The application of hydrodynamic models as integrative tool between flood protection and ecological demands using a morphologically based evaluation method

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ABSTRACT:
On the basis of a case study at the Kamp River / Lower Austria the possibilities of an integrative evaluation of an ecologically oriented flood protection measure are discussed. Beside the hydrodynamic modelling of predefined flood events, low and mean discharge situations were simulated to evaluate the abiotic conditions for main fish species. The morphological developments of the flood protection measure were documented by terrestrical survey in 2003 and 2004. Furthermore it was possible to create a digital terrain model (DTM) of the former, natural river bed (1890) which was used as the "Leitbild" situation. With a geomorphologically based evaluation method the success of ecologically orientated flood protection measures was discussed according to the "Leitbild" situation using ecological and economical parameters.

1 INTRODUCTION

In August 2002 a catastrophic flood event occurred in Austria and in several countries of Central Europe (Habersack & Moser, 2003). Beside deaths the huge economic damage reflected in some cases the suboptimal management of our river systems. As a reaction to these catstrophic events some governments decided to build so called initial measures for flood protection. In Lower Austria river widenings have been chosen as the first step for an improved flood management. Additionally it was tried to reconstruct typical natural river patterns in these areas of cross section enlargement. A main project is performed at the Kamp River. Such an integrative river restoration aiming for improved better flood protection consisting the European Water Framework Directive (WFD) is only found in pilot protects so far. River widening for flood protection including river restoration was documented in the Netherlands (Baptist et al., 2004). More studies are dealing with river restoration. In Denmark two major projects on River restoration were performed. At the River Brede and the River Skjern the straight, regulated river bed was reconstructed with the former natural meandering character, better hydraulic interaction between the river and its meadows was introduced and former lakes, bogs, ponds and marshes were established (Neilsen, 2002). An example for a restoration protect from France is presented by Poudevigne et al., 2002, where at the River Seine the method of simplifiaction of river processes on certain units was tested. In this study the work was focused on two attributes of the ecosystem at different scales: community organisation and landscape organisation. Reach scale hydraulic assessment of instream restoration is presented by Lacey & Millar (2004). Other river restoration projects and their benefits to aquatic ecology are discussed in Rohde et al., 2004 and Kamp et al., 2004. A target setting for river restoration is presented in Pedroli et al. (2001). Their work concentrates on the concept of setting targets for river restoration as exemplified by the Meuse River. A modelling exercise shows the restraints of current habitat configuration and the potential for habiat restoration along the river. State of the art in relationships between form and processes in a river according to river restoration were discussed in Niezgoda & Johnson (2005) and standards for ecologically successful river restoration were defined by Palmer et al. (2005). The development of an ecohydraulic model for stream and river restoration was tested in a British River by Bockelmann et al. (2004). Further numerical modelling for river restoration processes was also included by Larsen & Greco (2002).

The aim of this paper is to discuss the effectiveness of an integrative method for analysing flood protection and the possibility of achieving a good ecological status (WFD) using a one dimensional cross sectional based model.

2 STUDY REACH

The study reach of this paper is situated in the northern part of Lower Austria. The origin of the Kamp River is near the village Karlstift (920 m.a.sl.). Its 160 km course discharges into the Danube River (182 m.a.sl.) at Altenwörth. The total catchment area is defined with 1.753 km² (Fig. 1).

