the study reach (LIEDERMANN et al. in press). A total of 40 artificial tracer stones with three different sizes were used for the experiment characterised by the ratio of their axes: The three sizes represent the arithmetic mean diameter of the current bed material (b-axis = 27.5 mm; 20 stones), the lower limit of the projected granulometric bed material (b-axis = 40 mm; equivalent to the d_{75} of the current bed material; 10 stones) and the upper limit of the allowance material (b-axis: 70 mm; equivalent to the d_{95} of the current bed material; 10 stones). Due to the high water depths at the Danube reach (up to 10 m at mean flow conditions), formerly used systems of inserting the transmitters into either artificial or natural gravel particles (ERGENZINGER et al. 1989; HABERSACK 2001) could not be used (LIEDERMANN et al. in press). For the presented study transmitters with strong signals and a 0.5 m long antenna were used. In order to achieve maximum signal power the transmitter were worked into a two component epoxy-based mass. In the last layer the antenna was placed in several circles around the stone without any lead balls, and pressed into the mould of the model stone (Figure 2).

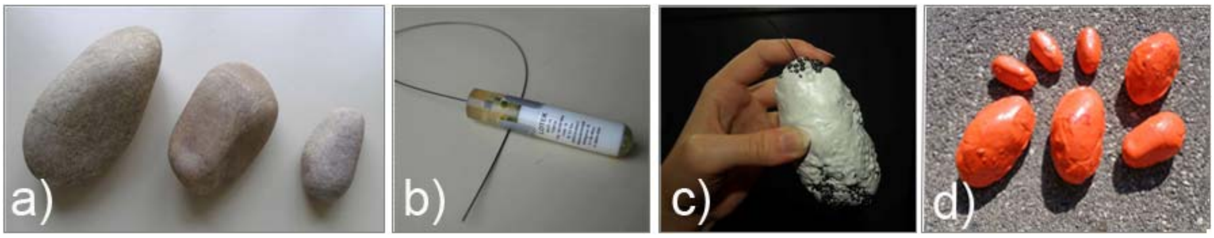

Figure 2: Tracer stone assembly; a) prototypes; b) transmitter produced by LOTEK-wireless ©; c) transmitter incorporated into resin material and lead balls before applying the external layer containing the antenna; d) finished tracer stones. (LIEDERMANN et al., in press)

The artificial tracer stones were dumped into the river, and their positions were determined individually approximately every week over an entire year, including a 15-year flood event, with a longitudinal and lateral position accuracy of about 10 to 15 m. Each particle transmits its own ID by using a unique code allowing for the different stones to be differentiated. Hence a total of over 1000 detections were performed leading to statistically significant results.

Basket Sampler

For the determination of the bedload transport a Basket Samplers was used. The high flow velocities and turbulences at the Danube River impede the utilisation of frequently used basket samplers. Thus a sampler developed by the BfG in Koblenz, was adapted to be applicable at the Danube. The sampler is characterised by a mesh size of 1 mm, an orifice size of 160 x 80 mm and a device weight of about 200 kg (Figure 3).

Figure 3: Adapted Basket sampler (based on the sampler of BfG, Koblenz, Germany).

Measurements were performed at three different cross-sections (all depicted in Figure 1) but mostly at the bridge cross-section, as thence it is possible to carry out measurements over the whole discharge spectrum. Over the last 5 years, a number of 37 measurements covering the entire discharge spectrum (between regulated low flow and a 15 years flood event) were performed.

In order to represent the spatial variability of bedload transport, for each measurement, 7-12 locations across the section were sampled. At each location, 3 consecutive single deployments of the sampler were performed to represent the temporal variability the transport. The transport over the cross section is calculated by integrating the medium loads for each location.

