Evaluation of potential reproductive habitats of European Sturgeon in the Lower Rhine River in Germany

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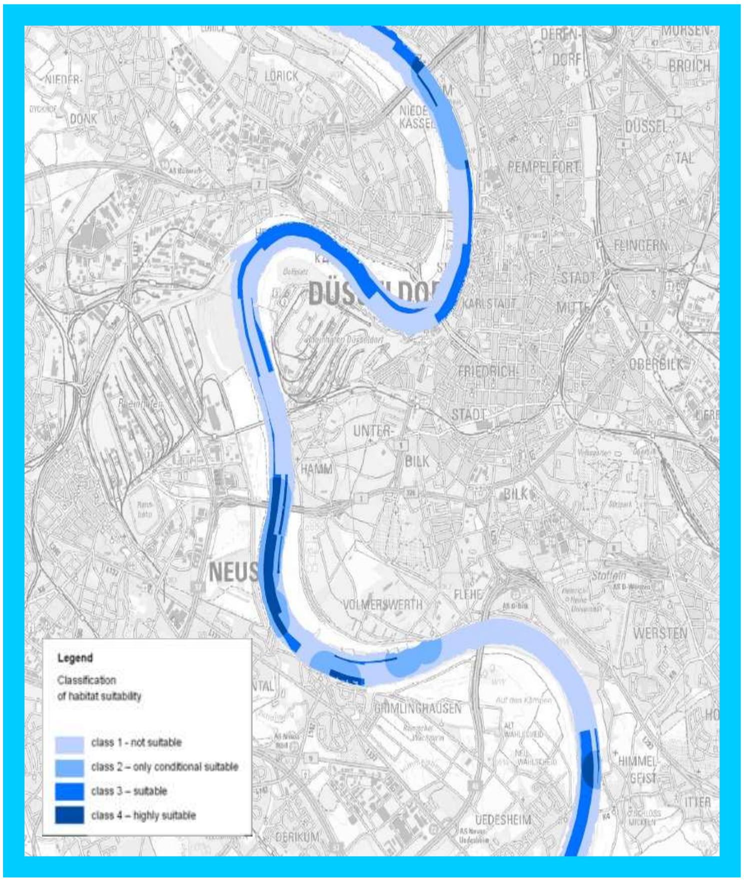
Literature study on key aspects of sturgeon reproductive habitats combined with GIS-based analyses of habitat availability



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Executive Summary

Subject Matter and Objective

The European sturgeon (*Acipenser sturio*) is a critically endangered fish species that is on the brink of extinction in the wild, with a last wild population in the Gironde River basin in France (Williott et al. 2010). The River Rhine with its numerous large tributaries historically housed a large population of sturgeon. During the first half of the 20th century it went locally extinct due overall habitat degradation and overfishing.

In 2012 the Stichting ARK, the World Wildlife Fund (WWF) as well as the Dutch Anglers Association started discussing a re-introduction of the European sturgeon in the Rhine basin. However, it is unknown whether quality and quantity of spawning habitats for European sturgeon are sufficient in the current state of the River Rhine. The objective of the current study was therefore to get a comprehensive overview of the suitability and availability of potential spawning habitat for European sturgeon in the German reach of the Lower River Rhine. This information is essential for further considerations regarding the eventual re-establishment of a self-sustaining population in the River Rhine.

Data Sources and Methods of Analysis

For the habitat evaluation, a GIS-based analysis of existing data sets (provided by waterway authorities and related institutions) on physical habitat parameters such as water depths, flow velocity and substrate composition, taking into account anthropogenic impacts on the river ecosystem (e.g. industrial navigation), was performed. The basis for the GIS-based analysis was formed by a digital terrain model (DTM) which provides absolute height data of the ground profiles in 1m^2-grids (e.g. the river bottom). Different waterway authorities provided a complete set of hydrological data on water depth and flow velocity, while data on substrate composition, based on granulometric analyses, were made available by the “Bundesanstalt für Gewässerkunde, Koblenz”. A section of approximately 220 km of the Northrhine-Westphalian Rhine stretch, including seven gauge stations, was examined in the study.

Habitat Characteristics of European Sturgeon

The unique feature in describing spawning habitats of sturgeon is the well documented preference of deep water in combination with rather strong flow velocities. This differentiates the sturgeon from most other abundant fish species in the River Rhine. The potential sturgeon spawning habitat can be described as a deep area of the river channel (depth > 2 m) with rather strong flow velocity (at least > 0.5 m, ideally > 1.0 m/s) and a substrate composition characterised by the absence of fine-grained fractions (silt, sand) as well as a dominance of large-grained fractions (resulting in mean diameters > 25 mm). Moreover, substantial amounts of larger pebbles and stones creating heterogeneity may be favourable.

In order to assess quality and quantity of currently available potential reproductive habitat for sturgeon in the River Rhine in accordance with the habitat suitability Index (HSI) method, water depth, flow velocity and substrate composition were identified as the most relevant factors to be examined in the present study. Moreover, water temperature and the threat of industrial navigation were taken into account. Due to their important role as spawning places and resting pools, the presence of deep potholes were recognized as a factor for upgrading the significance of potential spawning habitats in the surrounding area.

Key Findings

From a total main channel area of 73.36 km^2 of the Lower River Rhine within the borders of Northrhine-Westphalia, representing a reach of approximately 220 km length, a percentage of 89.97 % could be examined. The GIS-based analysis revealed that a main channel area of 21.84 km^2 (representing 33.09 %) can be qualified as “suitable” potential spawning habitat for sturgeon, while a total area of 44.16 km^2 (representing 33.09 %) was qualified as not or only conditionally suitable as potential spawning habitat for sturgeon. Taking into account the upgrading criterion “presence of deep river-bed potholes”, the GIS-based analysis revealed that out of the area already qualified as “suitable”, an area of 2.40 km^2 (representing 3.64 %) can be qualified as “highly suitable”. However, taking into consideration the industrial navigation channel, the surface area of potential habitats located outside of the designated navigation channel become reduced to 9.20 km^2 of ‘suitable’ (representing 13.9 %) and 0.91 km^2 of ‘highly suitable’ (representing 1.38 %) habitat respectively. This implies that considering the negative implications of intensive industrial navigation leads to a reduction of potential spawning habitat for European sturgeon in the Lower Rhine River by more than 50 %. The total area of potential spawning habitat partly represents the sum of numerous small areas, each of which may be too small to be perceived as spawning habitat by the fish. Therefore, the area of spawning habitat that will actually be used by the fish will probably be much lower than the calculated area. Therefore, a “plausibility check by hand” was conducted, resulting in a number of six river stretches representing concrete potential reproductive areas in the Lower Rhine River. Summing up, the application of the GIS-based analysis method to the lower Rhine River revealed that potential suitable spawning habitat of sturgeon make up roughly 1/3 of the lower River Rhine’s surface area in its current state.

Conclusions

The surface areas of potential spawning habitat classified as “highly suitable” (due to the vicinity of deep river potholes) is rather low (2.4 km^2, representing 3.6 % of the main channel area). Considering the potential importance of these resting pools for adult spawning sturgeon, focus should be placed on preservation of the remaining potholes. Another striking outcome of the present study is the observation that potential spawning habitats in the lower River Rhine are located in a river stretch characterised by intensive industrial navigation. This implies that 54 % of potential spawning habitat area is immediately subjected to the potential negative impacts of industrial shipping. Still, the negative implications of navigation will likely not cause a total loss in reproduction.

Limitations and Recommendations

The present study covers the aprox. 220 km stretch of the lower Rhine River in Northrhine-Westphalia, representing only a fraction of the area in the Rhine-system where reproduction of the former sturgeon population probably took place. Therefore, it seems worthwhile to expand the analysis to this reach of the River Rhine. The evaluation of potential reproductive habitat of European Sturgeon in the River Rhine should be continued and expanded to the more upstream reaches of the Middle and Upper Rhine (up to the dam at Iffezheim at Rhine-km 336) and possibly to more downstream parts of the Lower Rhine in the Netherlands.

Besides habitat requirements of spawning adult sturgeon and the successful development of eggs, the fulfilment of habitat requirements of hatched fry and young-of-the-year juveniles during their downstream migration to the estuary determine the species' reproductive success as well. Knowledge on the actual effects of vessel passages on spawned eggs and larvae of sturgeon on the river bottom as well as on the effects of navigation induced disturbances on the behaviour of adult spawners should be invested in to enable a realistic evaluation of the actual impairment of sturgeon reproduction by industrial navigation. River restoration measurements that will reduce or exclude the negative implications of industrial navigation (e.g. the establishment of side-channels), should be promoted and favoured.

1 Introduction

The European sturgeon (*Acipenser sturio*) is a critically endangered fish species that is on the brink of extinction in the wild, with a last wild population in the Gironde River basin in France (Williott et al. 2010). The River Rhine with its numerous large tributaries historically housed an important sturgeon population. It went locally extinct in the first half of the 20th century due overall habitat degradation and overfishing, like all other anadromous fish species in the Rhine. The last adult sturgeons in the German reach of the Lower Rhine River were caught in the 1940s.

Since the end of the 1980s numerous initiatives to improve the ecological quality of the River Rhine have been undertaken, which at that time was one of the most polluted rivers in Europe. Additionally habitat conditions were heavily deteriorated due to extensive channelization and embankments. Initially the improvement of water quality was focused on, followed by aspects of longitudinal connectivity at dams and aspects of structural habitat quality and floodplain restoration in more recent decades (with the latter being promoted especially by the European Water Framework Directive). These initiatives resulted in considerable improvements and in consequence an impressive recovering of the River Rhine's fish fauna could be observed. Stocks of some anadromous species recovered without human intervention (river lamprey, *Lampetra fluviatilis*, sea lamprey, *Petromyzon marinus,* sea trout, *Salmo trutta trutta*), others were successfully re-introduced (houting, *Coregonus oxyrhinchus*) or are subject of successfully ongoing re-introduction programmes (Atlantic salmon, *Salmo salar* and allis shad, *Alosa alosa*). The European sturgeon is the last (anadromous) fish species of the former natural fish fauna of the River Rhine that is still missing. A natural recolonisation with fish from the Gironde basin is highly unlikely and cannot be expected in the near future.

In 2012 the Stichting ARK, the World Wildlife Fund (WWF) and the Dutch Anglers Association started considerations regarding an eventual re-introduction of the European sturgeon in the Rhine basin. In this context a "Rhine sturgeon platform" was introduced and a desk study on habitat quality for the European sturgeon in the Dutch Rhine and southern North Sea was conducted (Winter et al. 2015). In this study the question was raised if sufficient habitat will be available in the River Rhine. This question had already arised in two former feasibility studies (Jacob 1996, Nemitz 2010), but was not comprehensively answered. Winter et al. (2015) emphasised that it is unknown whether quality and quantity of spawning habitats for European sturgeon are available in sufficient quality and quantity in the recent state of the River Rhine. It was recommended to assess suitability and availability of potential reproductive habitats for European sturgeon in the Rhine basin, since this information is essential for further considerations regarding the eventual re-establishment of a self-sustaining population in the River Rhine.

The objective of the current study was therefore to get a comprehensive overview of the suitability and availability of potential spawning habitat for European sturgeon in the German reach of the Lower River Rhine. It was aimed to conduct he habitat evaluation using the tool of a GIS-based analysis of already available environmental data on physical habitat characteristics and to develop the methods and procedures of data processing that enables the expansion of habitat evaluation to a larger investigation area which covers the historically documented distribution area of European sturgeon in the Rhine system.

2 General approach of the study

Since both location and physical characteristics of historical sturgeon reproductive habitats in the River Rhine are unknown, reproductive areas can only be identified as “potential” reproductive areas”. The identification has to be based on knowledge of the species’ habitat requirements derived from scientific literature on other sturgeon populations as well as comparable studies at different river systems. From existing literature (catch statistics) it can be derived that the main spawning areas of sturgeon in the Rhine-system had been located in the Lower River Rhine (Kinzelbach 1987).

Habitat evaluation of a large area, such as the former sturgeon distribution area in the River Rhine, cannot be conducted on the basis of actual mapping work. It is impossible to gather the required information through fieldwork with own measurements and mappings. Mapping becomes particularly problematic with regard to habitat characteristics like substrate composition in a river bed more than several meters deep or the current velocity in a navigation channel, whose assessment requires elaborate and expensive techniques and equipment.

Therefore, it was suggested to use the constructive approach of a comprehensive GIS-based analysis of already existing data sets (collected by scientific institutions or waterway authorities) on physical parameters that can be used to characterize sturgeon reproductive habitats. In consequence of the fact that the River Rhine is one of the most important shipping routes in Europe, intensive monitoring and measuring programs regarding riverbed characteristics, which are relevant for navigation purposes, are continuously conducted by the waterway authorities. Therefore it could be expected that a large quantity of data sets would be available which may also provide valuable information regarding habitat characteristics of the sturgeon. In preparation of the study, all institutions possibly relevant were contacted. It was investigated which kind of data would be available, what quantity and quality these data sets would have, if they could be provided for the project and if extra costs for fees would arise.

After confirmation that data on the most important factors characterizing physical habitat conditions, such as water depths, current velocity, substrate composition of the river bed and water temperature, would be available and would be provided for the project, it was decided to consistently follow the approach of a comprehensive GIS-based analysis of the available data sets.

3 Literature review on habitat requirements of European Sturgeon (and related species) during the reproductive phase

From a systematic review of scientific literature information on habitat requirements of adult European sturgeon (and related species) during the reproductive phase and subsequent habitat requirements of early life stages (eggs and fry) as well as age 0+ juveniles were compiled. Emphasis was placed on direct spawning observations and valid specifications of parameters describing actual spawning habitats. As mentioned above, the original sturgeon population inhabiting the River Rhine became extinct before any serious scientific work on its ecology was conducted. There is no literature available dealing with the natural reproduction of sturgeons from the former River Rhine’s population. Neither localisation of spawning grounds, nor information of habitat requirements have been documented. Some information can be extracted from Kinzelbach (1987), dealing with general distribution and catch statistics of sturgeons in the Rhine system.

Specifications of environmental parameters concerning the reproductive phase, obtained from existing literature, are listed in Tab. 3.1 – 3.3. Although scientific literature on valid specifications of habitat requirements during the reproductive phase is sparse, some specifications were deviating and had to be summarized to define a parameter setting for the GIS-based analysis (compare Tab. 4.71 – 4.7.4).

In determining the suitability of spawning habitats for European sturgeon, water depth, flow velocity and substrate composition were identified as the most relevant factors. These factors are also measurands in intensive examinations of riverbed characteristics by the waterway authorities. It could thus be expected that a satisfactory data base would be available for identifying potential spawning habitats.

The unique feature in the description of spawning habitats of sturgeon is the well documented preference of deep water in combination with rather strong flow velocities. This differentiates the sturgeon from most other abundant fish species in the River Rhine, which, in case of rheophilic species generally prefer shallow water in near bank regions and moderate flow velocities. Although according to Khoroshko & Vlasenko (1970) the species ide (*Leuciscus idus*) and asp (*Aspius aspius*), both very common in the River Rhine, utilize the same habitats for spawning as the sturgeon this is questionable or does not apply to the River Rhine (spawning habitats of asp has not been documented yet, eggs of ide have been found in shallow bank zones). Therefore, an approach of looking for abundant indicator species with similar spawning habitat requirements would not have been productive.

Table 3.1 Specifications of parameters describing <u>spawning habitat of the sturgeon</u> (European Sturgeon and related species)

Parameter	Spawning	Reference
Water depth	"Great" water depths	Ninua 1976
	> 2 m for spawning, > 2.5 m for potholes as resting habitat	Tautenhahn & Geßner 2014
	> 5 m	Jego et al. 2002
	1 - 12 m	Vlasenko 1974
Flow velocity	0.8 - 2 m/s	Ninua 1976
	0.5 - 1,5 m/s	Jego et al. 2002
	1.5 – 2.1 m/s	Kolman & Zarkua 2002
	0.4 - 2 m/s	Ninua 1976, Elie 1997
	Diversity of current patterns (meander structures), resting areas: deep potholes in the river bed, spawning areas: gravel banks with oxygen-rich and well-irrigated interstitial gravel spaces, morphology similar to pool-riffle-sequences, 0.6 - 2,2 m/s	Tautenhahn & Geßner 2014
Substrate	Coarse gravel	Ninua 1976
	Bedrock, boulders, coarse gravel	Holčik 1989
	Heterogeneous (Ø 3 - 250 mm)	Jego et al. 2002
	Rocky - gravelly	Sulak & Clugston 1999
	Rocky meanders	Zhang et al. 2009
	Coarse gravel > 3 cm or boulders 10-30 cm	Elie 1997
	Coarse gravel/cobble > 25 mm	Tautenhahn & Geßner 2014
Water temperature	17 - 20 °C	Ehrenbaum 1936
	17 - 22 °C	Geßner et al. 2010
	17 - 22 °C	Tautenhahn & Geßner 2014
	17 - 22 °C	Geßner & Schütz 2011
Threat of industrial navigation	Collisions with vessels and its propellers possible	Geßner et al. 2010
	Increased mortality due to navigation	Winter et al. 2015
	Spawning areas should be free of navigation, sufficient height of water column between river bed and ship's hull	Tautenhahn & Geßner 2014
Other comprises	Spawning may occur below dams and weirs	Jego et al. 2002
	No sedimentation on spawning grounds	Sulak & Clugston 1999
	Oxygen supply in interstitial gravel spaces > 5 mg/L	Geßner et al. 1999
	Spawning season in Gironde: May - June	Magnin 1962
	Former spawning season in River Rhine: probably June-July	Kinzelbach 1987
	Spawning ground in reaches with pool-riffle-sequence	Zhang et al. 2009
	Oxygen concentration 7.4 – 9.5 mg/L	Ninua 1976
	Suitable fry habitats located nearby downstream of spawning grounds are needed	Jakob 1996
	A surface area of 300 m² of spawning ground is needed for successful egg deposition per adult female	Jakob 1996

Table 3.2 Specifications on parameters describing <u>habitat for embryonic and larval development of the sturgeon</u> (European Sturgeon and related species)

Parameter	Embryos / larvae	Reference
Water depth	Largely unknown	Acolas et al. 2011
	> 2 m	Tautenhahn & Geßner 2014
Flow velocity	Largely unknown	Acolas et al. 2011
	Gravel banks with oxygen-rich and well-irrigated interstitial gravel spaces, 0.6 – 1.2 m/s (max. 2.2 m/s)	Ninua 1976
Substrate	Interstitial gravel spaces	Rosenthal et al.
	Eggs stick to stony substrate	Holčik et al. 1989
	Larvae colonise interstitial gravel spaces close to spawning grounds	Geßner et al. 2010
	Almost not known	Acolas et al. 2011
	Coarse gravel/cobble > 25 mm, clean, not overgrown (for larvae)	Tautenhahn & Geßner 2014
	Grain size t > 17 mm (for larvae)	Richmond & Kynard 1995

Table 3.2 (continued)Specifications on parameters describing habitat for embryonic and larval development of the sturgeon (European Sturgeon and related species)

Parameter	Embryos / larvae	Reference
Water temperature	17 - 20 °C	Rosenthal et al.
	17 - 20 °C (for eggs), 15 - 22 °C (for larvae)	Geßner & Schütz 2011
Food	Initially pelagic: plankton; later benthic: invertebrates (oligochaets, chironomids)	Magnin & Beaulieu 1963, Ehrenbaum 1894, Kinzelbach 1987, Holčik et al. 1989
	After absorption of yolk sac feeding on small zooplankton organisms, downstream drift to more productive river reaches	Geßner et al. 2010
	After 10 day shift to benthic behaviour	Smith et al. 1980, 1981
	Active food uptake 16 d after hatching	Kirschbaum & Williot 2011
Threat of industrial navigation	Spawning areas should be free of navigation	Tautenhahn & Geßner 2014
Other comprises	Sufficient exchange of interstital water is needed	Elie 1997, Jego et al. 2002
	No sedimentation	Elie 1997, Jego et al. 2002

Table 3.3 Specifications on parameters describing habitat of age 0 juveniles of the sturgeon (European Sturgeon and related species)

Parameter	AG 0 juveniles	Reference
Water depth	Largely unknown	Geßner et al. 2010, Acolas et al. 2011
	> 2 m	Tautenhahn & Geßner 2014
Flow velocity	Largely unknown	Geßner et al. 2010, Acolas et al. 2011
	Areas with reduced flow, insular areas, in deeper stretches: 0.1 – 0.6 m/s	Tautenhahn & Geßner 2014
Substrate	Preferably sand and gravel	Charles et al. 2009
	Largely unknown	Geßner et al. 2010, Acolas et al. 2011
	Sand and soft substrate	Acolas et al. 2011
	Sand and soft substrate (mud, silt)	Tautenhahn & Geßner 2014
Food	Oligochaets, insect larvae, chironomids, crustacaea	Ninua 1976, Magnin 1962, Acolas et al. 2009
Threat of industrial navigation	Increased mortality due to navigation	Winter et al. 2015
	Accidental drifting due to shearing forces	Engelhardt et al. 2004
	Height of water column between river bed and ship's hull should be at least 1 m	Tautenhahn & Geßner 2014

4 Material and methods of GIS-based analysis of reproductive habitat suitability

4.1 Selection of key factors describing physical habitat

Specifications regarding environmental parameters in reproductive phase that were obtained from the literature review (Tab. 3.1 - 3.3) are summarized in Tab. 4.1 to form the basis to define a parameter setting for the GIS-based analysis (compare Tab. 4.71 – 4.7.4).