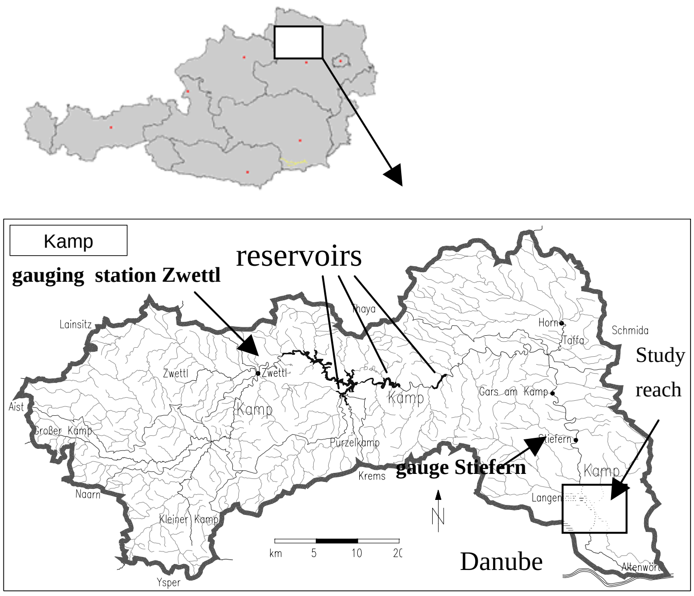


Figure 1. Catchment area of the Kamp River

In the recent past (1954 – 1957) three large hydropower plants were build. The reservoirs of Ottenstein, Dobra and Thurnberg influenced the sediment transport and the hydrological regime significantly. The whole part of the Kamp River from river station km 73+ 500 to the Danube river can be described as a residual flow zone with no bedload input from upstream and reduced input from tributaries since that time. The hydrologic characteristics of the catchment area are described in Table 1.

Table 1. Hydrological characteristics (Hydrologisches Jahrbuch, 1999)

Gauging station	NQ* $[m^3s^{-1}]$	MQ** $[m^3s^{-1}]$	HQ*** $[m^3s^{-1}]$	NQ:HQ
Neustift	0.04	0.87	18.5	1:462
Zwettl	0.21	5.88	140	1:677
Rosenburg	1.36	7.93	153	1:113
Stiefern	1.84	7.48	162	1:88

* NQ = low flow, ** MQ = mean flow, *** HQ = high flow

The area of riverbed widening for flood protection and for detailed analysis is found between the river station km 20.650 and km 21.700 with a length of 1.050 m. The average bed slope in this part of the Kamp River is defined with 0.0007 m m^{-1}.

3 METHODS

Based on terrestrical surveys, which were taken in the years 1890, 1900, 2002 and 2003, different Digital Terrain Models (DTM) could be constructed of the investigation area at the Kamp River. The historical geometry of 1890 was derived from a data set of 290 points which showed the main characteristics of the river section (riffles, pools, bankfull, etc..). Based on that information breaklines were constructed and based on the interpolation method of Kriging a DTM model with 450 points could be made. The geometry of the year 1900 was taken from a river regulation project. The data set provided cross sectional information every 50 m. The measurement of the river topography in 2002 was done before the riverbed widening (350 points), the geometry data of 2003 (320 points) is representing the situation immediately after the cross sectional enlargement. The data of the cross sectionally based surveys were transferred to a one dimensional hydrodynamic numerical model (HEC – RAS) for analysing different discharge scenarios. These scenarios were split into below bankfull analysis (1.4 m^3s^{-1}; 3 m^3s^{-1}; 5 m^3s^{-1}; 8 m^3s^{-1}; 12 m^3s^{-1}; 16 m^3s^{-1}; and 87 m^3s^{-1}) and into calculations of specific flood events (40 m^3s^{-1}, 50 m^3s^{-1}, 60 m^3s^{-1}, 70 m^3s^{-1}, HQ_1, HQ_5, HQ_{10}, HQ_{30}, HQ_{50}, HQ_{100}, HQ_{200}). Only the results of below bankfull analysis were taken for studies on ecological benefits. To link the hydraulic simulation results with suitability indices the method of Bovee (1986) was used. This method of multiplying suitability indices was first utilized in the PHABSIM model (Milhouse, 1989) and is shown in equation 1.

$$SI_{ges} = SI_d \cdot SI_v \cdot SI_{CI} \quad \text{or.} \quad SI_{ges} = \prod_{i=1}^{I} SI_i \tag{1}$$

where SI_d = Suitability Index depth, SI_v = Suitability Index velocity, SI_{Cl} = Suitability Index channel index, SI_{ges}= Suitability Index total, SI_i= Suitability index variable

For generating suitability curves of nase (*Chondrostoma nasus*) the results of the observations by snorkelling at the Pielach River were taken. From the surveyed fish (by snorkelling) Melcher (1999) developed the following suitability classes (Table 2).