Sediment transport model iSed

Sediment transport patterns were also simulated using iSed, specifically designed to suit the needs of large gravel bed rivers (TRITTHART et al. 2011).The model was coupled with the river simulation model RSim-3D, a three-dimensional hydrodynamic model to obtain the flow field and bed shear stress patterns as a prerequisite for deriving sediment transport processes. The model is capable of independently calculating both suspended and bedload transport. A nonuniform formulation of the Meyer-Peter/Müller equation featuring a hiding-exposure correction was selected for the presented study. Resulting bed level differences are derived by solving the Exner equation for every node of the computation mesh based on the sediment balance. All equations are evaluated for an unlimited number of sediment size fractions, allowing for the consideration of sorting processes.

Calibration and validation of the model were conducted using separate data sets of velocity and turbulence measurements obtained from ADCP and ADV instrumentation, bed grain size distributions from over 100 samples, gauge hydrographs and officially published water surface elevations. Further details of the model validation results for the pilot reach at the Danube River east of Vienna are given in TRITTHART et al. (2009).

Habitat Model

Habitat modelling tools were used to allow an integrated interpretation of abiotic and biotic monitoring results concerning the success of river restoration measures. The newly designed Habitat-Evaluation-Model (HEM) was selected for quantitative analyses on different scales (micro / meso) based on various measured and/or modelled parameters. Within the HEM-framework the Microhabitat-Suitability-Model (MSM) was applied to evaluate instream habitats by multiplying suitability- or preference indices of single target (fish) species. The necessary database for deriving the microhabitatmodelling based on preference curves was delivered by a biotic work group (KECKEIS 2012). For the integrative evaluation microhabitat-maps for the Danube have been generated especially for those fish species and life stages (e.g. juvenile cyprinids).Moreover, related to thehigh number of fish species within the monitoring section (n=61) and the lack of data concerning habitat preferences (for various life stages of fish) the Danube habitats were additionally modelled on a meso-scale approach (hydro-morphological units). The used MEM module (Mesohabitat-Evaluation-Model) combines a more general biological model (e.g. fish guilds) with hydro-morphological classes (e.g. pools, backwaters) (HAUER et al. 2008) in order to evaluate the impact of morphodynamic processes and/or restoration measures on aquatic ecology (e.g. fish).

Results

Major progress was achieved regarding the process understanding of sediment transport at the Danube within the National Park. Position data obtained from the observation of the 40 tracer stones over one year was analysed and a set of essential results was found. The analysis of the data showed size selective transport of the pebbles – thus the smaller sizes were transported more often and farther than the larger sizes. Surprisingly the difference between the medium and the large sizes was not as large as expected. Also the differences between the small sizes and the other pebbles were not particularly large – especially at lower flow conditions. 18.7 % of the tracer stones characterised by the mean diameter of the current bed material were moved in average during discharges smaller than medium flow. The stones sized at the upper limit of the material that will be added in the future (b-axis: 70 mm) were moved at a transport probability of 6.3% for the same discharge range (Figure 4a).

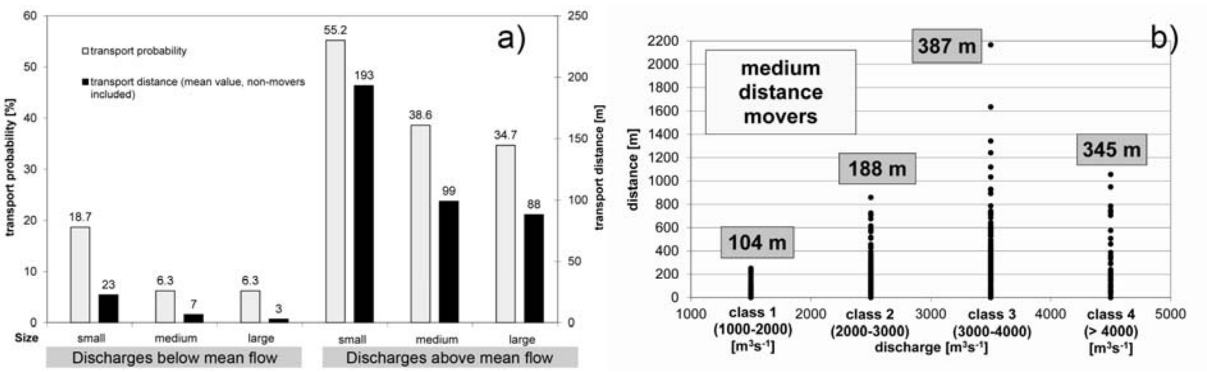

Figure 4: (a) transport probability and transport distance for the different sizes and discharges below medium flow (left) and above medium flow (right); (b) medium distance movers for 4 different discharge classes.