As most relevant factors in determining the suitability of spawning habitats for European sturgeon the factors water depth, flow velocity and substrate composition can be identified. The unique feature in description of spawning habitat of sturgeon is the well documented preference of deep water in combination with rather strong flow velocities.

Table 4.1 Summary of specifications of parameters describing spawning and YOY habitat of the sturgeon (European sturgeon and related species)

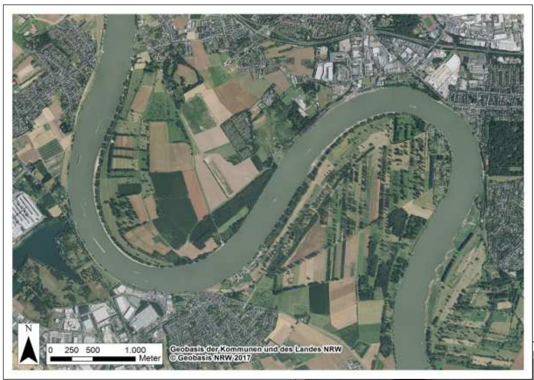
	Mature adults (spawning habitat)	YOY / Fry and juveniles	
		Embryos / larvae	Juveniles
Water depth	2 - 5 m	> 2 m	> 2 m
Flow velocity	0.5 – 2.2 m/s	Gravel banks, with interstitial sufficiently oxygenated and oxygenated flow through 0.6 – 1.2 m/s (max 2.2 m/s)	Lentic zones, at banks and islands, with deeper areas, 0.1 – 0.6 m/s
Substrate	Heterogeneous, > 25 mm, no fine-grained / soft substrate	Stones, pebbles, gravel > 25 mm (interstitial gravel space)	Sandy – muddy, soft substrate
Temperature	17 - 22 °C	15 - 22 °C	

4.2 Key factor "Water depths"

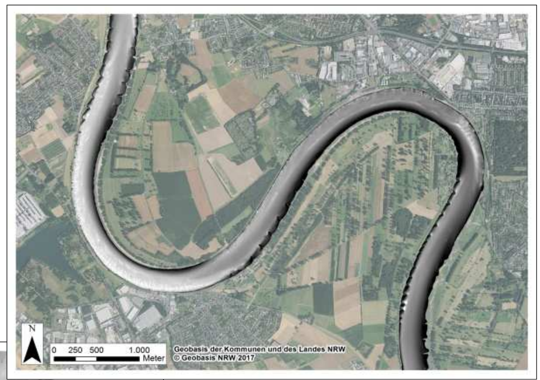
The information on water depths had to be derived from a combination of a digital terrain model (DTM) (providing absolute heights data of river bottom profiles) and computed hydrological data (providing information regarding the height of water column in a given area related to a specific gauge station) and a given time frame (the reproductive phase of the sturgeon).

4.2.1 Digital terrain model (DTM)

The basis for the GIS-based analysis was formed by a digital terrain model (DTM), which was provided by the waterway authority "Wasser- und Schifffahrtsamt Duisburg-Rhein". This model covers the surface of the River Rhine's riverbed and the adjacent floodplain area in bands of circa 300 m widths on each side. It provides absolute height data of the ground profiles in 1m^2-grids (e.g. the river bottom), which were obtained by a combination of satellite laser scanning and echo sounding (details regarding the DTM can be obtained from Prinz (2012)). The DTM was available for the stretch between Rhine-km 840 (at the city of Meckenheim) and Rhine-km 880 (at the city of Arnheim). It therefore covered the area of the River Rhine within the borders of Northrhine-Westphalia/Germany, ranging from (approximately) Rhine-km 639 (right side) / 642 (left side) – to Rhine-km 857 (right side) / 863 (left side). Due to the enormous size of the data set, computer processing required tremendous capacities. For this reason its size was reduced by cutting of the floodplain areas and limiting the surface area to the main channel (see Fig. 4.2.1).



a – aerial photograph



c – reduction of DTM to main channel and transfer of depths zoning to shades of grey

b – overlying DTM (for river bed and adjacent floodplain area)

Figure 4.2.1. Schematic representation of adopting the DTM and reduction to main channel area (exemplary for the stretch Rhine-km 712.0-719.0)

The visual shown in Fig. 4.2.1 represents a number of 3.2 million data points, the complete river stretch to be analyzed consists of approximately 60 million data points.

The DTM represents the data base with the highest spatial resolution (height values in a 1m^2-grid), to which all data regarding other habitat parameters were linked. It provided the basis for the area calculations and graphical visualizations in the analysis of potential reproductive habitat for the sturgeon.

4.2.2 Hydrological data

A complete set of hydrological data was provided by the waterway authority "Wasser- und Schifffahrtsamt Duisburg-Rhein". The data set comprised a 100-year time series of water level data for each of the seven gauge stations located in the Northrhine-Westphalian Rhine stretch (for details of gauge stations see Tab. 4.2.1). As the first step of processing the data, missing values were reconstructed and corrections were made for changes of gauge station zero point values within the considered time span. Secondly, the (daily) mean water level and its standard deviation were calculated from the 100-year time series in order to obtain a long term characteristic yearly water level curve for each gauge station. Based on these curves, a specific mean water level value for the selected time period 'beginning of May to end of July', supposed to cover the reproductive season of the sturgeon in the Rhine River (for explanation see chapter 5.3.1), was calculated. As a next step of data treatment, all water level values were converted to absolute height values to make the data compatible with the digital terrain model.

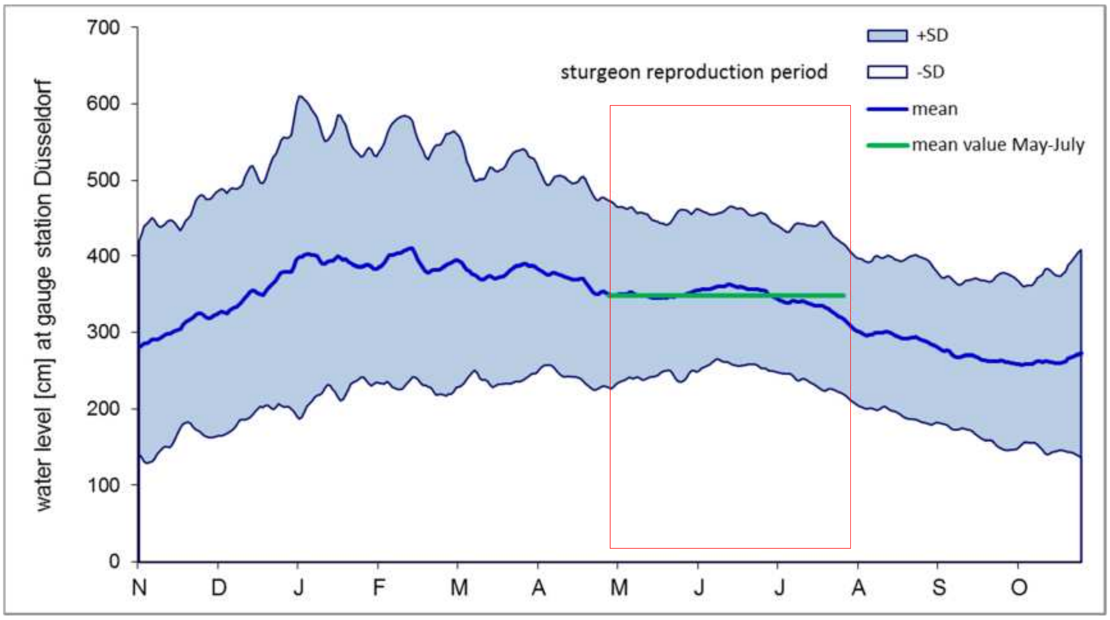


Figure 4.2.2. Result of hydrological data analysis: Long-term (100-year) mean water level (± standard deviation) trend line in hydrological year (Nov. 1st – October, 31th), the red frame indicates the assumed sturgeon reproduction period with the green line indicating the calculated mean water level for that period used to determine water depths from the DTM, example of gauge station Düsseldorf

4.2.3 Data combination

In the final step of data processing, the calculated values for the "typical water level situation" within the sturgeon reproductive period (for each gauge station) were added to the digital terrain model in the GIS. That data combination resulted in the sought after comprehensive water depth information (in 1 m^2-grid resolution). Because water level data correspond to a specific gauge station, the combination of the DTM with water level data required the definition of a "sphere of influence" for each gauge station. In order to solve this problem, height data assigned to grid points between two gauge stations were obtained by linear interpolation. Due to the lack of a second reference gauge station, this procedure had the effect that the river stretches below the most downstream gauge station (Emmerich at Rhine-km 852.2) and above the most upstream gauge station (Bonn at Rhine-km 654.8) were excluded from the analyses automatically.

4.2.4 Gauge stations

Within the approximately 220 km long section of the Northrhine-Westphalian Rhine stretch, seven gauge stations are located. Tab. 4.2.1 portrays the relevant information of all gauge stations considered in the analysis.

Table 4.2.1 Overview of the gauge stations at the Upper, Middle and Lower Rhine region and their characteristics, the analysis in this report is restricted to the Lower Rhine's gauge station from Bonn to Emmerich

City	Rhine-km	Height [m] above sealevel	Calculated mean water level in reproductive period (May, 1st - July, 31th)	Reach	Distance [km]	Heigth difference [m]	Slope [%]
Plittersdorf	320.2	106.76					
Maxau	362.3	97.79		Plittersdorf - Maxau	42.1	8.970	0.02
Speyer	400.6	88.52		Maxau - Speyer	38.3	9.270	0.02
Mannheim	424.9	85.16		Speyer - Mannheim	24.3	3.360	0.01
Worms	443.4	84.16		Mannheim - Worms	18.5	1.000	0.01
Mainz	498.3	78.43		Worms - Mainz	54.9	5.730	0.01
Bingen	528.4	76.18		Mainz - Bingen	30.1	2.250	0.01
Kaub	546.2	67.66		Bingen - Kaub	17.8	8.520	0.05
Andernach	613.8	51.47		Kaub - Andernach	67.6	16.190	0.02
Bonn	654.8	42.66	46.02	Andernach - Bonn	41	8.810	0.02
Köln	688	34.97	38.42	Bonn - Köln	33.2	7.690	0.02
Düsseldorf	744.2	24.48	27.96	Köln - Düsseldorf	56.2	10.490	0.02
Ruhrort	780.8	16.09	20.86	Düsseldorf - Ruhrort	36.6	8.390	0.02
Wesel	814	11.22	15.57	Ruhrort - Wesel	33.2	4.870	0.01
Rees	837.4	8.73	13.12	Wesel Rees	23.4	2.490	0.01
Emmerich	852	8.03	11.63	Rees - Emmerich	14.6	0.700	0.00

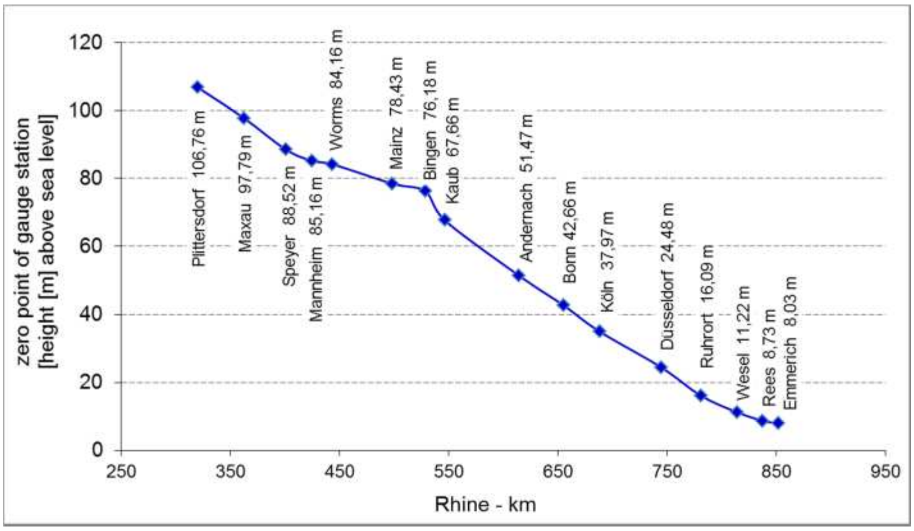


Figure 4.2.3. *Overview of the location and heights above sea level of the gauge stations, gauge station considered in the analysis are situated in the Lower Rhine River downstream of Andernach (gauge stations from Bonn to Emmerich)*

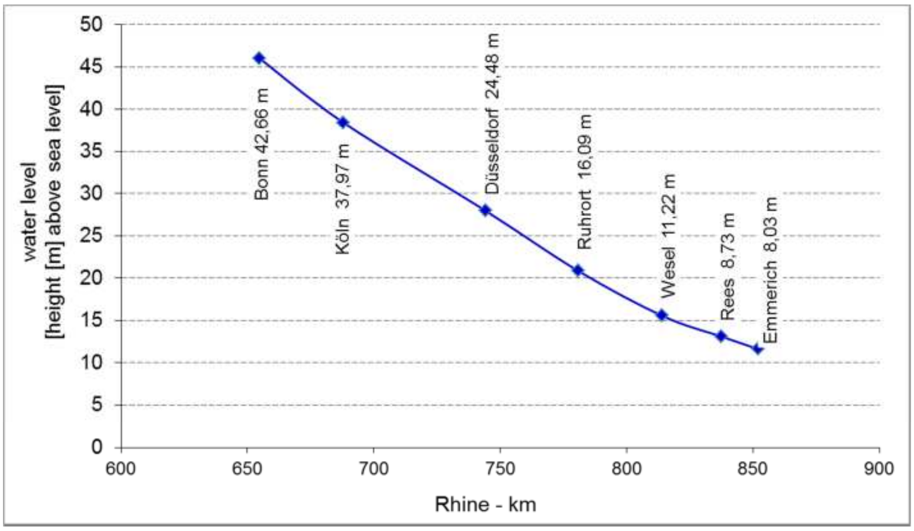


Figure 4.2.4. *Calculated long-term mean water levels (in meter above sea level) in assumed sturgeon reproductive period (May, 1st – July, 31th) at the different gauge stations in the Northrhine-Westphalian stretch of the River Rhine (explanation see Chap. 4.2.2.)*

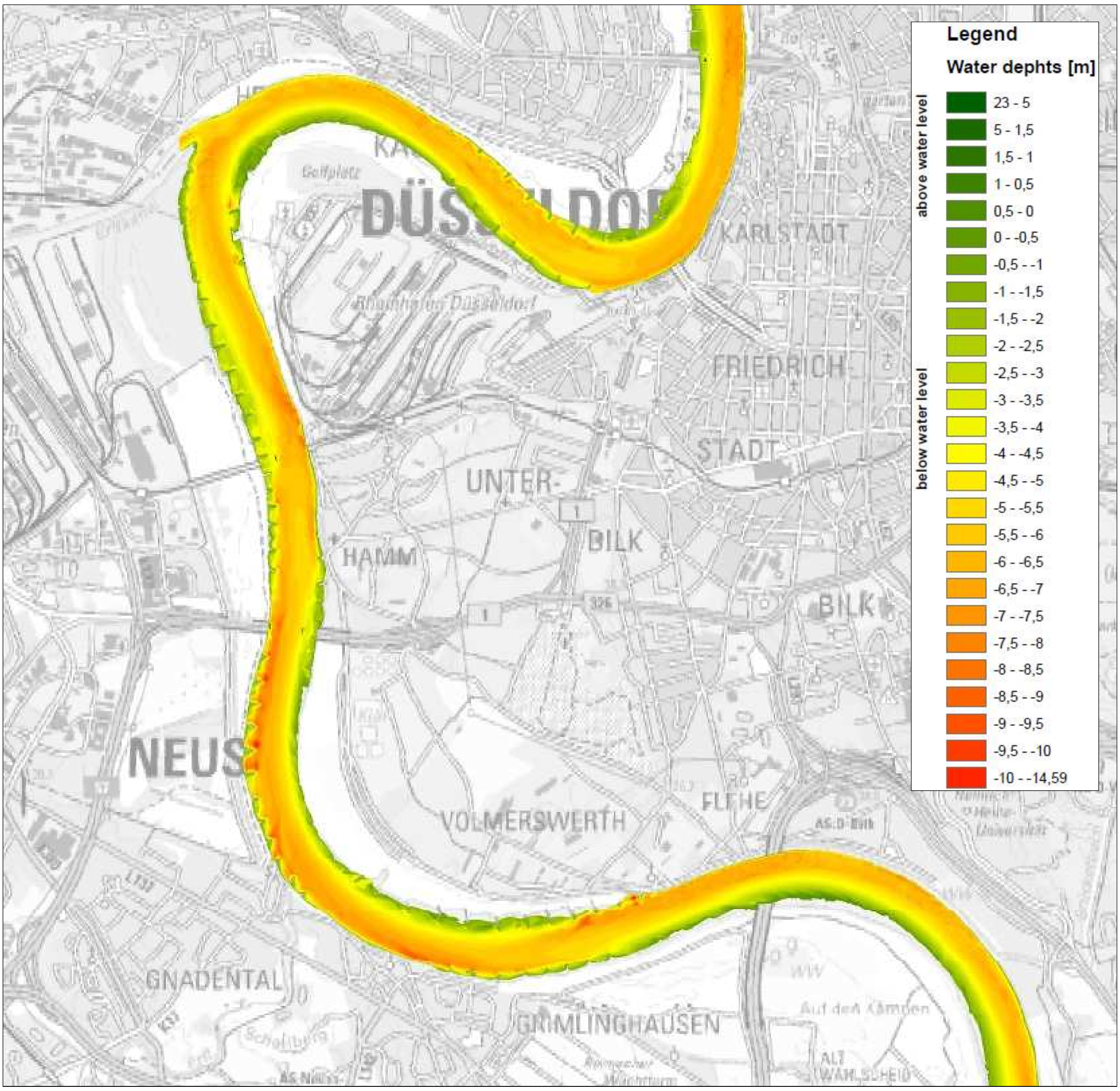


Figure 4.2.5 *Exemplary visualisation of depth maps resulting from the combination of DTM and hydrological analysis showing water depth in long-term mean water level situation in the sturgeon reproductive period (May, 1st – July, 31th). Example demonstrates high resolution of depth mapping, revealing even the small-area deep potholes in the riverbed*

4.2.5 Deep river bed potholes as a factor for upgrading the significance of reproductive habitats

Several authors mention the observation that during the reproductive season, adult sturgeons were caught particularly often in very deep potholes in the river bed. Occasionally, it was assumed that spawning places were located there. Although it is not clear if actual spawning took place in these potholes, at least an important role as resting pools (where adult sturgeons gather or rest during the spawning season) can be attributed to the potholes in the river bed for certain. Therefore, the presence of deep potholes can be recognized as a factor for upgrading the significance of potential spawning habitats in the surrounding area.