Table 2. SI of nase (Melcher, 1999)

Suitability index [SI]	very high	high	low	no SI
Spa. depth [cm]	15 - 30	30 – 45	45 – 90	<15,>90
Spa. velocity [cm s^{-1}]	100 - 110	80 - 120	70 – 80 130 - 140	<70,>140
Spa. substrate	Microlithal	Mesolithal		
Juv. depth [cm]	0 – 30	30 – 60	60 – 120	>120
Juv. velocity [cm s^{-1}]	0 – 5	10 – 15	20 – 35	> 35
Juv. substrate	Pelal Microlithal	Mesolithal Macrolithal	Psammal Megalithal	

Ad. Table1: Pelal (< 0,063 cm), Psammal (0,063 – 0.2 cm), Akal (0,2 – 2 cm), Microlithal (2 – 6.3 cm), Mesolithal (6,3 – 20 cm), Macrolithal (20 – 40 cm), Megalithal > 40 cm

Spa. – Spawning / Juv. - Juvenile

For analysing the effects of riverbed widenings to flood protection, the calculated water surface levels of the year 2002 (before widening) and 2003 (after widening) were compared.

4 RESULTS

4.1 *Riverbed widening and flood protection*

The effects of the cross sectional enlargement of 2003 to the water surface levels are presented in Figure 2. It is obvious, that the lowering of the water levels is clearly found at discharges beneath bankfull (< 190 m^3s^{-1}). At discharges with recurrence intervalls > 10 years the positive effect for flood protection can be neglected (reduction < 0.1 m).

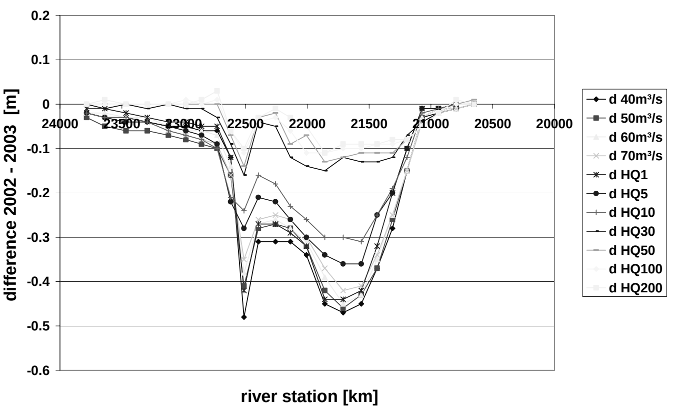


Figure 2. Effects of cross section enlargement on flood protection (d = discharge)

Beside the local effects of riverbed widenings, the influence of theses artificial measures is found additionally in upstream direction. The increase of the conveyance through the cross sectional enlargement is documented up to 300 m upstream for discharges around 50 m^3s^{-1}.

4.2 *Effects of restoration measures*

To evaluate the benefits of the restoration measures to aquatic ecology the method of habitat modelling was used. The abiotic data were combined with the preference function of nase, one of the main fish species (Tab. 2). The analysis was performed for below bankfull discharges. In Figure 3 (a), (c) the percentage of Weighted Useable Areas (WUAs) is documented for the historical natural "Leitbild situation" (1890), the regulated river bed of 1900, the geometry data of 2002 (before widening) and 2003 (after widening).