Additionally the mean transport velocity was calculated from the data. For the current bed material it was found to be 10.6 m per day, leading to a yearly transport length of about 3 km. When plotting the transport distance forfour different discharge classes (Figure 4b), it becomes apparent that travel distances increase with rising discharge but unexpectedly reach a maximum value at around bankfull discharge. This observation also goes along with the findings from the basket sampler measurements, but it is contrary to the calculated transport when applying commonly used uniform bedload transport formulae. Contradicting data was also found when looking at the incipient motion. Both tracer data and the results of the basket sampler measurements showed that relevant transport starts at discharges around regulated low flow (915 m^3s^{-1}), while uniform bedload transport formulae predict initiation of motion at around 3.000 m^3s^{-1} (LIEDERMANN et al. 2012).

Figure 5 depicts examples of the bedload transport rate plotted over the cross-section, and the calculated bedload transport for each measurement compared to the Danube discharge. The determination of a function describing the bedload transport – discharge relationship is a current research issue. When deriving a rough estimation from the gained data, the yearly load lies at around 320.000 m^3, which corresponds to the values gained by analyzing consecutive bathymetric data of the section (transported load by calculating height differences between consecutive years lies at 360.000 m^3) (TRITTHART et al. 2012b).

Bedload transport is strongly affected by the movement of gravel sheets, which were detected by bathymetry analysis. The medium distance between the dune crests lies at 10 m, the medium dune height is strongly dependent on Danube discharge history and varies between 5-7 cm (determined for March 2007) and 9-26 cm (determined for April 2006) (ACKERL 2010).

The hydrodynamic numerical model could also reproduce the movement of the gravel sheets. Sorting processes lead to a high variability in sediment transport influenced by the transport of the gravel sheets. The variability in sediment transport, the mean grain diameters and the gravel sheets are depicted in Figure 6.

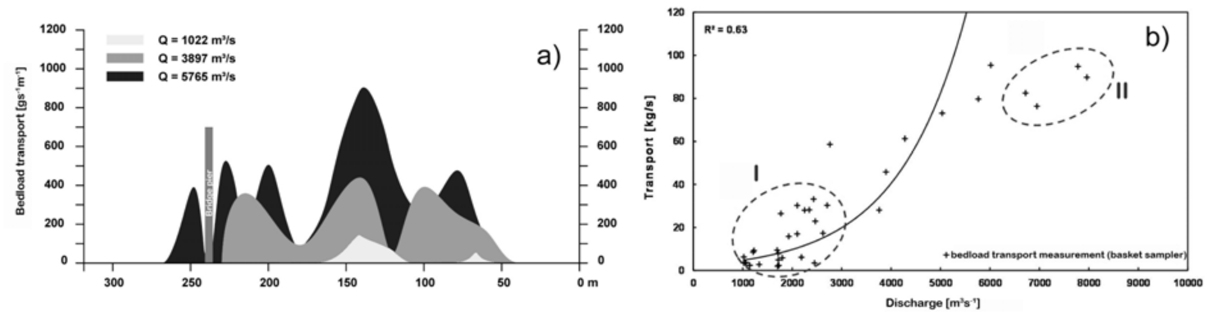

Figure 5: (a) Examples for bedload transport measurements and (b) sediment transport - discharge relationship showing (I) significant transport at low flows and the slower increase above bankfull discharge (II) (modified from LIEDERMANN et al. 2012).

A sensitivity analysis regarding the used time steps in the calculation, showed that gravel sheets occur no matter which parameter is chosen and therefore reflect a real phenomenon (TRITTHART et al. 2011). Also the suspended sediment transport and the bedload transport rates at different discharge stages were well reflected by the sediment transport model, which is remarkable as spatial and temporal bedload variability was until now rarely reflected by numerical models (TRITTHART et al. 2012a).