Because it proved to be very complicated to program an automatic procedure to identify the relevant potholes (depending on location, size and depth) and the upgrading of potential spawning areas in relation to a specific pothole proved to be challenging, the identification was conducted "by hand", scanning the depth maps and marking the potholes assumed to be relevant (> 8 m depth and localized outside of the navigation channel). The indication of potholes and deep areas was consequently transferred into the GIS. Fig. 4.2.5 provides an example of how the marking of potholes assumed to be relevant was conducted and in which way the information was transferred to the GIS. The upgrade criteria was defined as follows: every potential reproductive habitat in the vicinity of the pothole, which is defined within a range of 200 m around the pothole, that has received the significance of "1" in the analysis, was formally upgraded as "1*". In case the surrounding area was not qualified as potential reproductive habitat (significance "0" or "0.5"), no calculative upgrading was conducted (compare Chapter 4.7).

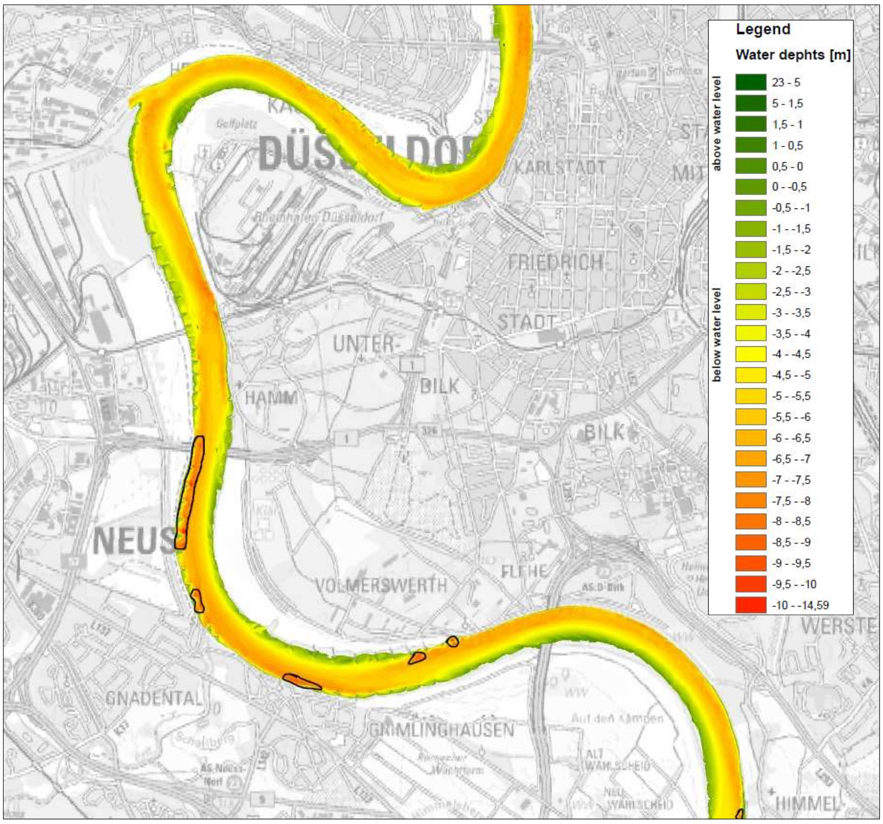


Figure 4.2.6 *Same exemplary visualisation of depth maps as Figure 4.2.5, with exemplary indication of deep potholes in the riverbed, that were thought to be relevant as sturgeon "resting pools". This information was transferred into the GIS as an upgrade criterium for the significance of potential reproductive habitat*

4.3 Key factor “Flow velocity”

The waterway authorities were asked to provide all kind of flow velocity data available. In the course of data acquisition it became apparent that velocity data would be very sparse with regard to large scale spatial distribution of measurement localities along the River Rhine. However, their quality with regard to small scale spatial distribution of measurement points in the river cross section appeared to be excellent.

The data set provided by the “Wasser- und Schifffahrtsamt Duisburg-Rhein” consisted of measurement results aquired with the ADCP-technique (Acoustic Doppler Current Profiler) at specific sampling sites. This kind of measurement results in in a two-dimensional profile of flow velocity values in a river cross-section. For each sampling location and date, results are given as a superimposition of up to five replicate measurements. It has to be considered that measurements are conducted from a vessel. Therefore, the very shallow bank zones, which are not accessible to the vessel, are excluded automatically. In a graphical visualisation, flow velocity values are given as mean values for a rectangle within the cross-section (see Fig. 4.3.1). The size of these rectangles can be adjusted in the data output options of the system. The delivered data matrices were processed in order to obtain homogenous data sets with a 0.25 m-grid in vertical direction and a 1.0 m-grid in horizontal direction (resulting in more than 350 columns of values per cross section). Moreover, processing was necessary to locate the depths layers of measurements and the bottom line in terms of height values, since this information is recorded in the system in terms of meters below surface.

Because flow velocity close to the river bottom is supposed to be decisive for describing spawning habitat conditions, the analysis was focussed on flow velocities in depths layers near the river bottom. Due to technical restraints of the ADCP-technique, flow velocities cannot be measured close to the ground. Hence, flow velocities in near ground layers are calculated based on measured values in the water column above. For the intended analysis it was essential to obtain flow velocities in the near ground layers.

Because the information on flow velocities had to be transferred into the GIS, it was furthermore essential to obtain information on the exact localisation of measurement points (columns) in the cross section of the river. Unfortunately, in standard output files of the system, coordinates for localising measurement points (columns) are generally not available. However, when output files of single measurements are chosen instead of the superimposed measurements, the system can provide Gauss-Krüger-coordinates for exact localisation of each measurement point (column). Still, in this case, flow velocities in the first layers above the ground were generally unavailable (partly up to six layers (of the 0.25 m-grid) above the ground; see Fig. 4.3.2).

To solve this problem, the “Bundesanstalt für Gewässerkunde, Koblenz” (which runs the ADCP-System together with the “Wasser- und Schifffahrtsamt Duisburg-Rhein“) provided a formula, which facilitated the calculation of theoretical flow velocities based on the measured flow velocities in the water column above:

$$v = a * h^{\frac{1}{6}} \quad \text{mit} \quad a = v_m \frac{(h_2 - h_1)}{(h_2^{\frac{7}{6}} - h_1^{\frac{7}{6}})} * 7/6$$

a: constant, h: distance to ground

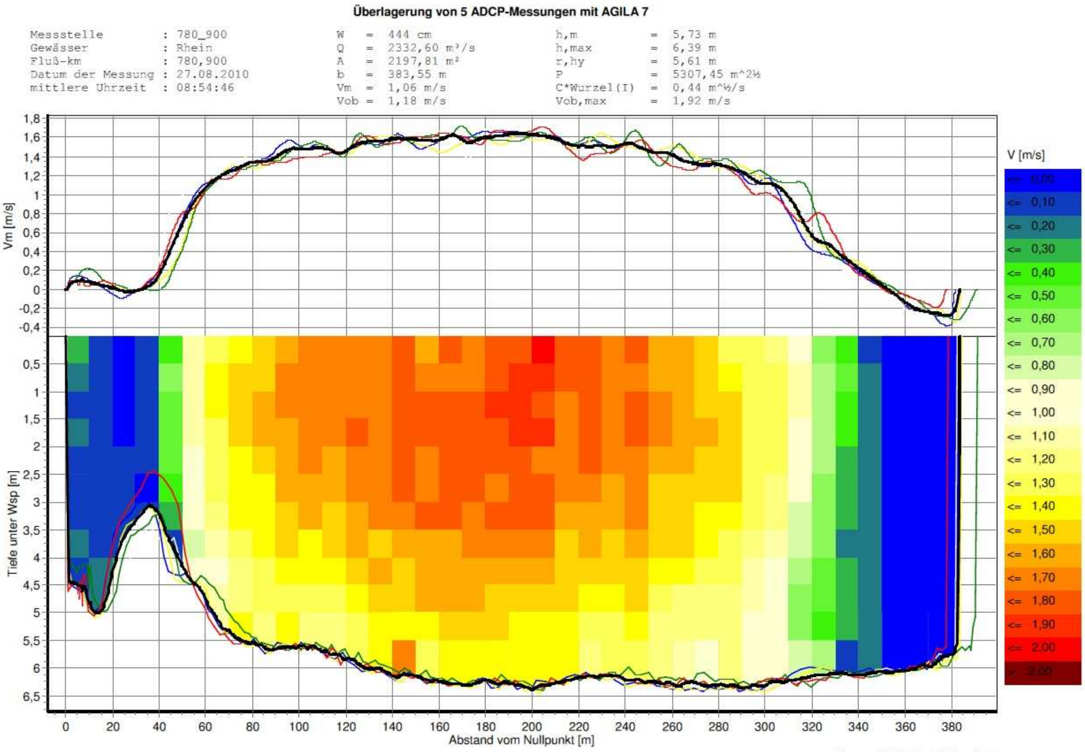


Figure 4.3.1 Graphical representation of the ADCP-measurement results of flow velocities in a river cross section at Rhine-km 780,90 from August, 10th 2010, superimposition of five measurements with theoretical calculation of flow velocities in the near bottom layers. In this type of output file, coordinates for localising measurement points (columns) are generally not available

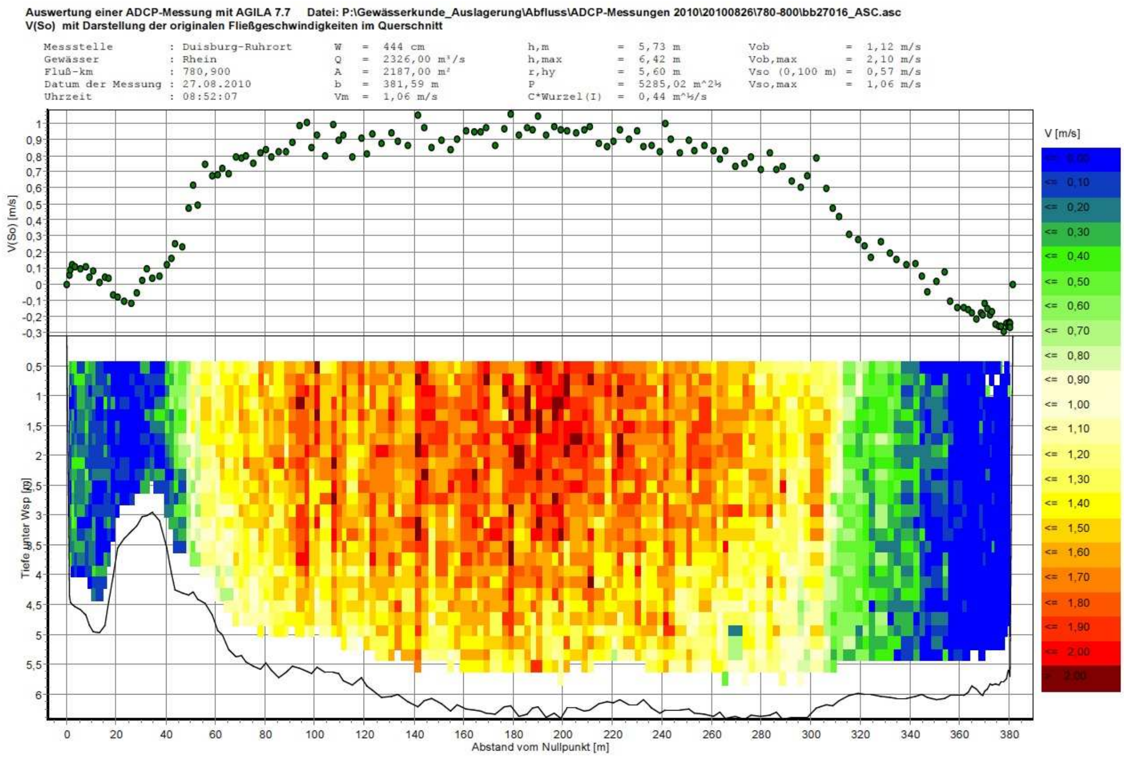


Figure 4.3.2 Graphical representation of the results of a single ADCP-measurement of flow velocities in a river cross section at Rhine-km 780,90 from August, 27th 2010. In this type of output file, near bottom flow velocities, which cannot be measured, are generally not calculated, but coordinates for localising measurement points (columns) are available

Using this formula, flow velocities for the next five layers above the river bottom (0.01 m, 0.25 m, 0.50 m, 0.75 m and 1.00 m) were calculated for each column in the cross section. From these results, a mean value for the >0-1.0 m layer was calculated. The final results of the procedure were cross sections of the Rhine River consisting of 300 – 400 points (in 1 m distance) with a mean value of flow velocity in the >0-1.0 m layer above the river bottom.

Table 4.3.1 Excerpt from an exemplary output file of ADCP-measurements of flow velocities (demonstrating the summarized of measurement points (columns) to an equidistant arrangement

Bonn km 854,8 280 cm 07.05.2014	Cross section Single measurement (without defined equidistant grid of measuring points) including coordinates							
Measuring point/ column	11.03	11.23	11.46	11.7	11.97	12.27	13.02	14.1
Time	07:56:26	07:56:27	07:56:27	07:56:27	07:56:28	07:56:28	07:56:29	07:56:30
Coordinates	2578286.94	2578287.7	2578287.7	2578288.51	2578288.51	2578288.51	2578290.87	2578290.87
	5622914.38	5622914.18	5622914.18	5622913.94	5622913.94	5622913.94	5622913.78	5622913.78
Depth Height [m] a.s.l.								
44.51	1.29	1.38	1.40	1.35	1.47	1.79	1.42	1.25
44.26	1.43	1.30	1.48	1.42	1.37	1.70	1.46	1.38
44.01	1.20	1.24	1.17	1.29	1.45	1.72	1.42	1.17
43.76	1.30	1.05	1.29	1.33	1.57	1.63	1.48	1.55
43.51	1.46	1.33	1.18	1.44	1.71	1.42	1.52	1.46
43.26	1.37	1.16	1.32	1.45	1.35	1.55	1.28	1.39
43.01	1.30	1.43	1.33	1.39	1.46	1.77	1.56	1.48
42.76	1.34	1.43	1.44	1.55	1.26	1.74	1.70	1.13
42.51								1.05
42.26								
42.01								
41.76								
Ground Height [m] a.s.l.	42.03	42.00	42.00	41.99	42.00	41.98	41.92	41.82

Averaged values for equidistant measuring points/columns

Measuring point/column	11	12	13	14
Coordinates	2578287.87	2578288.51	2578290.87	2578290.87
	5622914.12	5622913.94	5622913.78	5622913.78
Depth Height [m] a.s.l.				
44.51	1.38	1.79	1.42	1.25
44.26	1.40	1.70	1.46	1.38
44.01	1.27	1.72	1.42	1.17
43.76	1.31	1.63	1.48	1.55
43.51	1.42	1.42	1.52	1.46
43.26	1.33	1.55	1.28	1.39
43.01	1.38	1.77	1.56	1.48
42.76	1.40	1.74	1.70	1.13
42.51				1.05
42.26				
42.01				
41.76				
Ground Height [m] a.s.l.	42.00	41.98	41.92	41.82

Table 4.3.2 Excerpt from an exemplary processed output file of ADCP-measurements of flow velocities (demonstrating the calculation of flow velocities in near ground layers)

Column no.	10	11	12	13	14
Coordinates	2578285.50	2578287.87	2578288.51	2578290.87	2578290.87
	5622914.69	5622914.12	5622913.94	5622913.78	5622913.78
Distance above ground [m]					
0.01	0.29	0.34	0.41	0.37	0.33
0.25	0.50	0.58	0.70	0.63	0.56
0.50	0.57	0.65	0.79	0.70	0.63
0.75	0.61	0.69	0.85	0.75	0.67
1.00	0.63	0.73	0.89	0.79	0.70
v (mean) (>0.01-1.0 m above ground)	**0.58**	**0.66**	**0.81**	**0.72**	**0.64**

Flow velocity data in form of ADCP-measurement results are available only for seven sampling locations in the Northrhine-Westphalian Rhine stretch, which are generally located in the immediate vicinity of the gauge stations (see Tab. 4.2.1). For each station, data of three to four measurements, conducted in the time period between 2014 and 2016 at varying water levels, is existing. From these data sets, those were chosen for further analysis that were obtained at water levels most similar to the calculated mean water level representing the typical situation during the reproductive season of sturgeon.

After processing the data, a plausibility check regarding the localisation by the coordinates of the output files was conducted. Results are demonstrated in Fig. 4.3.3. Unfortunately, the sampling sites of ADCP-measurements of flow velocities do not reflect typical river sections with regard to hydromorphological features in every case.