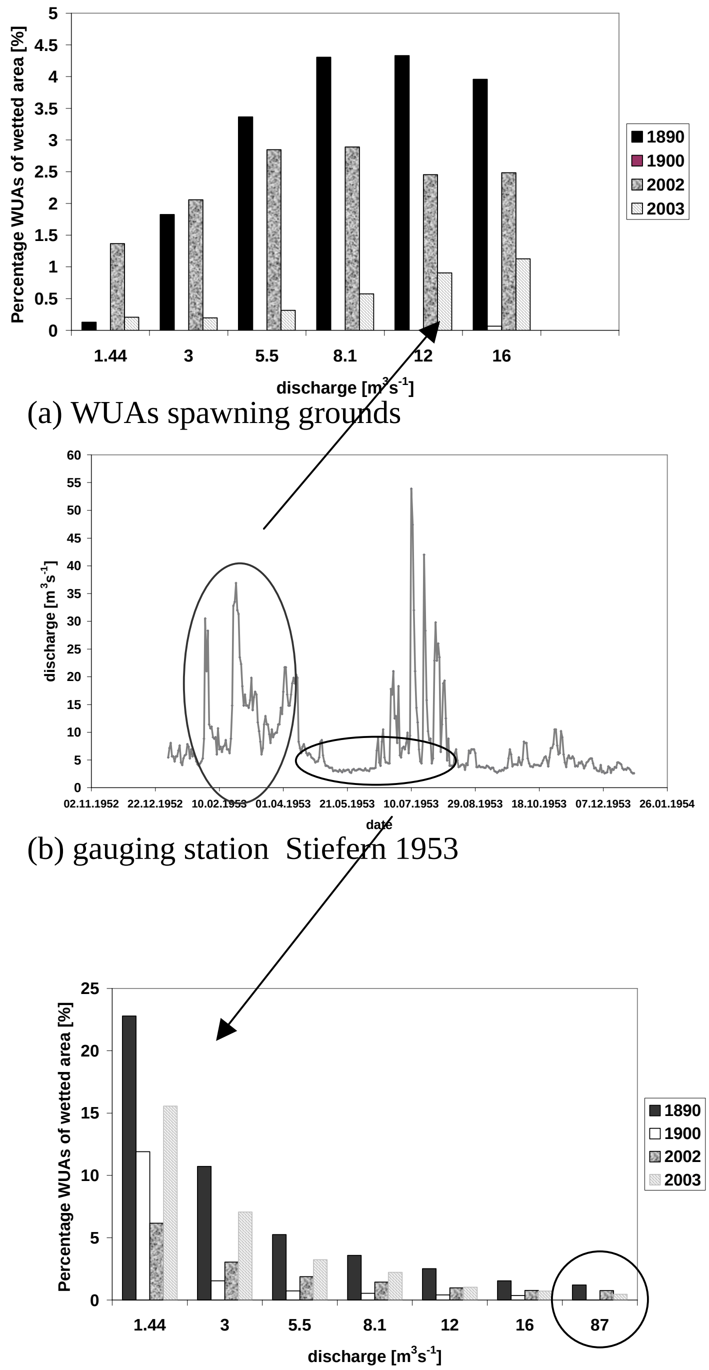


Figure 3. Development of fish habitat quality 1890 - 2003

It was found as an interresting result, that the modelling of the historical "Leitbild" situation showed a good correlation between the maximum percentage of useable areas and the hydrological regime (Fig. 3). Spawning of nase is highly correlated to a certain water temperature and is found in spring-time (Lelek & Penaz, 1963; Maier, 1993). In this period the average flow of the Kamp River is increased caused by the natural regime

(Mader et al. 1996). Frequently discharges around 15 m^3s^{-1} (Figure 3b) were documented. During the low flow season in summer with discharges < 3 m^3s^{-1} the channel geometry of the historical river morphology provided also the best habitats for the juvenile nases which are described in Table 2. In cases of small to mid-size flood events (87 m^3s^{-1}), which may happen in summer (Fig. 3b), the historical geometry provided additionally the best refugial habitats (Fig. 3.c). The regulation project of 1900 with its straight course caused a total reduction of riffles (Fig. 3a) which are well known as spawning habitats of nase (Stein, 1992; Keckeis, 1991; Maier et al. 1992). Also the juvenile habitats, defined as shallow water areas (Tab. 2), were reduced compared to the historical "Leitbild" situation. Following on, the construction of the three large power plants caused a massive change in the hydrologic characteristics. In Figure 4 the gauging stations of Zwettl (non influenced, Fig. 1) and Stiefern (influenced by power plants since 1954, Fig. 1) are compared.