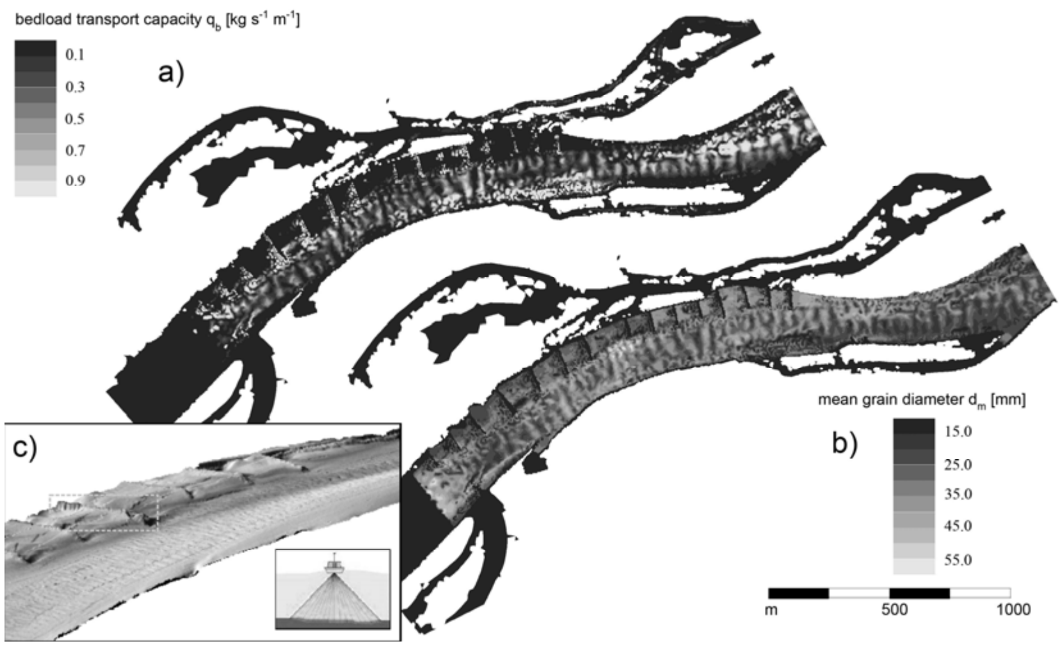

Figure 6: (a) modelled bedload transport capacity, (b) modelled mean grain diameter and (c)measured gravel sheets (modified from TRITTHART et al. 2012a).

Habitat modeling serves as a linkage between changing abiotic parameters and biotic effects and enables a quantification of a changing environment for target species (fish, invertebrates).The integrative habitat modelling analysis has been applied to evaluate changes in river bathymetry over the monitoring period. Hence, it was possible to quantify habitat shifts, which have been related to morphodynamic processes under high flow conditions. The results showed on both, the meso- and the microscale, that for characteristic discharges (e.g. mean annual low flow) those changes were only minor compared to the possible impacts on habitat distribution due to flow variation. Moreover, it was found, based on the habitat modelling on various scales that flow variation, its magnitude and the differences in each of the monitoring years is one of the trigger parameters for the Danube fish fauna. On the macro-scale, which is related to the morphological and hydrological features of the entire study reach, the connectivity to secondary channels is crucial for reproduction of many of the Danube fish species. The connectivity was given in spring 2006, however, in spring 2007 the lateral movement was not possible due to low discharges. Additionally the HEM-application allowed the modelling of the entire life circle of Danube target fish species (Figure 6), like the rheophilic cyprindis nase and barbel, in which fluctuations of flow have to be seen once more as crucial and possible bottleneck features.