The graphical visualisation of the near bottom flow velocities in cross sections demonstrates that the majority of values lay above the critical threshold of 0.5 m/s and within the range of 0.5 – 2.2 m/s (Fig. 4.3.4). Nevertheless, some cases can be identified where flow velocity in areas near the riverbank drops significantly below the threshold of 0.5 m/s. Therefore, river morphology of stretches, where sampling profiles were located, was verified through aerial photos. In all cases, special circumstances like bridge pier foundations, groynes, mouth areas of sidewaters or generally shallow bank zones (particularly in inner curves of meanders) could be identified as a cause for reduced flow velocities. Tab. 4.3.3 provides information on extent and portion of cross section of the zones characterized by reduced near ground flow velocities (derived from database of Fig. 4.3.4).

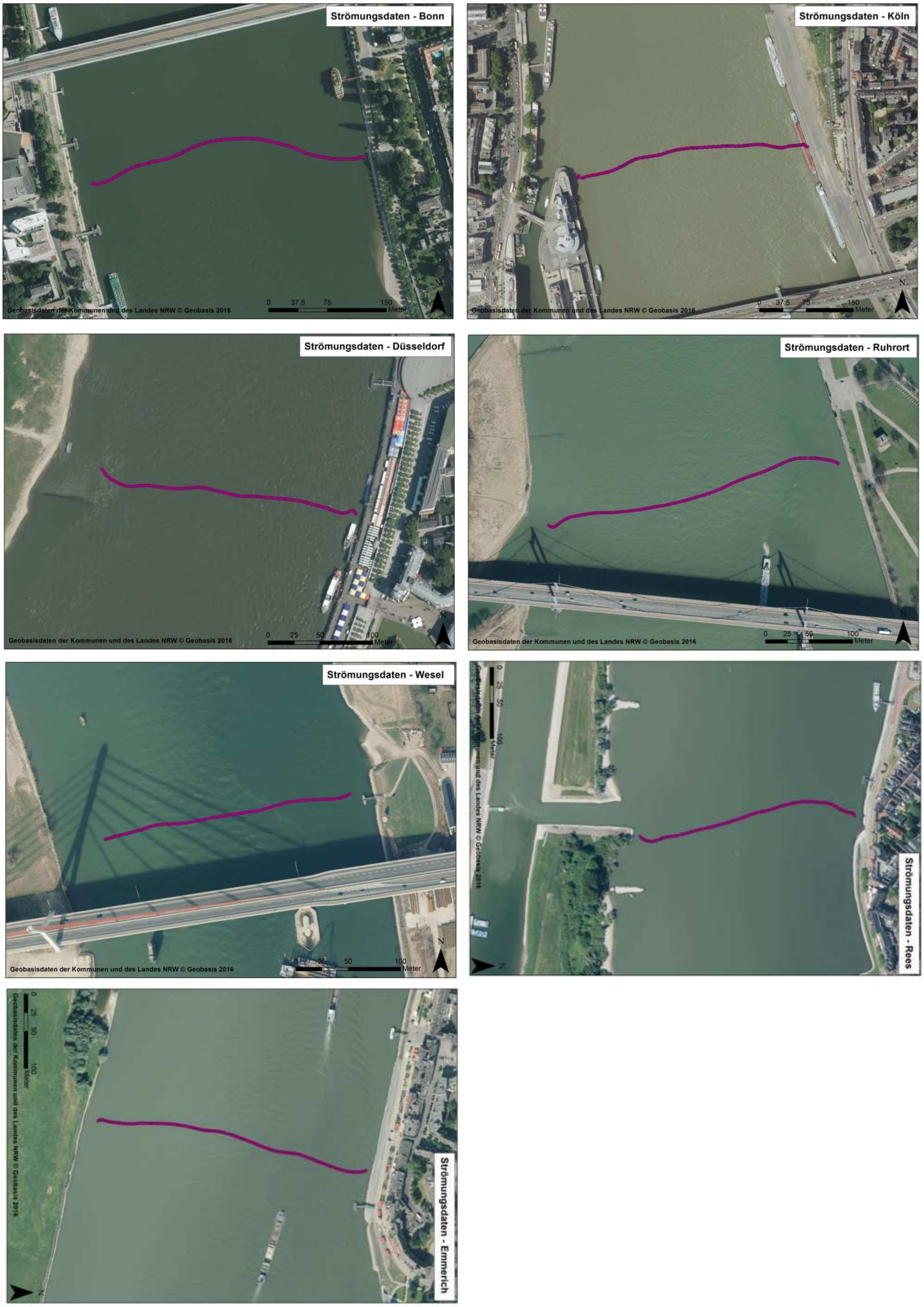


Figure 4.3.3 Aerial photographs of sampling sites for ADCP-measurements of flow velocities, with violet dots representing exact localisation of measurement points (columns) by Gauss-Krüger-coordinates

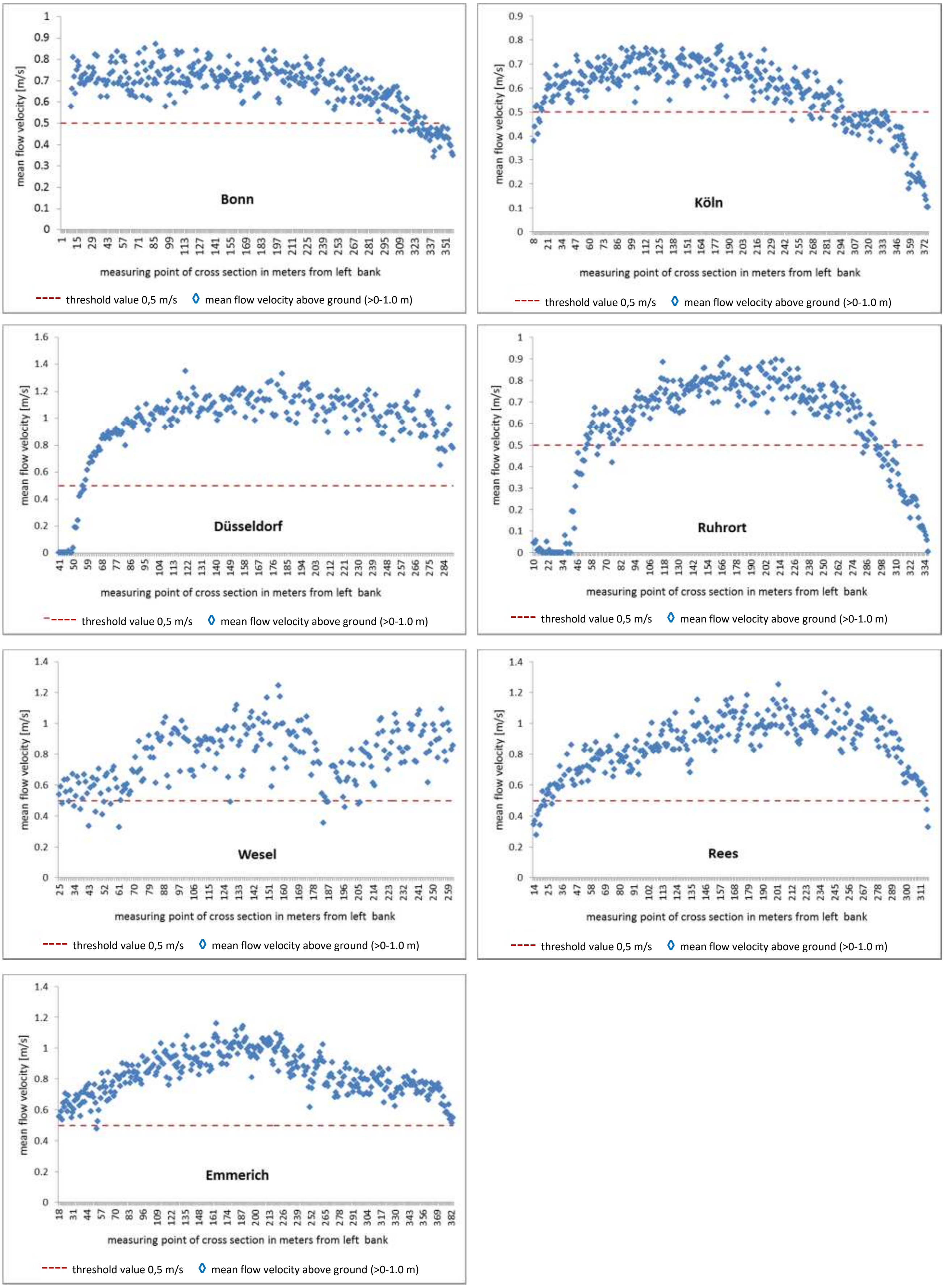


Figure 4.3.4 Mean flow velocities in the >0 -1.0 m above ground layer (derived from ADCP-measurements) in river cross sections at seven sampling sites in the Lower Rhine River (red line indicating a threshold of 0.5 m/s of minimum flow velocity in spawning habitats of the sturgeon)

Table 4.3.3 Extent (distance from bank) and portion of cross section where mean flow velocities (derived from ADCP-measurements) in the near ground layer (>0-1.0 m above ground) drops below the threshold of 0.5 m/s

Sampling site	Rhine-km	Extent (distance from bank [m])	Portion of cross section
Bonn	654,8	50 m from right bank	14 %
Köln	687,5	20 m from left bank 110 m from right bank	5 % 29 %
Düsseldorf	744,2	60 m from left bank	20 %
Ruhrort	780,9	50 m from left bank 55 m from right bank	14 % 16 %
Wesel	814,0	*special case: midchannel effects of bridge pier foundations*	
Rees	837,4	30 m from left bank	9 %
Emmerich	852,0	-	-

For the major habitat factor “flow velocity” was available was is of very good quality, but very sparse (seven cross sections in a 220 km river stretch represent only a very small sample).

With regard to the intended analysis, dealing with such a marginal data basis is unsatisfactory. This problem is put into perspective when analysis results of available data are considered. It can be stated that the factor flow velocity is probably of minor importance for determining the suitability of potential spawning habitat for sturgeon, since for the vast majority of cases, measured (respectively calculated) flow velocities considerably exceed the threshold of 0.5 m/s. The River Rhine is a fast flowing river and flow velocities near bottom depths layers usually exceed the threshold of 0.5 m/s. Thus, flow velocity is barely a limiting factor for suitability of potential spawning habitats.

To deal with these aspects and to link general flow information to the DTM (sparse data basis with regard to spatial density, minor importance for habitat suitability), extrapolation of available data in the GIS-analysis was conducted as follows: surface areas, where flow velocities can be expected to fall below 0.5 m/s as designated in Tab. 4.3.3., were assigned as quality class “0” (not suitable); all other surface areas were assigned as quality class “1” (suitable).

4.4 Key factor “Substrate”

4.4.1 Data base and parameter used in analysis

Substrate data were provided by the “Bundesanstalt für Gewässerkunde, Koblenz”. Available data are also compiled in a data base, published online (*http://geoportal.bafg.de/Projects/SedimentOracleDatabase/WebReport/*). For the River Rhine data are available for the reach between Rhine-km 639.0 and 867.0., supplied data are results of a granulometric analysis, whereat analysed substrate samples were taken (in most cases) by a diving shaft vessel. For the Northrhine-Westphalian Rhine riverbed, substrate samples from 715 different sampling sites were available (portraying a very satisfactory data base for the projected analyses). Mostly, several data sets from multiple samplings in different years were available for each site. A single data set for a sampling site consists of the results of granulometric analyses of several (generally 3-10) samples, arranged in a cross section of the river bed (samplings of one site in different years did not always contain the same number of samples per cross section). Each sample represents a surface area of 1 m^2. In most cases, samples were taken and analysed in two or more depths layers of the river bed. Fig. 4.4.2 demonstrates what substrate conditions of the surface layer on the river bed in situ look like. Parameters of analysis are the percentage of weight for threshold grain sizes, minimum, maximum and mean grain size diameters as well as several coefficients. Additionally, information regarding the localisation of each sampling point in the cross section is given (see below).

From available substrate data, the parameters “mean grain size” (DM), “uniformity coefficient (U)” and the “grain diameters” D75 and D25 were selected to be linked in the GIS, since most specifications from scientific literature describing sturgeon spawning habitat refer to this parameters.

From the complete data base, data files for further analysis were selected according to the highest spatial density of substrate information. Therefore, every sampling site possible was included, with the most current data file (if possible from the last five years, files older than 20 years were excluded from analysis) and the most comprehensive data file (in terms of numbers of samples per cross section). In every case data files from analysis of the depths layer next to the surface of the river bed were used. Following this procedure, a total of 348 data sets (sampling sites) could be used in the GIS-based analysis.

Tab. 4.4.1 provides an example of data file structure. In that case,” three samples were taken in the cross section (“131”, “181”, “231”) for two different depth layers of the river bed (“0.10-0.50 m” and “0.00-0.1.00 m”) at the sampling site “Rhine-km 733.000. The table displays percentage of weight for threshold grain sizes (D10-D80), information regarding the fractions of minimum and maximum diameters and the parameter “mean diameter” (DM), which was used in further analysis.

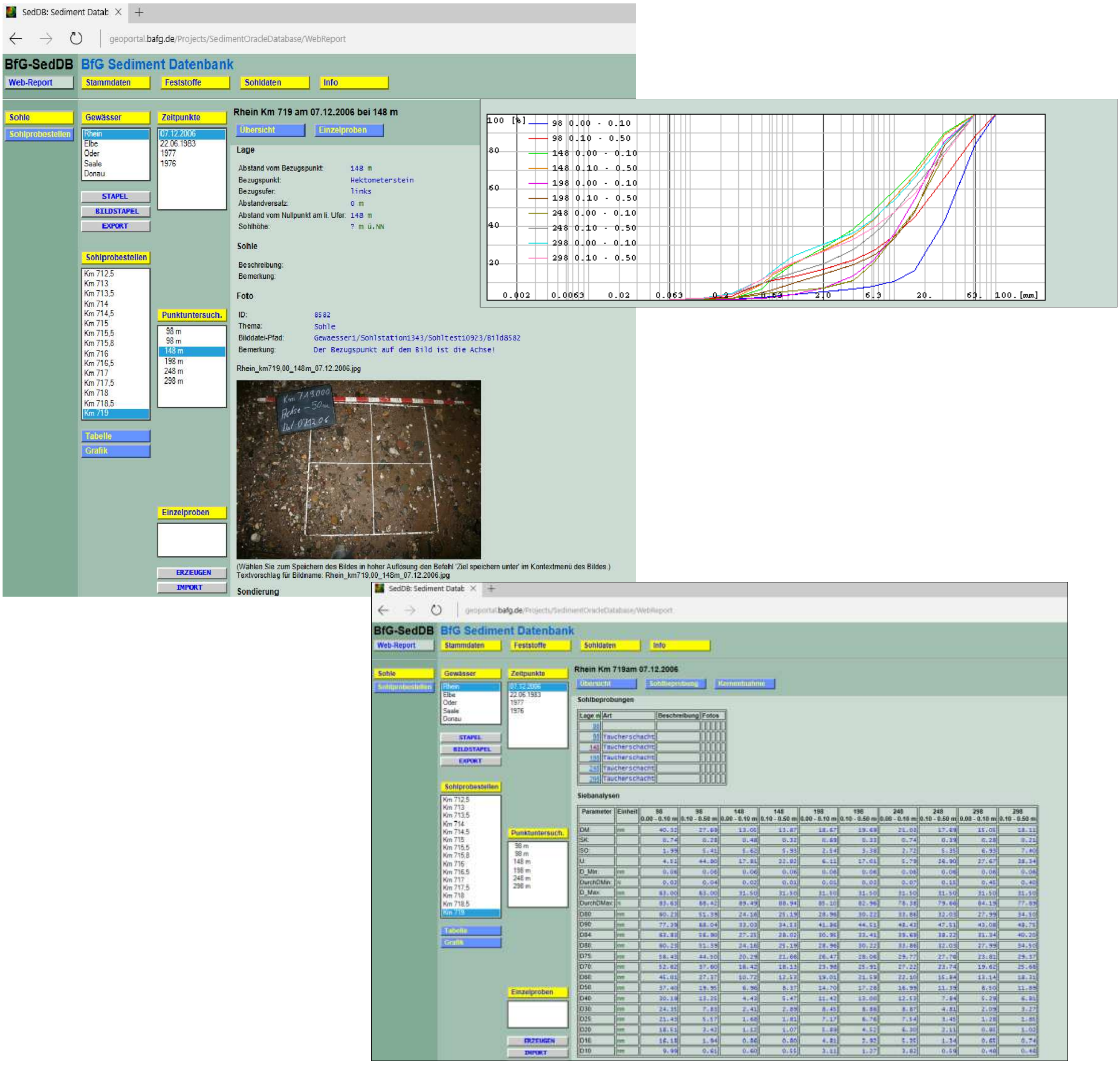


Figure 4.4.1 *Exemplary screenshots of published sediment data base of the "Bundesanstalt für Gewässerkunde, Koblenz" (http://geoportal.bafg.de/Projects/SedimentOracleDatabase/WebReport/)*

Table 4.4.1 Exemplary excerpt from the export data file, with results of file of granulometric analysis provided by the "Bundesanstalt für Gewässerkunde, Koblenz"

Parameter	Dimension	131 0.10 - 0.50 m	131 0.00 - 0.10 m	181 0.00 - 0.10 m	181 0.10 - 0.50 m	231 0.00 - 0.10 m	231 0.10 - 0.50 m
DM:	mm	10.75	19.90	20.32	14.59	14.61	13.16
SK:		0.46	0.28	0.20	0.17	0.56	0.56
SO:		6.17	9.16	10.26	7.42	3.43	3.80
U:		17.36	40.60	41.89	33.84	10.39	13.78
D_Min:	mm	0.06	0.06	0.06	0.06	0.06	0.06
DurchDMin:	%	0.08	0.41	0.07	0.04	0.01	0.06
D_Max:	mm	31.50	63.00	63.00	31.50	31.50	31.50
DurchDMax:	%	92.60	92.70	97.06	87.41	90.70	91.51
D80:	mm	19.23	37.61	42.90	26.58	24.50	22.03
D90:	mm	28.97	57.61	54.69	37.98	31.04	30.26
D84:	mm	23.12	45.61	47.62	29.24	27.12	25.32
D80:	mm	19.23	37.61	42.90	26.58	24.50	22.03
D75:	mm	15.06	29.69	37.01	23.26	21.23	17.92
D70:	mm	12.29	25.06	30.97	19.95	17.97	15.10
D60:	mm	8.05	15.85	15.50	14.13	13.77	11.73
D50:	mm	5.51	9.41	10.45	9.59	10.59	8.88
D40:	mm	3.30	5.09	6.85	5.64	7.96	6.71
D30:	mm	1.54	1.90	3.68	1.69	5.57	4.56
D25:	mm	0.98	1.08	1.11	0.89	4.41	3.51
D20:	mm	0.76	0.70	0.52	0.61	3.25	2.50
D16:	mm	0.61	0.54	0.45	0.53	2.31	1.75
D10:	mm	0.46	0.39	0.37	0.42	1.33	0.85

4.4.2 Localisation of sampling sites

In the substrate data base, the localisation of the sampling points within the cross section of a given sampling site was conducted by indicating the distance to specific reference points on the bank of the river. Although the data states that in general, reference points were the "Hektometersteine" located on the left bank, it became apparent that several different kinds of reference points were used after transferring the information into the GIS, either on the left or the right bank of the river. This turned out to be a major problem, a large amount of work had to be invested to clarify and correct the information regarding the exact localisation of cross section sampling points. It turned out that different kinds or terms for landmarks like "Hektometerstein" or "Ordnungsprofilpunkt" and alternatively "Sichtzeichen" or "Schifffahrtszeichen" were used. However, only in the case of "Hektometersteine" a basis for localisation in form of Gauss-Krüger-coordinates was existing. For other reference-points, no direct information for localisation was available. With extensive help of the "Wasser- und Schifffahrtsamt Duisburg-Rhein, Sachbereich 3 – Gewässervermessung, Ansprechpartner Herr Schräder)" it became possible to export Gauss-Krüger-coordinates of the positioning of "Sicht- und Schifffahrtszeichen" from older mappings, which could be used for plausibility

Figure 4.4.2 Exemplary in situ-photographs of substrate samples on the Rhine's river bed which were used for granulometric analysis (compare table 4.4.1)

<table>
<tr><td colspan="2">a) sample from Rhine-km 667,5, 50 m from reference point,
mean grainsize diameter 140 mm</td></tr>
<tr><td>b) sample from Rhine-km 647,0,
281 m from reference point,
mean grainsize diameter 63 mm</td><td>c) sample from Rhine-km 766,0,
100 m from reference point,
mean grainsize diameter 89 mm</td></tr>
<tr><td>d) sample from Rhine-km 863,0,
50 m from reference point,
mean grainsize diameter 1 mm</td><td>e) sample from Rhine-km 647,0,
181 m from reference point,
mean grainsize diameter 31 mm</td></tr>
</table>

verification. In cases where no positioning information of landmarks used as reference points was available, the visualisation of landmarks in maps and aerial photos of several online-information-systems[1] were used to readout Gauss-Krüger-coordinates of reference points for transferring to the GIS. All coordinates of reference points that were subsequently determined and the respective localisation of sampling points in the river cross section were checked for plausibility in the GIS. This way, all data files for each sampling site in the Northrhine-Westphalian stretch of the River Rhine could be edited to make them usable in the GIS-analysis.