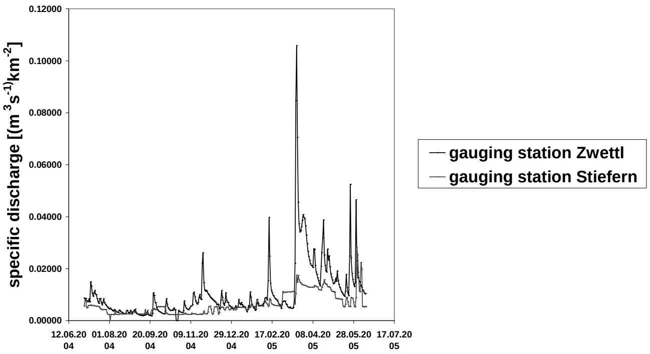


Figure 4. Specific discharge Zwettl / Stiefern (06.2004 – 06.2005)

Figure 4 shows the reduction of small and mid-size flood events by the hydrological management of the power plants. Therefore a cross sectional decrease of the originally regulated cross section of 1900 arose, from the loss of stream power, for almost 30%. As a result of this loss in dynamics, the bankfull discharge was reduced from 170 m^3s^{-1} to 145 m^3s^{-1}. During this 100-years of morphological development (50 years with an influenced regime) the habitats (spawning, juvenile) became a similar characteristic like in the historical "Leitbild" situation (Fig. 3a and Fig. 3c). Only the quantified usable areas were reduced.

The effects of the flood protection measures and the effects of the restoration features are presented in the modelling results of the year 2003 (Fig. 3a and Fig 3c). It is obvious that the habitat characteristics changed totally by the cross section enlargement. The spawning areas were drastically reduced and the shallow water areas, prefered by juveniles, increased.

4.3 *Evaluation method*

For evaluating the benefits of these measures to flood protection and aquatic ecology, according to the Water Frame Work Directive, a morphologically based evaluation method was tested. At the beginning it was necessary to define parameters for channel characterization. Depth- and width variance are often used for describing channel – habitat characteristics (Jungwirth et. al, 1984). In Figure 5 the depth and width variance are presented for mean flow (8.1 m^3s^{-1}).