The larvae and juvenile habitats, however, had to be modelled on the microscale, due to the fact, that shallow water habitats (mesoscale) at the Danube have been classified with water depths < 1 m and thus overestimating the depth sensitive zones of the functional larvae habitats. Moreover, the stability analysis of gravel spawning sites allowed a quantitative estimation, if there are possible impacts of high flows on the reproduction success of target fish species at the investigated Danube reach. Hence, for the presented case study it has to be stated, that microhabitat- and mesohabitatmodelling is complementary and important to evaluate instream habitat dynamics in the investigated large river system (HABERSACK et al. in press).

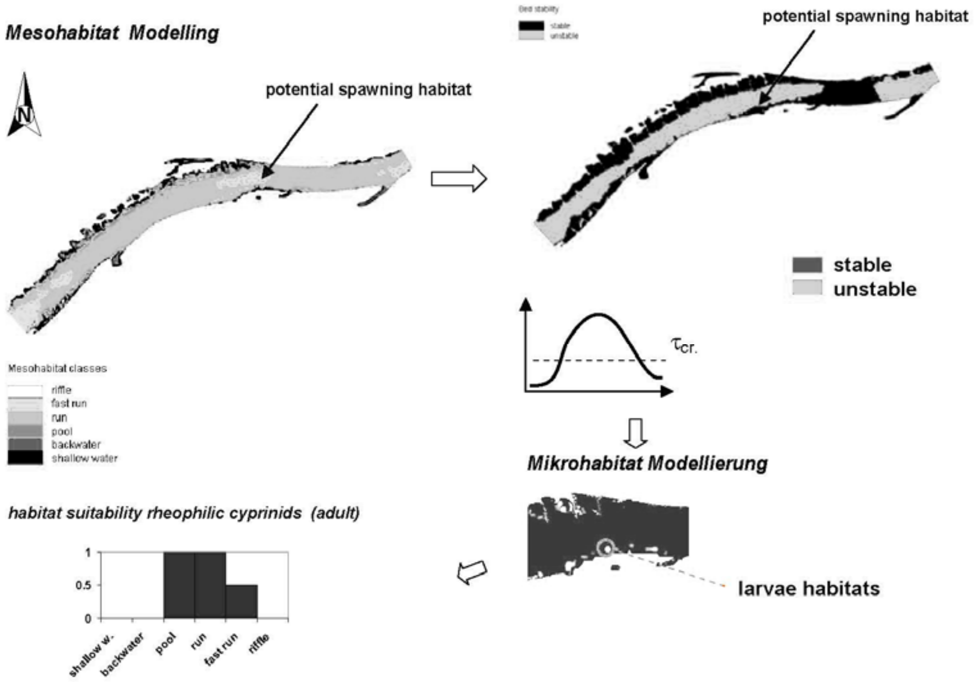

Figure 7: Analysis of the entire life circle of Danube target fish species based on HEM-Model application considering various river scales (meso- / micro-units) (HAUER et al. 2012).

Conclusions

In the study reach within the Alluvial Zone National Park at the Austrian Danube, major progress was achieved in the understanding of sediment transport behaviour due to innovative monitoring and modelling techniques. Applying different methodologies (tracer pebbles, basket sampler measurements, iSed) it was shown that incipient motion starts at low flow conditions, bedload transport increases less or even stays constant after reaching bankfull discharge and that gravel sheets significantly influence bedload transport at the Danube River. All these findings are unique and partly contrasting to previous believes rooted on uniform bedload transport formulae. Additionally, the tracer experiment showed a significant size-selective behaviour, but to a smaller extent than expected. The mean transport velocity for the current bed material was detected at 10 m per day. The 3D numerical models helped confirming the findings by providing hydraulic data such as bed shear stresses for all discharge stages and by extrapolating measured data to the entire reach. Using the MEM, a specific evaluation tool was adapted and improved which allows the assessment of river engineering measures in future, already before their implementation and to determine their potential impacts on the ecological conditions. For the presented analysis especially the variability in modelling different scales has to be seen as important issue in addressing the instream habitats of large rivers. Mesohabitat modelling has been identified as useful tool to identify possible spawning habitats (e.g. riffles) and/or addressing the suitable habitats of adult species.

The presented research answers – at least partly – relevant research questions of the National Park and helps optimizing and minimizing human impact in protected areas.

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