Around each localised grid-point with available substrate information, a buffer-zone was determined, defined in lateral and longitudinal direction by half of the distance to the next grid-point with assigned substrate information. Each grid-point within the buffer-zone was assigned with the same substrate information as the centre grid point.

[1] https://www.tim-online.nrw.de" or "http://atlas.wsv.bund.de" or "http://www.elwasweb.nrw.de/elwas-web

4.5 Additional factors affecting potential spawning habitat quality

4.5.1 Factor “Industrial navigation”

The intensive utilisation of the River Rhine for purposes of navigation, flood control, discharge of wastewaters and other aspects has caused severe alterations of the functioning of the ecosystem and the habitat quality in the River Rhine. Potential reproductive habitat quality is affected by several anthropogenic factors, which need to be taken into account in this study. A very important factor is the intensive industrial shipping, which severely affects fish and their habitat. Passages of large cargo ships cause heavy wave action along the banks, particularly affecting inshore YOY habitats and impairing reproductive success and recruitment. The sturgeon is a special species in many respects, due to the large body size of adults, its preference for deep and fast flowing sections of the river and the special behavioural aspect that it has to swim to the surface and gulping air to inflate its swim bladder. All of this increases the probability of encounters with ships and therefore the risk of being heavily injured or killed, especially if it comes to a contact with the propeller (Spierts 2016). Aside from the risk of being damaged by direct contact, the shipping activities also impair the quality of reproductive habitats. Vessel passages over spawning grounds may disturb spawning adults through the propeller induced slip stream and turbulences as well as the noise and thereby hamper successful spawning.

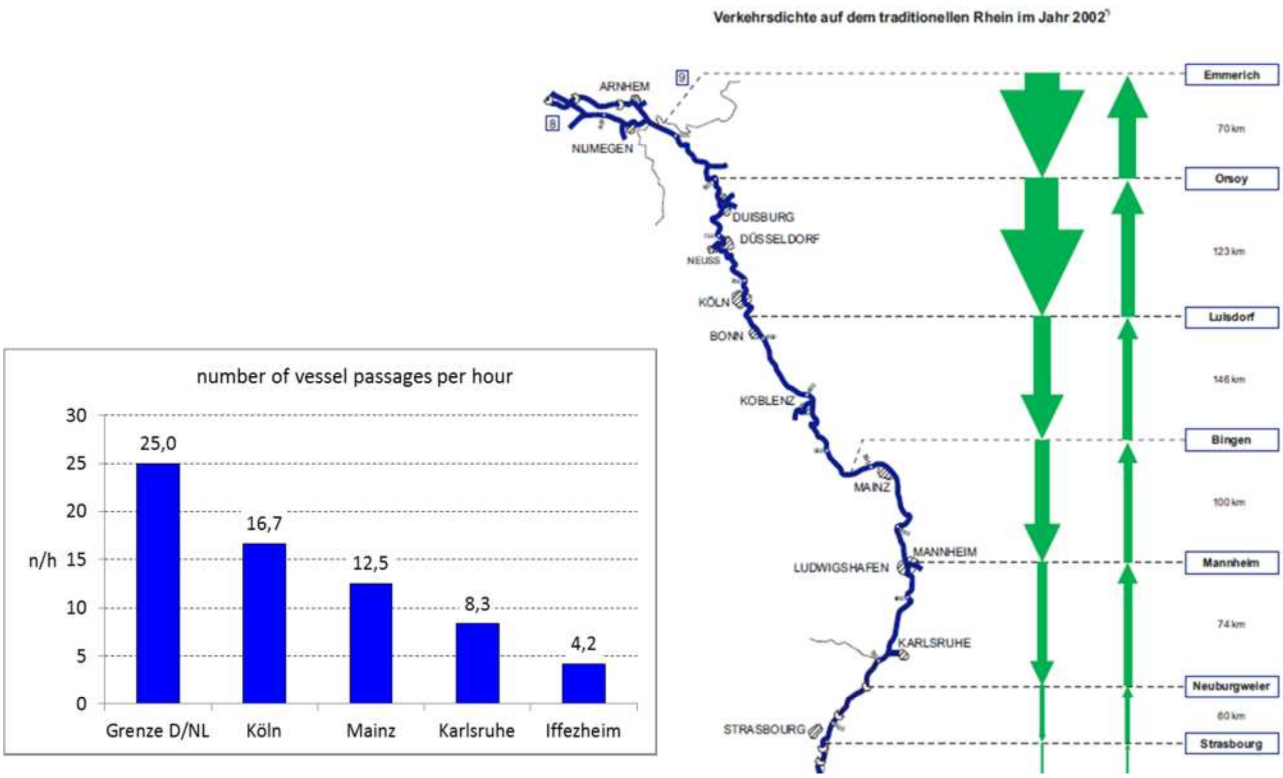


Figure 4.5 *Intensity of industrial navigation on the River Rhine; left: number of vessel passages per hour at several stations; right: visualisation of “traffic density” in different reaches (retrieved from: Zentralkommission für die Rheinschifffahrt (ZKR) – Wirtschaftliche Entwicklung der Rheinschifffahrt 2002)*

Impairment of sturgeon reproduction by industrial navigation can be treated as a problem of major importance in the Lower Rhine River region, because navigation activity there is significantly higher (in terms of transported tonnage and number of vessel passages) than in more upstream reaches. The average of 25 vessel passages per hour at the Dutch-German border portrays an almost permanent disturbance and impairment. Intensity of navigation decreases in upstream direction with distance to the sea and number of inland ports localised downstream.

Because of this impairments caused by shipping activities, navigation is considered as a crucial factor affecting habitat suitability. The route of vessels in the river channel is specified by a designated navigation channel with a width of about 150 meters (which is fixed in all navigation systems for industrial shipping). In general, it covers about 50 percent of the total channel width. The exact localisation of the navigation channel was provided by the waterway authority ("Wasser- und Schifffahrtsamt Duisburg-Rhein") and transferred into the GIS. In case of intersection with potential reproductive habitat displayed by the GIS-analysis, the information can either be used to downgrade the habitat suitability of these areas or to exclude them from area calculations in general.

4.5.2 Factor "Existence of deep potholes in the river bed"

Due to the fact that several authors mention the observation that, during reproductive season, adult sturgeons were caught conspicuously often in very deep potholes in the river bed (in some cases it was assumed that spawning places were located there), it can be assumed that deep potholes play an important role as resting pools (where adult sturgeons gather or rest during the spawning season). Therefore, the presence of deep potholes will be used as a factor for upgrading the significance of potential spawning habitats in the surrounding area in the GIS-based analysis.

The upgrade criteria was defined as follows: every potential reproductive habitat in the vicinity of the pothole, which was defined as a range of 200 m around the pothole, that has received the significance of "1" in the analysis was formally upgraded as "1*". In case that the surrounding area was not qualified as potential reproductive habitat (significance "0" or "0.5"), no calculative upgrading was done.

4.6 Water temperature as an environmental factor

In addition to the already mentioned parameters, water temperature is an important factor for reproductive success of sturgeon. Sturgeon can be considered as late spring and summer spawning species (spawning normally takes place from May to July). It is adapted to correspondent intermediate to high temperatures during spawning as well as embryonic and larval development (Tab. 5.3.1).

The River Rhine is affected by cooling water discharges, influencing the temperature regime and causing a significant increase of yearly average water temperature in the last decades (IKSR 2004). Additionally, possible effects of climate change have to be taken into account. Consequently it has to be examined if anthropogenic alteration of the natural temperature regime might be a factor affecting the potential reproduction of sturgeon in the River Rhine.

Unlike the parameters water depths, flow velocity and substrate composition, which have to be analysed with regard to their spatial distribution and therefore will be subject of a GIS-based analysis, temperature regime is a general factor of the riverine ecosystem that does not need to be analysed in a small-scale spatial distribution. The meaning and possible impacts of the recent water temperature regime in the River Rhine are presented and discussed apart from the GIS-based analysis in Chapter 5.3.

4.7 Overview of data sets used and processed for GIS-analysis

Tab. 4.7 provides an overview of the data sets regarding the parameters used to describe potential spawning habitat of sturgeon that were used and processed for the GIS-analysis.

Table 4.7 Overview of all data sets used and processed for GIS-analysis

		Data sets	**Time-frame**	**Source**
Parameter	Hydrological data (water level, discharge)	7 gauge stations	1900 – 1999 analysis of 100 year time series	WSV, Duisburg Rhein
	Flow velocity	7 gauge stations	2014 – 2015 selection of most current data sets	WSV, Duisburg Rhein
	Substrate	348 sampling sites	1996 – 2016 selection of most current data sets	BfG, Koblenz
	Temperature	3 gauge stations	1995 – 2015 analysis of 20 year time series	LANUV, Recklinghausen

A geographical representation of the localisations of gauge stations (which are sampling sites of flow velocity data at the same time) and sampling sites of substrate analyses is given in Fig. 4.7, also in which the geographical situation and relevance of the investigated reach of the Lower Rhine River in Northrhine-Westphalia within the Rhine system is indicated as well.

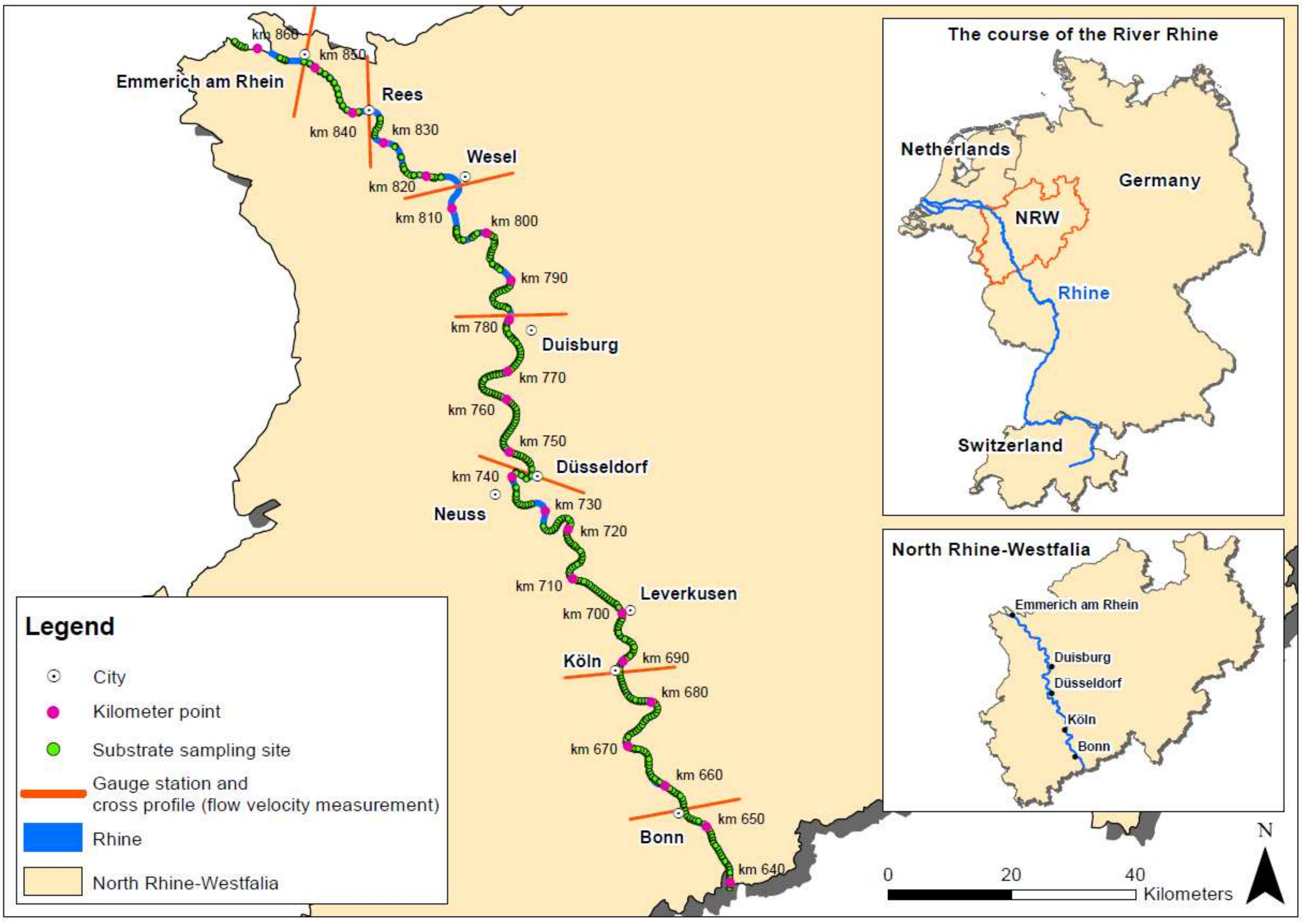


Figure 4.7 *Geographical representation of the investigated reach of the Lower Rhine River with localisation of gauge stations and sampling sites of substrate analyses*

4.8 Parameter settings for GIS-based analysis

The potential sturgeon spawning habitat can be described as a deep area of the river channel (depth > 2 m) with rather strong flow velocity (at least > 0.5 m, ideally > 1.0 m/s) and a substrate composition characterised by the absence of fine-grained fractions (silt, sand) as well as a dominance of large-grained fractions (resulting in mean diameters > 25 mm). Moreover, substantial amounts of larger pebbles and stones creating heterogeneity may be favourable, genuine rock surfaces are likely to be most suitable (Gessner, personal communication).

In order to assess quality and quantity of currently available potential reproductive habitat for sturgeon in the River Rhine in accordance with the habitat suitability Index (HSI) method, the following parameter setting was determined for the GIS-based analysis (Tab. 4.7.1 – 4.7.4).

Table 4.8.1 Suitability of the water depth classes for adults and age 0+

Water depth	Adults	Age 0+ (fry)
Shallow (>0 – 1 m)	0	0
Moderately deep (>1 – 2 m)	0.5	0.5
Deep (> 2 – 5 m)	1	1
Very deep (> 5 m)	1	0

Table 4.8.2 Suitability of the flow velocity classes for adults and age 0+

Flow velocity	Adults	Age 0+ (fry)
Slow (0 – 0.5 m/s m/s)	0	1
Moderate (> 0.5 – 1 m/s)	1	0.5
Strong (> 1 – 2 m/s)	1	0
Very strong (> 2 m/s)	0.5	0

Table 4.8.3 Reduction of suitability of flow velocity classes for adults and age 0+, due to constraints in data availability (see Chapter 4.3)

Flow velocity	Adults	Age 0+ (fry)
slow (0 – 0.5 m/s m/s) not suitable	0	1
moderate - strong (> 0.5 m/s) suitable	1	0.5

With regard to the factor „substrate“, a more complex procedure considering several indices was developed. However, following consultations with the customer, it was not used in the present study. In the first step of the present study, substrate conditions were only considered as mean grain size diameter.

Table 4.8.4 Suitability of the substrate classes for adults and age 0+
*(1) not considered in the present study, analysis restricted to *)*

Substrate	Adults
DM ≥ 25 mm *	1
DM < 25 mm *	0
U < 5 (uniform)	0.5
5 < U < 15 (inhomogenous) 1)	0.75
U > 15 (very inhomogenous) 1)	1
D75 (≥ 63 mm) 1)	1
D75 (< 63 mm) 1)	0.5

Substrate	Age 0+ (fry)
D25 (grain diameter > 2 mm) 1)	0
D25 (grain diameter ≤ 2 mm) 1)	1

Adults:

Regarding spawning habitats of adult sturgeon (*A. sturio*), the parameters DM, U und D75 were selected and calculated.
For the mean diameter (DM), the values "0" for DM < 25 mm and "1" for DM > 25 mm were assigned.
For the uniformity coefficient (U), the values "0.5" for uniform substrate samples (U < 5), "0.75" for inhomogeneous (5 < U < 15) and "1" for very inhomogeneous (U > 15) samples were assigned.
For the grain diameter D75, the values "0.5" for D75 (< 63 mm) and "1" for D75 (≥ 63 mm) were assigned.

The three parameters are factored in together, while the minimum value is decisive for the assessment. For example:

DM = 1, U = 1, D75 = 0.5; the total value is 0.5, as 0.5 is the minimum value
DM = 0, U = 0.75, D75 = 1; the total value is 0

The mean diameter gets the strongest weighting, as substrate samples with DM < 25 mm cause a value of "0".

As the sturgeon (A. *sturio*) prefers substantial amounts of larger pebbles and stones the parameter D75 was chosen to indicate relevant amounts of coarse substrate (here 25 %).

Age 0+:

For the grain diameter D25, the values "0" for D25 (> 2 mm) and "1" for D25 (≤ 2 mm) were assigned.

The total value is equivalent to the value for the grain diameter D25.

As juveniles (A. *sturio*) prefer sand and soft substrate, the parameter D25 was selected to indicate relevant amounts of fine substrate (here 25 %).