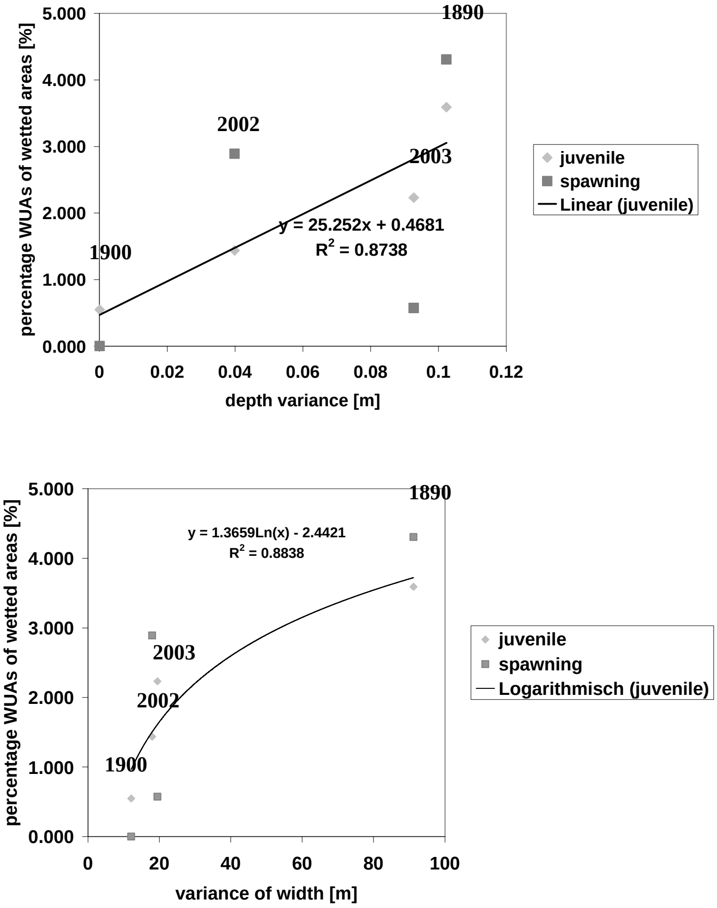


Figure 5. Depth and width variance / useable juvenile habitats

It is obvious that the variance of depth and width is correlating with the percentage of weighted useable areas (WUAs) of juveniles nases (Fig. 5). The modelled spawning grounds, based on the surveyed preferences, showed no response to these parameters. Therefore a new parameter derived from the 1-D modelling results had to be taken to characterize a linear relation between the increase of the 1-D variable and the percentage of the useable spawning areas. Various analysis were performed and finally the variance of bottom shear stress showed the best response to the occurrence of spawning grounds. These results are presented in Figure 6.

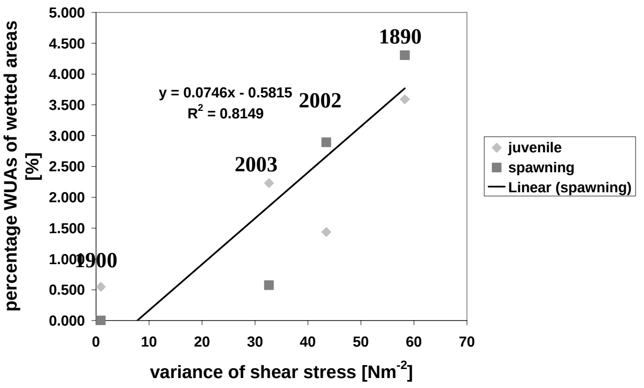


Figure 6. Bottom shear stress / useable spawning habitats

In Figure 7 the integrated evaluation of the measures at the Kamp River are shown. In x-direction the improvement to flood protection is shown. The increase of the bankfull discharge was taken as parameter to evaluate the success according to flood protection because, as it was proven in Figure 2, the events with a high recurrence interval (> 10 years) were only less influenced by the artificial riverbed widening.

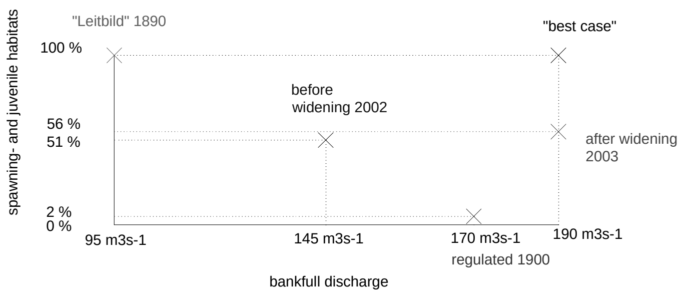
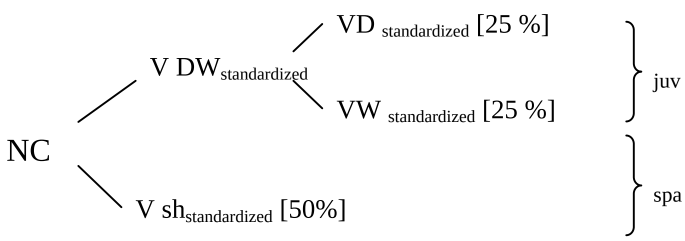


Figure 7. Integrated evaluation of geometric datas

In y – direction the percentage of natural habitat characteristics is presented. The values are describing the morphological conditions for spawning- and juvenile habitats based on the variance analysis of the 1 – D model (Fig. 5 – 7). Juvenile and spawning habitats were equally weighted. A splitting was further done for depth and width variance.