5 Results

5.1 Surface area calculations of potential reproductive habitats

The major outcomes of the GIS-based analysis of available and processed data concerning major key factors characterising potential reproductive habitats of European sturgeon in the Lower River Rhine are (analysis A):

From a total main channel area of 73.36 km^2 of the Lower River Rhine within the borders of Northrhine-Westphalia, representing a reach of approximately 220 km length, a percentage of 89.97 % could be examined. An area of 7.36 km^2 (10.03 % of total area) had to be excluded from the analysis for two reasons. Firstly, a second reference gauge station at most downstream and upstream reaches was missing, which would have been necessary for determining water depth data (see Chapter 4.2). Secondly, some portions of bank zones fall dry in the reference water level situation (long-term mean water level in assumed reproductive period (see Chapter 4.2.2).

In a first step, the GIS-based analysis revealed that a main channel area of 21.84 km^2 (representing 33.09 %) can be qualified as "suitable" potential spawning habitat for sturgeon (with regard to an appropriate combination of habitat key factors water depth, flow velocity and substrate). Correspondingly, a total area of 44.16 km^2 (representing 33.09 %) was qualified as not or only conditionally suitable as potential spawning habitat for sturgeon.

In a second step, taking into account the upgrading criterion "presence of deep river-bed potholes", the GIS-based analysis revealed that out of the area already qualified as "suitable", an area of 2.40 km^2 (representing 3.64 %) can be qualified as "highly suitable".

By modifying the analysis (analysis B) through considering the localisation of the designated navigation channel, results change considerably:

With regard to the overlap of the designated navigation channel with areas qualified as "suitable" and "highly suitable", surface area of potential habitats located outside of the designated navigation channel become reduced to 9.20 km^2 (representing 13.9 %) and 0.91 km^2 (representing 1.38 %) respectively. This implies that taking into account the negative implications of intensive industrial navigation leads to a reduction of potential spawning habitat for European sturgeon in the Lower Rhine River by more than 50 %. This reduction can be treated either as a total loss of potential reproductive habitats or alternatively as a downgrading of habitat suitability.

The localisation of areas assigned to specific quality-classes of habitat suitability by GIS-based analysis is documented and shown in overview maps No. 1 – 4 (see digital appendix). An exemplary map section is shown in Fig. 5.1.

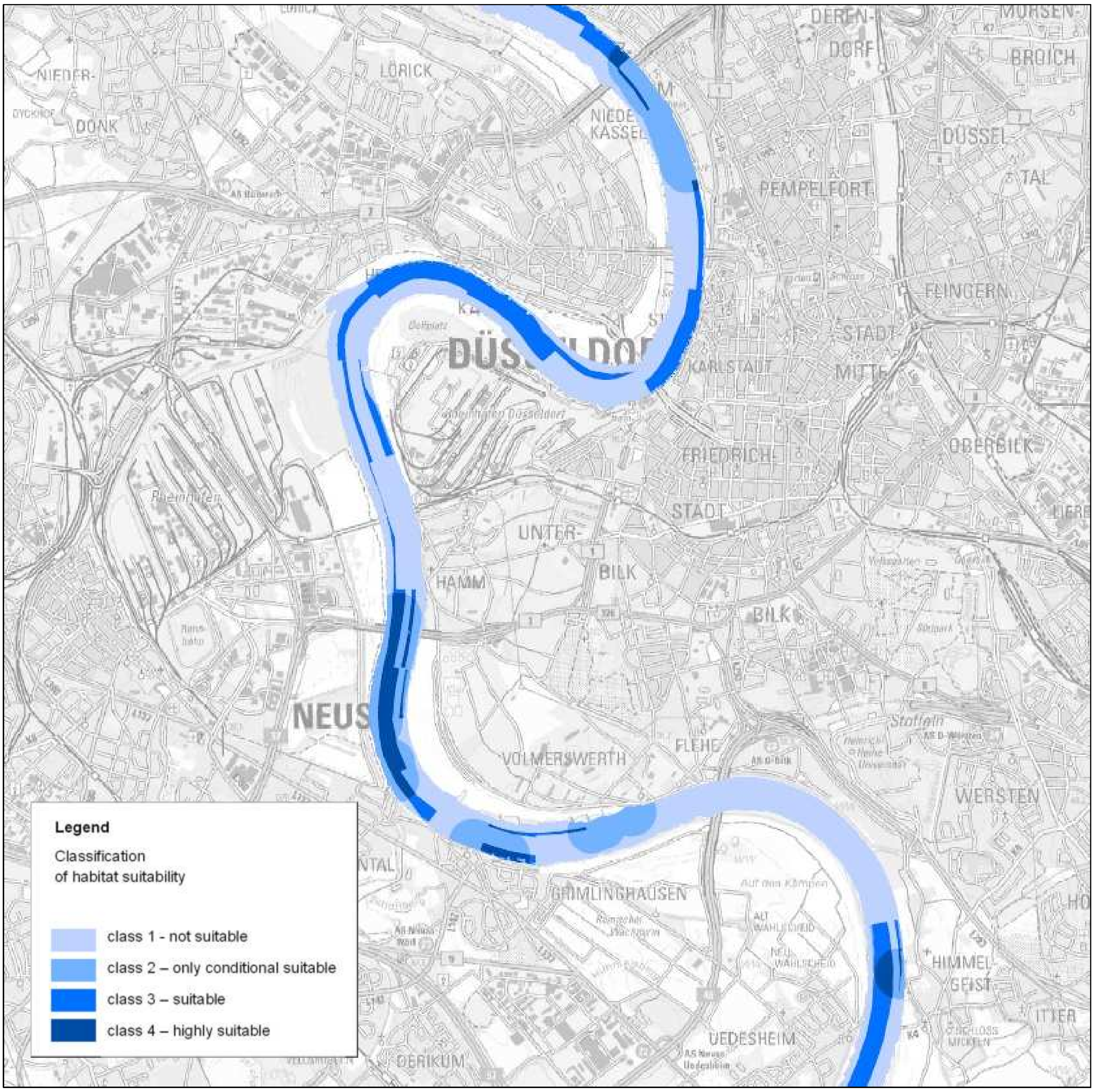


Figure 5.1 *Exemplary map section from overview maps No. 1 – 4 (see digital appendix) demonstrating results from GIS analysis of potential reproductive habitat suitability (note: roughly rectangular shape of areas is caused by extrapolation procedures for parameters "flow velocity" and "substrate"; roughly circular shaped areas indicate the sphere of influence of riverbed potholes for upgrading habitat suitability)*

Table 5.1 Basic outcome of GIS-based analysis in analogy to HSI-modelling concerning area calculations of potential reproductive habitats in the Lower Rhine River

		Total		**Within navigation channel**			**Outside navigation channel**		
		[km²]	[%]	[km²]	[%]		[km²]	[%]	
Total main channel area analysed		66.00	100	29.95	100		36.05	100	
		Total		**Within navigation channel**			**Outside navigation channel**		
HSI model outcome **Analysis 1**	**Quality**	**[km²]**	**[%] [1]**	**[km²]**	**[%] [2]**	**[%] [1]**	**[km²]**	**[%] [2]**	**[%] [1]**
Excluded area (*)		7.35		2.74			4.61		
Class 1 - area	Not suitable	43.22	65,48	18.17	60.65	27.53	25.06	69.51	37.97
Class 2 - area	Only conditional suitable	0.94	1,42	0	0	0	0.94	2.61	1.42
Class 3 - area	Suitable	21.84	33,09	11.79	39.35	17.86	10.05	27.88	15.23
Class 4 - area	Highly suitable	*not assigned*		*not assigned*			*not assigned*		
Sum (total):		73.35		32.70			40.66		
Sum (without excluded area):		66.00	100	29.96	100	45.39	36.05	100	54.62
Analysis 2 considering upgrading criterion "presence of riverbed potholes")		**[km²]**	**[%]**	**[km²]**	**[%] [2]**	**[%] [1]**	**[km²]**	**[%] [2]**	**[%] [1]**
Excluded area (*)		7.35		2.74			4.61		
Class 1 - area	Not suitable	37.40	56.67	15.20	50.75	23.03	22.21	61.59	33.65
Class 2 - area	Only conditional suitable	6.71	10.17	2.97	9.92	4.50	3.74	10.37	5.67
Class 3 - area	Suitable	19.49	29.53	10.29	34.36	15.59	9.20	25.51	13.94
Class 4 - area	Highly suitable	2.40	3.64	1.49	4.97	2.26	0.91	2.52	1.38
Sum (total):		73.35		32.69			40.67		
Sum (without excluded area):		66.00	100	29.95	100	45.38	36.06	100	54.64

* *areas excluded because of missing water depth data (areas without 2nd reference gauge station or fallen dry)*
[%] [1] percentage of total main channel area
[%] [2] percentage of "within navigation channel" area or "outside of navigation channel" area

5.2 Designation of concrete potential reproductive areas

The GIS-based area calculations represent formal summations of numerous, sometimes small-sized areas recognised automatically by an appropriate combination of habitat characteristics. Thereby, the ecological aspect that some of these distinct areas may not be recognised as potential spawning habitat by the fish, because they are to small-sized or because they might be affected by disturbing influences in the surrounding area (e.g. entrance areas of harbours with intensified shipping activities, inlets of wastewater discharges, and others), is disregarded.

In scientific literature, the aspect of “minimum size of spawning habitat” is occasionally emphasised and discussed in terms of a “carrying capacity”. Jacob (1996) mentions that a surface area of 300 m^2 is needed by one adult female sturgeon to successfully deposit its eggs. Although there is no valid information concerning a minimum size of spawning habitats accepted and utilised by spawning sturgeons from field observations that could be used to define a minimum threshold size of potential spawning habitats, it definitely will be expedient to consider this aspect in further analysis.

Therefore, an additional “plausibility check by hand” was executed. From overview maps visualising the results of GIS-based habitat suitability analysis, river stretches with a minimum length of 500 m and a high coverage (> 75 %) of areas with assigned quality classes “suitable” and “highly suitable” were identified. This could be due to the existence of rather large suitable areas or due to the existence of numerous small suitable areas in immediate vicinity within a river stretch. These areas can be clearly separated from adjacent stretches with significant lower coverages of suitable areas. The procedure was based on the assumption that only larger areas (covering at least several 100 m^2) will successfully function as a reproductive area, may it be due to the probability that habitats are detected by the fish or due to “carrying capacity” effects (with regard to surface area for egg deposition or space in resting pools).

Resulting from this procedure, a number of six river stretches representing concrete potential reproductive areas were identified in the Lower Rhine River, portrayed in aerial photographs in Fig. 5.2.1 – 5.2.6.

Figure 5.2.1 Potential spawning area No.1 ("Wesel") – Rhine-km 813.0 – 815.0 (length 2 km)

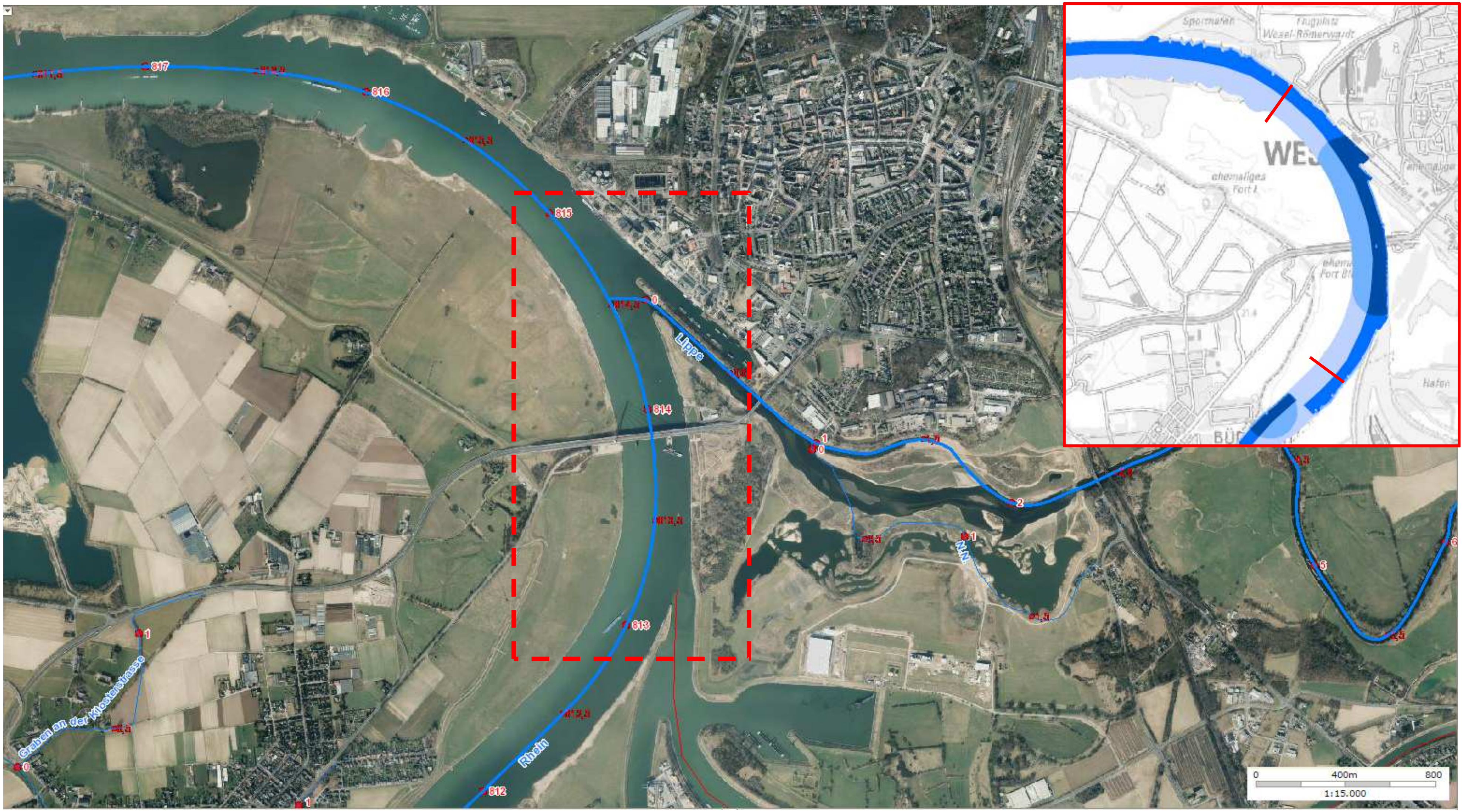


Figure 5.2.2 Potential spawning area No.2 ("Rheinberg") – Rhine-km 801.5 – 806.5 (length 5 km)

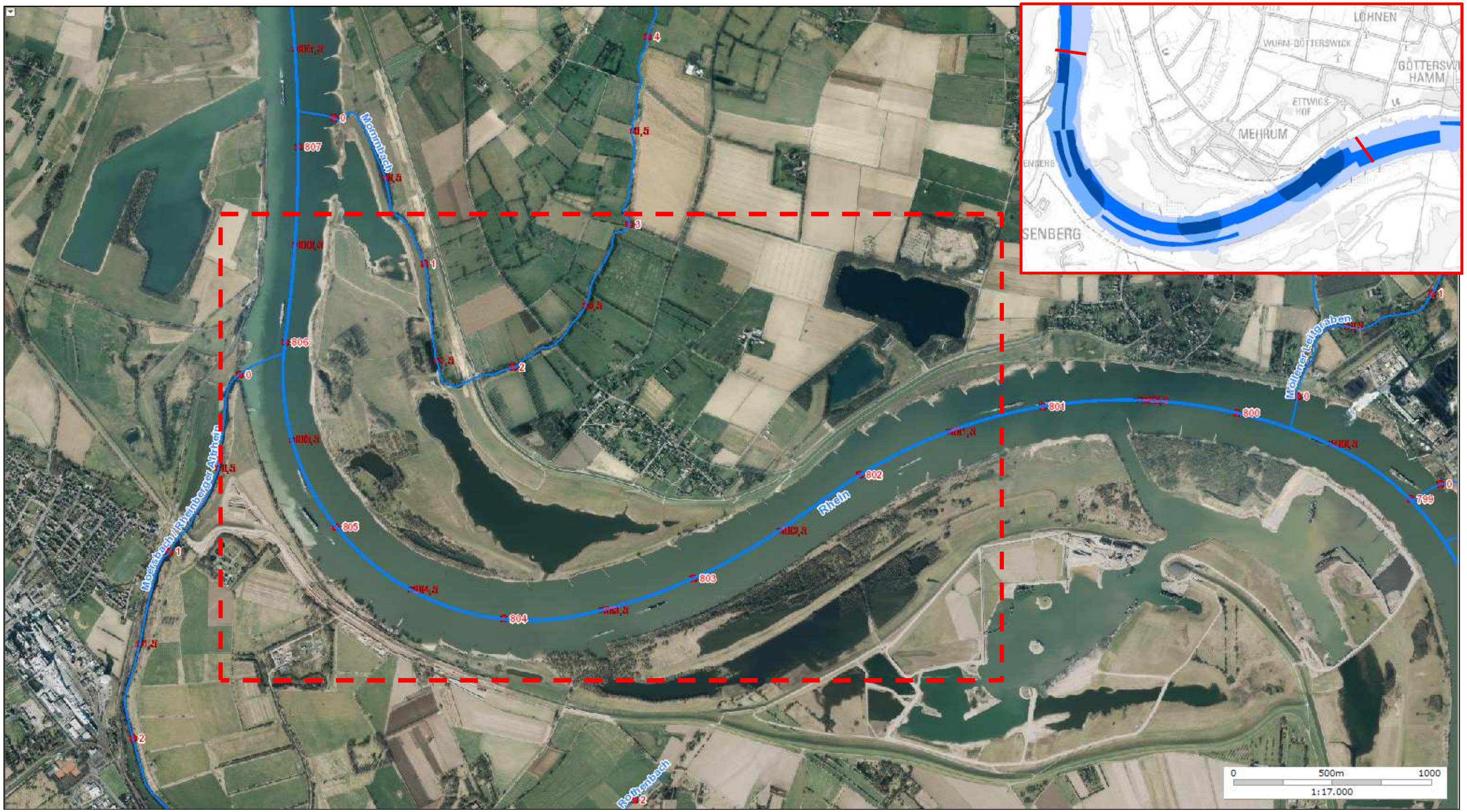


Figure 5.2.3 Potential spawning area No.3 ("Meerbusch") – Rhine-km 750.0 – 755.0 (length 5 km)