NC .. Natural Characteristics [%]; Vsh….variance shear stress [N m^{-2}]; VD…. variance depth [m]; VW….variance width [m];

For interpretating the evaluation method, two totally different points of Figure 7 can be mentioned. The “Leitbild” situation of 1890 is representing the non influenced morphological conditions with its natural characteristics (100 %). The opposite situation can be seen in the river regulation of 1900. The natural morphological characteristics was reduced to 2 % of the former river bed structure. During the 100 years development (50 years influenced by the hydropower plants) the river restructured itself by erosion and deposition of material (influenced since 1954 by power plants, Fig. 3). Therefore the 51 % of natural characteristics calculated for 2002 can be seen as the maximum possible heterogeneity under the consisting boundary conditions (reduced coarse sediment input and discharge regime). The artificial widening, with its restoration measures in 2003, caused an increase of the bankfull discharge up to 190 m^{3}s^{-1}. Furthermore the morphological situation changed. The analysis of variances of depth, width and shear stress (according to the correlation to certain habitat types) showed that 56 % of the natural geomorphologic habitats were found in these areas of artificial widening. But it can be mentioned, based on the knowledge of the River System (literature and modelling), the situation 2003 (190 m^{3}s^{-1}/ 56 %) is not sustainable. Caused by the reduced sediment transport capacity, effected by the Riverbed widening, aggradation of material is expected. This will lead to a shift of 2003 (190 m^{3}s^{-1}/ 56 %) towards the situation of 2002 (145 m^{3}s^{-1}/ 51 %). 2002 can be seen, as it was mentioned, as the best possible morphologic characteristics under the existing boundary conditions. A monitoring of the morphologic development has started to proof the assumption.

5 DISCUSSION

For some cases the problems of mid- to long term development of riverbed widening were documented (Habersack & Nachtnebel, 1995). Hauer et. al., (sub.) investigated the effects of riverbed aggradation to the habitat quality of the rheophilic cyprinid nase over a three year time period at the Sulm River. The results showed that fish react immediately to changes in morphological characteristics. Similar effects can be expected for the initial measures at the Kamp River. The problem of such artificial measures is that in these areas of artificial river bed widening the rivers are not “in regime” anymore. Therefore a regime analysis was done based on the work of Simond & Albertson, 1960. Their studies were taken because their regime equations were found comparable to rivers with less sediment transport like the Kamp River is. The results showed for the historic bankfull discharge (95 m^{3}s^{-1}) that a bankfull width of 41 m and a bankfull depth of 2.8 m are characterizing a river in regime. Compared to that, the results of the hydrodynamic modelling with the historical geometric data (1890) showed an average width of 48 m and a depth of 2.2 m. That means, there are differences in the singular parameters (width, depth) but the wetted areas [m^2] are quite similar. Therefore it can be mentioned, that the study reach was in regime before river regulation (1900). The regime calculations also emphasis the thesis that the riverbed widening of 2003 is not sustainable. Based on the geomorphologic characteristic and the aggradations of suspended sediments, which increased by the change of wood- to farmland in the catchment area beneath the reservoirs, the bankfull capacity will be reduced and will lead to a development of the measures towards the situation of 2002 (145 m^3s^{-1}/ 51%).

6 CONCLUSIONS

The results of this study demonstrate that it is possible to use a one dimensional model for an integrative analysis according to the demands of the European Water Framework Directive (WFD). It was shown that variables of the 1-D models (depth-, width- and shear stress variance) are well correlating with the occurrence of spawning- and juvenile fish habitats which were defined by preference analysis. Furthermore an evaluation method was tested, based on the one dimensional parameters, and showed a good response to river characteristics comparing flood analysis and fish habitat characteristics.

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