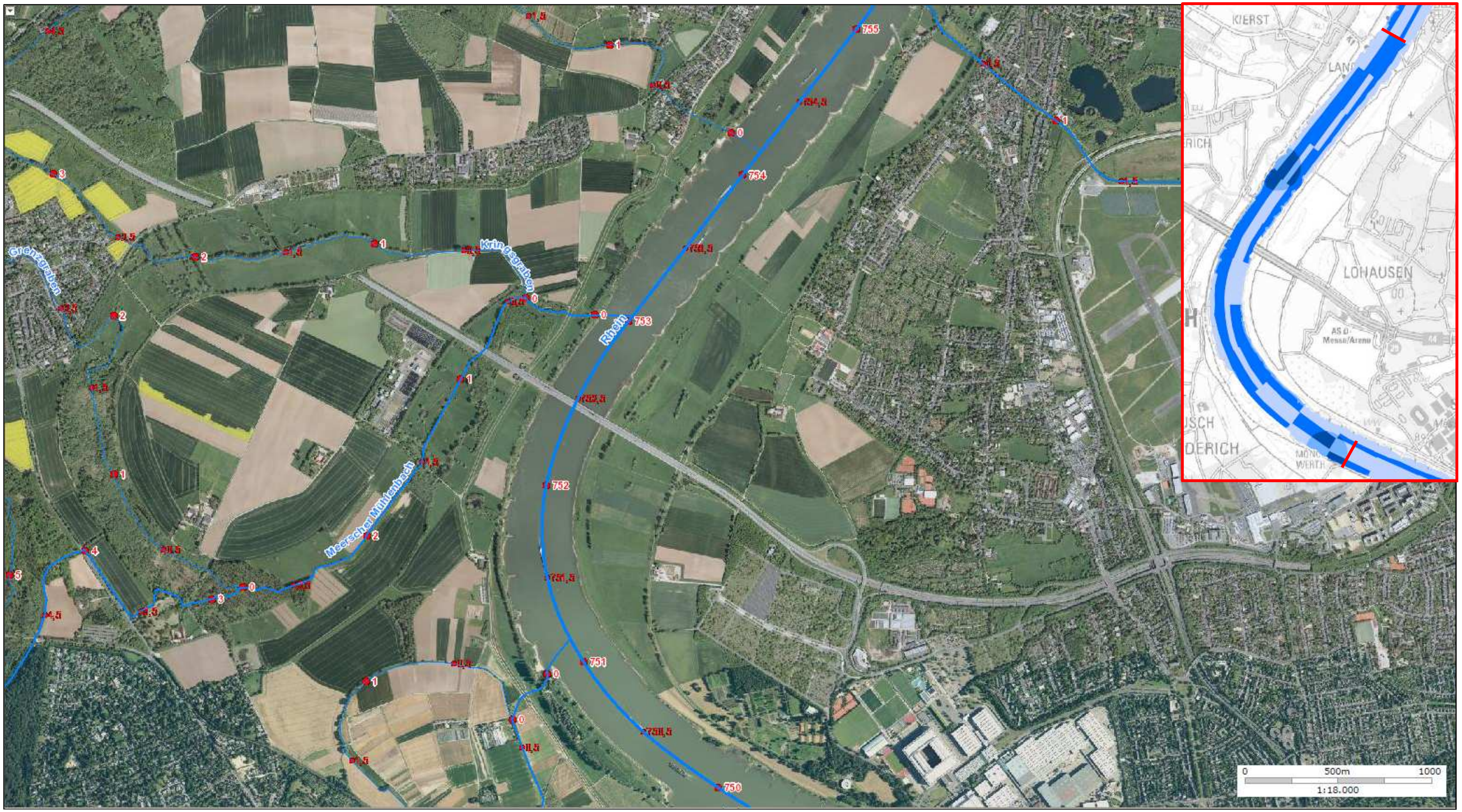


Figure 5.2.4 Potential spawning area No.4 ("Neuss") – Rhine-km 726.0 – 730.5 (length 4.5 km)

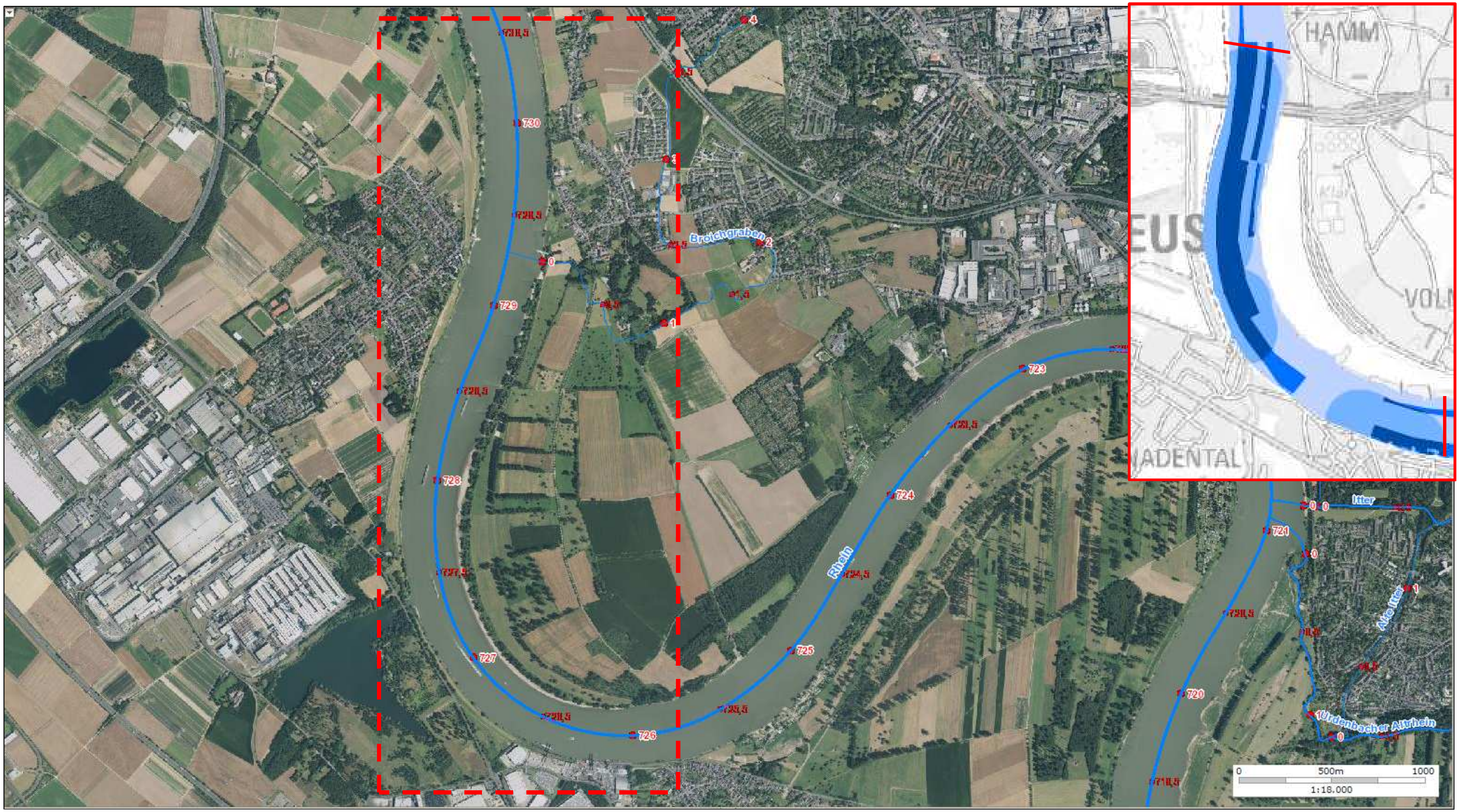


Figure 5.2.5 Potential spawning area No.5 ("Köln-Porz") – Rhine-km 677.5 – 681.0 (length 3.5 km)

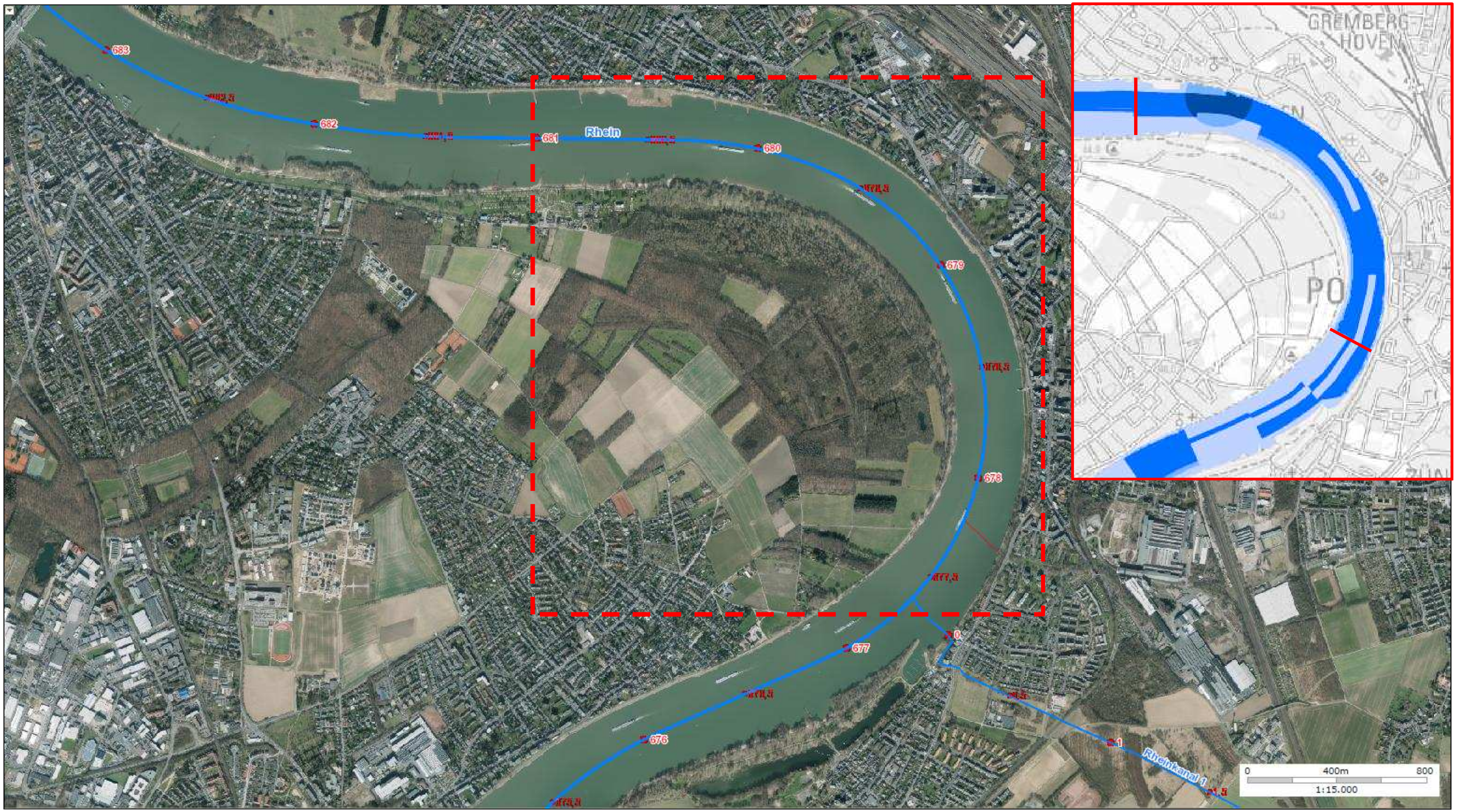


Figure 5.2.6 Potential spawning area No.6 ("Wesseling") – Rhine-km 668.5 – 674.0 (length 5.5 km)

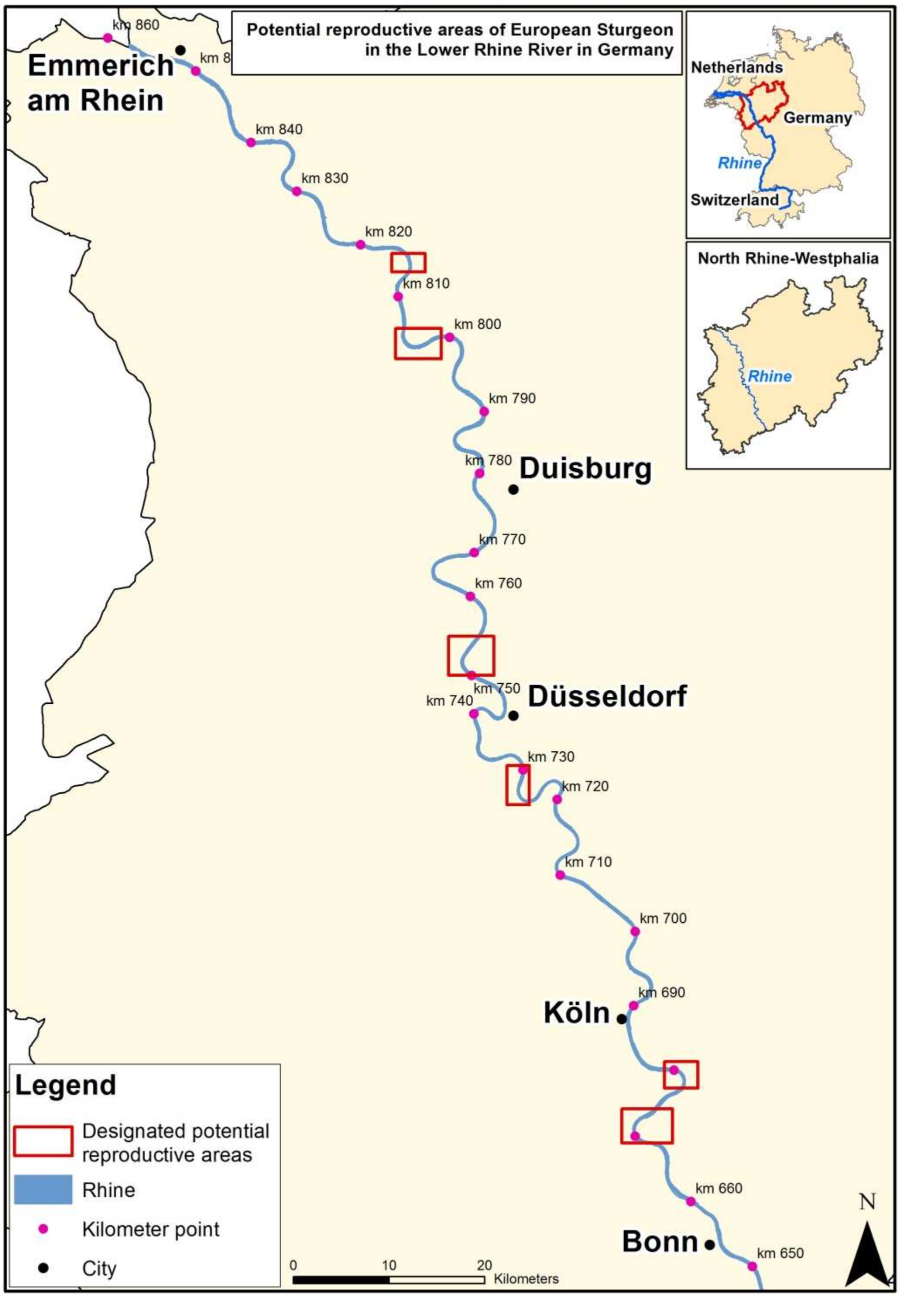


Figure 5.2.7 Overview of the localisation of designated potential spawning areas along the Northrhine-Westphalian reach of the Rhine River

5.3 Potential impairment of sturgeon reproduction by thermal loads and warming of the River Rhine

5.3.1 Temperature requirements of European sturgeon during reproductive season

European sturgeon can be considered as a late spring and summer spawning species. Spawning normally takes place from May to July, but it is also reported that reproductive season might start earlier in April and last longer up to August. Therefore, sturgeon is adapted to correspondent intermediate to high temperatures during spawning as well as embryonic and larval development. Tab. 5.3.1 summarises specifications from a literature review regarding temperature requirements of European sturgeon.

Table 5.3.1 Summary of specifications from literature regarding temperature requirements of European sturgeon (observed spawning temperatures and suitable temperatures for egg and larval development)

	spawning	author
temperature	17 - 20 °C	Ehrenbaum 1936
	17 - 22 °C	Geßner et al. 2010
	17 - 22 °C	Tautenhahn & Geßner 2014
	17 - 22 °C	Geßner & Schütz 2011
	18.5 - 19 °C	Magnin1962
	17 - 21 °C	Ninua 1976
	7.7 - 22 °C	Holcik et al. 1989
	8 - 25 °C	Dettlaff et al. 1993

	Development of eggs / larvae	author
temperature	17 - 20 °C	Rosenthal et al.
	17 - 20 °C (eggs), 15 - 22 °C (larvae)	Geßner & Schütz 2011

The range of 17 – 22 °C is reported as typical spawning temperature, corresponding to the upper range of a typical annual temperature curve of rivers in the temperate zone. Even when the temperature regime of the River Rhine is affected by cooling water discharges, which have caused a significantly increase of yearly average water temperature, it seems unlikely that the reproductive success of a species adapted to such high temperatures may seriously be impaired by the recent temperature regime of the River Rhine. Most fish species inhabiting the River Rhine with well-established and successfully reproducing stocks possess significantly lower thermal limits during reproductive season.

Nevertheless, the potential impairment of sturgeon reproduction in the Rive Rhine by its recent temperature regime change and its affected anthropogenic warming is examined in Chapter 5.3.2 in more detail.

5.3.2 Thermal loads and warming of the River Rhine

The water temperature regime of the River Rhine is influenced by different factors including overall atmospheric conditions, discharge of main tributaries, groundwater influences and anthropogenic thermal effluents. In the future, global warming and climate change may also have increasing effects on the water temperature of the Rhine River.

The topic of thermal effluents and its effects on water temperature is subject of monitoring and results are reported by the IKSR. The most recent survey of thermal effluents on German territory refers to the year 2006, in which 78% of thermal load originates from cooling water discharges from power plants.

The River Rhine is located in the temperate zone, where water temperature under natural conditions should range from 0 to 25 °C. However, due to thermal pollution and climate change, summer water temperatures of 28 °C (and above) could increasingly be observed in recent years.

Despite the fact that large scale measurement programs of water temperature were only set up during the last decades and techniques and concepts still have to be optimised and coordinated in a better way, there is substantial evidence that since the 1970s, an increase of yearly mean temperature of 2.5 °C has occurred (Fig. 5.3.1). From data collected at the Dutch station Lobith since 1900, an increase of mean temperature by 3 °C has been identified, of which 2 °C have been related to thermal effluents and 1°C has been related to climate warming. The number of days on which water temperature thresholds of 23 °C and 25 °C are exceeded respectively have significantly increased during the last years (Fig. 5.3.2). At the same time, the number of days on which water temperature fell below 1°C has significantly declined since the 1980s.

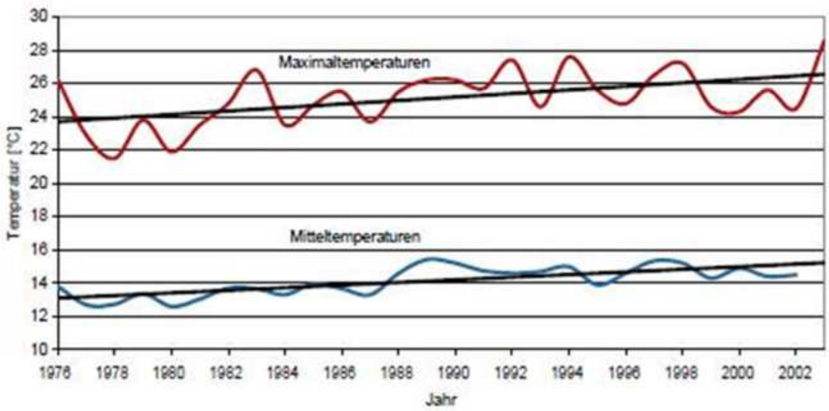


Figure 5.3.1 Curves of mean annual water temperature (blue line) and yearly maximum water temperature (red line) based on man daily water temperature values in the River Rhine at Mainz from 1976 to 2003 (retrieved from IKSR, 2004)

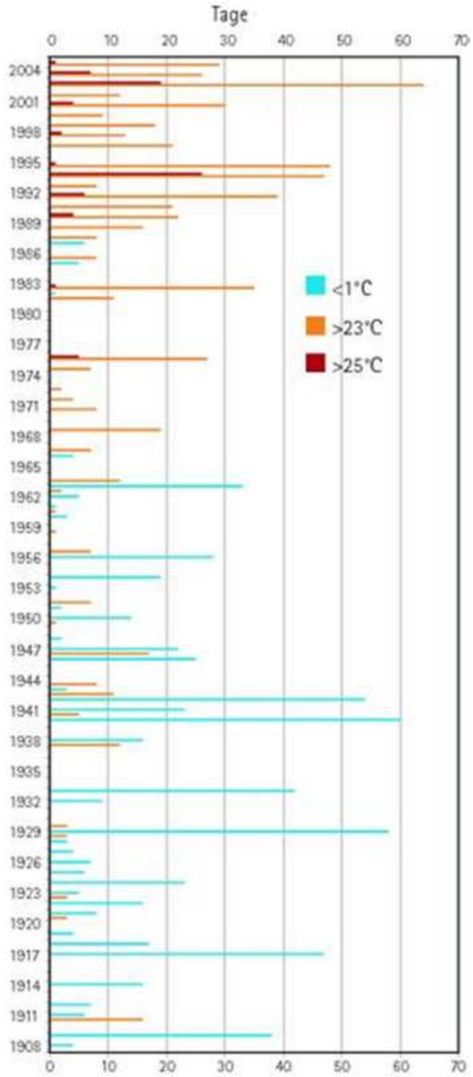


Figure 5.3.2
Number of days on which water temperature in the River Rhine fell below (1°C) or exceeded (23 °C or 25 °C) the threshold for water temperatures in time span 1908 – 2005) (retrieved from www.waterbase.nl)

When it comes to Northrhine-Westphalia, between the time periods 1978-1988 and 1995-2005 the mean temperature of the Rhine River has increased by 1.2 °C, whereat a subsequent numeral increase and elongation of periods with elevated water temperatures is expected (MUNLV 2007a,b). Special attention is paid to this problem. A water temperature model for the purposes of monitoring, evaluation and forecast water temperature development (with special emphasis on the effects of anthropogenic thermal loads) was established (Jacob 2013).

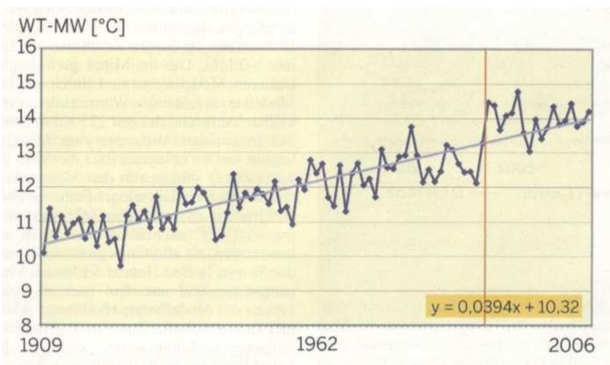


Figure 5.3.3 Annual mean water temperature in the River Rhine and long-term linear trend at Mainz from 1976 to 2003 (measuring station Lobith) (retrieved from Jacob 2013, based on data source www.waterbase.nl, Rijkswaterstaat)

Actual temperature data (2004-2015) from three different measurement stations along the Northrhine-Westphalian reach of the Rhine River were analysed in terms of monthly mean temperature per year (for months May, June and July, representing the potential reproductive season of sturgeon). Results (Fig. 5.3.4) reveal that monthly mean temperature in May and June never exceeded the threshold of 22 °C (which marks the upper range of reported spawning temperature for sturgeon). Therefore, an impediment of the reproduction of sturgeon during the months May and June by recent water temperature regime change of the River Rhine can be ruled out. In July, monthly mean temperatures occasionally (in some years) exceeded the 22 °C – threshold. This can be interpreted as an indication that in exceptional cases (some years), in late spawning season some impairment of reproduction due to elevated temperature cannot be excluded. Because the 22 °C-threshold is not a physiological critical thermal limit but just the upper range of reported spawning temperatures, sturgeon may also reproduce successfully at temperatures above that threshold. Moreover, it has to be considered that sturgeon may react to elevated temperatures with an earlier start of spawning activities at suitable temperatures. Therefore, the analysis of recent water temperature data gives no evidence that reproduction of sturgeon may be seriously impaired by anthropogenic warming of the River Rhine.

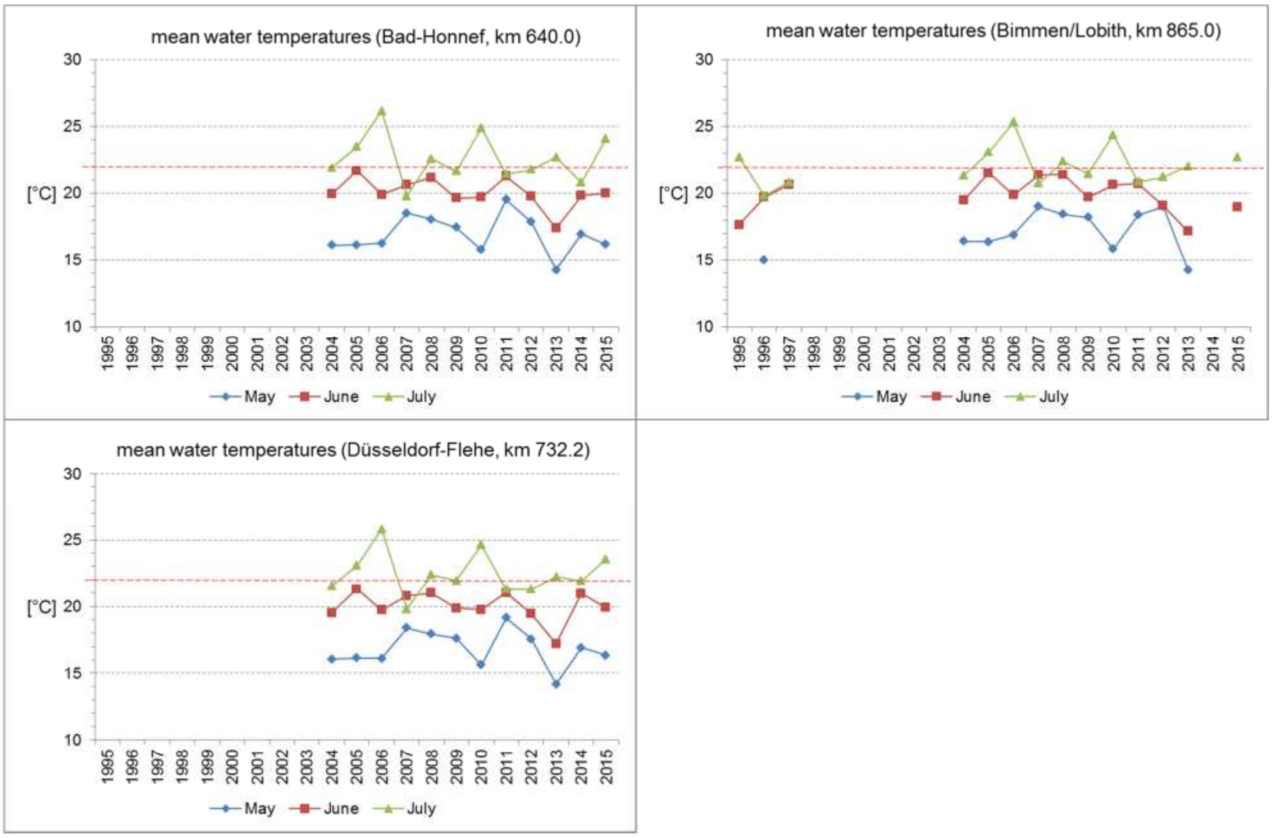


Figure 5.3.4 Monthly mean water temperatures at three different measurement stations along the Lower Rhine River (red line indicating the 22 °C-threshold, which marks the upper range of spawning temperature reported in literature) (Data provided by the Landesamt für Natur, Umwelt und Verbraucherschutz NRW)

The phenomenon of more or less continuously increasing mean water temperatures in the River Rhine generally implicates a thread to fish reproduction, because the reproductive cycle (gametogenesis) may be disturbed or because temperatures in the reproductive season may shift outside of the preferred or tolerated range of a species, thereby affecting spawning behaviour or egg and larval development. This is particularly relevant for species adapted to low temperatures in their reproductive season. Nevertheless, species adapted to warmer temperatures may be affected by anthropogenic warming of rivers as well.

However, it can be stated that the recent and foreseeable temperature regime of the River Rhine (affected by anthropogenic thermal loads and climate warming) does not represent a threat to reproduction of European sturgeon. Predicted effects of climate change may even improve spawning habitat quality (with regard to temperature conditions) in the River Rhine basin during the next 50 to 100 years (Lasalle et al. 2011).

In this context it has to be mentioned that it is has not yet been assessed which effect the very recent turnaround of energetic policy in Germany with the corresponding shut-down of several nuclear power plants along the Rhine will have. Due to the cessation of large amounts of cooling water discharges, the temperature increase may be decelerated remarkably, but this has not been verified yet.

6 Discussion and recommendations

The main objective of the present study was to evaluate the suitability of potential reproductive habitats for European sturgeon in the River Rhine. For this purpose, it was necessary to develop a methodology in order to evaluate (qualitative) suitability and (quantitative) availability of reproductive habitats. A GIS-based analysis of existing data sets (provided by waterway authorities and related institutions) on physical habitat parameters such as water depths, flow velocity and substrate composition, taking into account anthropogenic impacts on the river ecosystem (e.g. industrial navigation), was performed. The successful development of such a method was essential for the intended comprehensive habitat evaluation within the former distribution area of European Sturgeon in the Rhine-system, because it proved to be impossible to conduct an equivalent evaluation by mapping work in the field in a large investigation area such as the given one.

The application of the GIS-based analysis method to the lower Rhine River revealed that potential suitable spawning habitat of sturgeon make up roughly 1/3 of the lower River Rhine's surface area in its current state. Out of the analysed area of 66 km^2, 21.8 km^2 could be classified as "suitable" spawning habitat. Based on these results, it can be concluded that the quantity of available potential spawning habitat in the lower Rhine River will be no bottleneck for natural reproduction of a future sturgeon stock in the lower River Rhine.

Nevertheless, a more detailed evaluation reveals that certain challenges might arise:

- The surface areas of potential spawning habitat classified as "highly suitable" (due to the vicinity of deep river potholes) is rather low (2.4 km^2, representing 3.6 % of the main channel area). Considering the potential importance of these resting pools for adult spawning sturgeon, this may affect the reproduction of sturgeon. The lack of deep river potholes is a consequence of waterway maintenance during the last decades, in which potholes were increasingly filled. Focus should be placed on preservation of the remaining potholes.
- The total area of potential spawning habitat partly represents the sum of numerous small areas, each of which may be too small to be perceived as spawning habitat by the fish. Therefore, the area of spawning habitat that will actually be used by the fish will probably be much lower than the calculated area. This aspect was taken into account by the designation of longer river stretches (> 500 m length) with high portions of areas classified as "suitable" spawning habitat (Chapter 5.2), resulting in the identification of five river stretches of 2 – 5 km length representing potential spawning areas. However, even after taking into account this reduction in surface area of suitable spawning habitat availability will be sufficient.
- Potential spawning habitats in the lower River Rhine are located in a river stretch characterised by intensive industrial navigation. Thus, the reproduction may be strongly affected and seriously hampered by the effects of navigation. From the total area classified as „suitable" reproductive habitat of 21.8 m^2 within the Northrhine-Wesphalian stretch of the River Rhine, 11.8 km^2 are situated within the designated navigation channel. This implies that 54 % of potential spawning habitat area is immediately subjected to the potential negative impacts of industrial shipping. Out of

the 2.4 km^2 of „highly suitable“ reproductive habitat (in the vicinity of deep river potholes), 0.9 m^2 are situated within the navigation channel, depreciating the area by 37.5 %. It can be assumed that intensive industrial navigation will have severe impacts on the reproductive success of sturgeon, although this cannot be quantified yet. Nevertheless, the negative implications of navigation will likely not cause a total loss in reproduction. In principle, successful reproduction will be possible.

The present study covers the aprox. 220 km stretch of the lower Rhine River in Northrhine-Westphalia, representing only a fraction of the area in the Rhine-system where reproduction of the former sturgeon population probably took place. Therefore, the scientific relevance of the study’s results depends on the yet unknown migration behaviour of a future sturgeon stock. If the fish will only migrate over short distances, its spawning grounds may be located in the investigated lower Rhine River. There is some evidence that this might be the case, because the sturgeons in the Garonne River migrate over a distance of approximately 180 km (where the first obstacles are located) or 280 km before spawning (Gessner, personal communication). If fish in the Rhine-system will show similar migration behaviour, the present study covered the exact river stretch, where future spawning grounds of sturgeon most probably will be located. However, it is also possible that the fish will migrate over longer distances and further upstream, with spawning grounds consequently located in the Middle or Upper Rhine region. Therefore, it seems worthwhile to expand the analysis to this reach of the River Rhine.

The main outcomes of the present study as presented above are not surprising, since the River Rhine can generally be classified as a fast flowing, rather deep river with a river bottom consisting predominantly of coarse substrate. This also applies to the downstream reaches of the German lower Rhine region. These general characteristics are only marginally affected by the habitat degradation caused by channelisation and embankments, as they mainly affect habitat conditions along the shallow bank zones. The same holds true for the Middle and Upper Rhine region, which is why generally similar results can be expected there. Nevertheless, the hydromorphological characterisation of the Middle and Upper Rhine differs significantly from the Lower Rhine River in combination with significantly lower navigation intensity. Hence, it seems worthwhile to acquire detailed information regarding potential spawning habitat availability in that reaches through further research.

Recommendations

- A comprehensive overview on reproductive habitat availability and quality in the River Rhine is required to assess the prospects of success for natural reproduction of a future sturgeon population in the River Rhine. Since the investigated reach of the lower Rhine River represents only a part of the former distribution area of European sturgeon in the Rhine-system where natural reproduction probably took place, the evaluation of potential reproductive habitat of European Sturgeon in the River Rhine should be continued and expanded to the more upstream reaches of the Middle and Upper Rhine (up to the dam at Iffezheim at Rhine-km 336) and possibly to more downstream parts of the Lower Rhine in the Netherlands. Such an extension of the investigation area is needed, because the migration behaviour of a future sturgeon population is yet unknown. It is possible that fish of an introduced population will migrate over longer distances and look for spawning grounds in the Middle and Upper Rhine region. However, it is also possible that the fish will migrate only over short distances and look for spawning grounds closer to the sea in the Dutch part of the Lower Rhine. For an expansion of the analysis it is necessary that environmental data sets (as used in the present study) will be available in sufficient quantity and quality for the additional river stretches to be analysed.

- The GIS-based analysis (of the environmental data sets) has so far been restricted to the aspect of suitability and availability of spawning habitats. However, besides habitat requirements of spawning adult sturgeon and the successful development of eggs, the fulfilment of habitat requirements of hatched fry and young-of-the-year juveniles during their downstream migration to the estuary determine the species' reproductive success as well. Therefore, it seems to be appropriate to expand the GIS-based analysis to the aspect of YOY habitat suitability and availability, although this may be difficult due to the lack of knowledge concerning YOY habitat use and requirements. In this context, additional factors beside physical habitat suitability and availability impacting the survival of YOY, such as food conditions and predation. For such an analysis, it would be interesting to take into account that the recent invertebrate fauna in the River Rhine is dominated by allochthonous species, whose relevance as a food resource is questionable. Moreover, it seems advisable to take into account the recent mass occurrences of potential benthic predators in form of the invasive goby species.

- The results of the present study emphasise the significant impact that industrial shipping may pose on spawning habitat suitability and reproductive success of sturgeon in the River Rhine. Although a high portion of potential reproductive habitat is situated within the designated navigation channel, it remains speculative to what extent reproductive success will be hampered by intensive shipping activities. Unfortunately, there are no scientific findings available yet regarding the concrete effects of intensive industrial shipping on behaviour and reproductive success of sturgeon, although the vulnerability to injury and killing caused by ship's propellers is documented (Spierts 2016). It can be assumed that the degree of immediate impairment (effects of propeller induced slipstream and turbulences on spawned eggs and larvae) depends on the water level situation during reproductive season, whereby the lower the water level, the more critical the situation will be. Due to the high inter-annual variability of discharge regimes, it can be assumed that there will be years with no or little potential impairment of sturgeon reproduction. Irrespective of these assumptions, it is unknown how adult spawners may react to intensive disturbances due to noise or turbulences caused by numerous vessel passages. It is possible that these disturbances induce an avoidance reaction and a further upstream migration into river stretches with significantly less navigation activity. As a consequence, highly suitable spawning habitats in downstream regions would not be used by the fish.

The industrial navigation is a factor that cannot be controlled by ecologists. Therefore, three conclusions can be drawn from the discussion:

- Scientific knowledge on the actual effects of vessel passages on spawned eggs and larvae of sturgeon on the river bottom as well as on the effects of navigation induced disturbances on the behaviour of adult spawners should be invested in to enable a realistic evaluation of the actual impairment of sturgeon reproduction by industrial navigation.
- River restoration measurements that will reduce or exclude the negative implications of industrial navigation (e.g. the establishment of side-channels), should be promoted and favoured. Since the establishment of side-channels is already a favoured measurement in Northrhine-Westphalia in order to improve the ecological state of the River Rhine, there will be synergetic effects with the implementation of measurements in context with the EU-water framework directive.
- The intensity of industrial navigation has to be considered in the evaluation of reproductive habitat quality. Hence, it should be focussed on river stretches with significantly lower navigation density than in the downstream part of the Lower Rhine River (up to the harbours in Duisburg or Cologne). Therefore, the habitat evaluation study should be expanded to Middle and Upper Rhine region.

Because it is considered to promote a possible re-introduction of European sturgeon into the Rhine River with experimental releases of young sturgeons (Houben, personal communication), the following recommendations for selecting stocking sites can be made. Release sites should be located within one of the designated potential reproductive areas located in the upstream reach (i.e. area no. 6 „Weseling“, area no. 5 „Köln-Porz“, area no. 4 „Nezss“), based on the following considerations and assumptions: On their downstream migration fish would have to pass the other potential reproductive areas located downstream of the release site and thereby fish may learn about river typology. This may facilitate their return as adult spawners and the recognition of potential spawning places. Futhermore, they have to pass the downstream parts of Lower Rhine River, which is rich of connected sidewaters (gravel-pit lakes, marinas, side channels). These sidewaters provide valuable food ressources different from the main channel and also represent potential shelter and resting habitats, which may be used by the fish for interrupting their migration resulting in an improved condition for further downstream migration.

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