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Historical Patterns of Anthropogenic Impacts on Freshwaters in the Berlin-Brandenburg Region

Historische Muster anthropogener Einflüsse auf das Gewässernetz in der Region Berlin-Brandenburg

With 10 Figures

Since humans are preferentially settling in flood plains they often influence freshwater systems intensely. The first signs of anthropogenic impacts on surface waters in the Berlin-Brandenburg region are approximately 3000 years old. Considering the multiple and intense human uses of surface waters in this region, we analysed when, how and to which extent regional rivers and streams became impacted by dams, water mills and fish weirs resulting in changes in morphology, hydrology and ecological functioning. We hypothesise that the development and growth of cities in this region necessitated (1) efficient navigability of rivers linking them, (2) efficient use of hydropower resources for mills, and (3) significant pollution of surface waters especially with the beginning of industrial development. We analyse these hypotheses by means of three regional examples and delineate the effects of human uses on selected surface water bodies. Understanding the effects of these historic modifications of surface water supports the identification of options for a sustainable use of surface waters that are currently still subjected to multiple uses but face a significant decrease in discharge due to climate change.

1. Introduction

Rivers, lakes and their floodplains have always formed preferential sites for human settlement, as they provide a number of economic benefits e.g. in terms of fishing, agriculture and transport. By use of these benefits, freshwater systems were considerably altered already in the Ancient World. People abstracted water for drinking as well as for horti- and agriculture. On the other hand, people had to protect themselves from the water, e.g. during flooding. Thus, facilities for water use and for protection against the water are among the oldest known technical systems (*Garbrecht* 1985). Today anthropogenic impacts on freshwater systems include a much wider array of human activities, including the building of weirs, dams and locks, flood protection by levees, navigation, loading by waste waters and industrial pollutants, and last not least human recreation (see also *Deutsch* 2004).

In the region of today's Berlin-Brandenburg – as in most parts of Europe – no pristine surface water bodies can be found any more, as rivers and lakes have played a key role in the socio-economic development of the region that can hardly be overestimated. The first signs of anthropogenic impact in the Berlin-Brandenburg region date back about 3000-4000 years. For example, a first correction of the Spree River may have occurred already in the late Bronze age, 3500 years ago (*Goldmann* 1982), first human-induced eutrophication started 2000 years ago (*Schelski* 1997, *Schönfelder* 2000), damming of small brooks and headwaters started in the 8th/9th century, with the largest numerical increase of water mills in Europe between 1150 and 1250 (*Reynolds* 1983). Fisheries are one of the oldest uses of surface waters, and fyke nets and nets excavated in the Havel region have been dated back 7000 years BP. Already 3000 years BP, at the end of the Bronze Age in Brandenburg, the waterway along the rivers Elbe, Havel, Spree, and Oder formed probably the main connection between the North Sea and Bohemia (*Natzschka* 1971), while the first documented use of the Havel River for inland navigation dates back to 789 AD (*Uhlemann* 1994).

Surface waters served as the main routes for transportation for several centuries, as terrestrial transportation was hampered by widespread sandy and swampy ground. For that reason, the west Slavic tribes of the Hevellers and Sprewans that populated the area since the migration period in the 5th and 6th century built their settlements and fortifications on the shores of major waterways, e.g. in Havelberg, Rathenow, Potsdam and Köpenick. At that time, lakes and lowland rivers still served as a continuous source of food, too, as fishing was well developed. The German expansion towards the east in the 13th century resulted in the foundation of major cities (Frankfurt/Oder and Berlin) located at fords in the largest rivers in the region, Oder and Spree. As mentioned earlier, the medieval times became the high season of damming and weir fisheries. The oldest dams in the main rivers of the region date back to 1000-1100 AD, even if they were often first documented not before the 13th century (*Natzschka* 1971, *Uhlemann* 1994, *Driescher* 2003). Fish weirs were first documented in 1187 and were ubiquitously used throughout the Middle Ages (*Bestehorn* 1913).

Considering these multiple and intense human uses of surface waters in the Berlin-Brandenburg region, we analysed when, how and to which extent regional rivers and streams became impacted by dams, water mills and fish weirs resulting in changes in morphology, hydrology and ecological functioning. We hypothesise that the development and growth of cities in this region necessitated (1) efficient navigability of rivers linking them, (2) efficient use of hydropower resources for mills, and (3) significant pollution of surface waters. Together, these effects did not only result in extensive use and alteration of regional freshwater resources in terms of water quantity (runoff) and quality (waste), but also significantly affected other traditional uses of surface waters. With the industrial revolution and rapid growth of Berlin in the 19th century pollution of rivers by urban and industrial wastewaters multiplied. After mechanisation of farming, drainage of large wetlands and the invention of artificial fertilizers water bodies received significant additional diffuse nutrient inputs. As a consequence, the importance of commercial fishing decreased significantly, and the ecological status of surface waters reached its minimum in the 2nd half of the 20th century, with significant consequences to human health and welfare.

In the following sections we analyse these hypotheses by means of three examples and delineate the effects of human uses on surface waters.

2. Material and Methods

As mentioned before, there are various signs for the early beginning and large extent of anthropogenic impact on freshwater resources in the Berlin-Brandenburg region. However, individual historical impacts and the effects they produced can often no longer be recognised, partly due to the superposition of several human impacts. As a result, we see in the environment only consequences of human impacts from the last c. 100 years. Following our hypotheses, we can derive three qualitatively different stages of anthropogenic impact in chronological order:

- Installation of local and heterogeneously distributed small-scale structures like dams, water mills, fish weirs;
- Development of the longitudinal navigability of entire river courses, large-scale landscape drainage, and establishment of flood control measures at regional scale;
- Direct and diffuse pollution of streams and rivers (waste water discharge), channelisation of the most streams.

The long-term consequences of these human impacts are only detectable for measures taken several decades ago at least, while older effects may have been superposed and cannot be readily discerned any more. Hence, we analysed the historical literature to discern which historical human activities probably had significant impact on the surface waters of Berlin and Brandenburg based on today's knowledge on so-called pressure-impact relationships in the aquatic sector.

3. Results and Discussion

3.1 Impact of inland fishing

The long-term history of multiple uses and modifications of lowland rivers and their impacts on fish composition shall be illustrated at the example of the lower Havel River, Germany. This largest right-hand tributary of the Elbe River is a 325 km long lowland river draining a total catchment of 24,297 km² with an average discharge of 96 m^3s^{-1} to the North Sea.

The Havel catchment was formed during the second stage of the Weichsel Glaciation about 10,300 years ago. First settling places and remains from fishing gears excavated in the lower River Havel region have been dated back to the Mesolithic, 9000 years ago (*Cunliffe* 1996). Numerous items – harpoons, nets, weights, floats and fishing hooks aged 6500-5200 years – indicated well-developed fishing in that period (*Cunliffe* 1996, *Cziesla* 2001). The lower River Havel was comparably densely populated during the Bronze Age (1500-700 BC) (*Goldmann* 1982) and formed the most important settlement area in Brandenburg of the pre-Roman Iron Age (600-1 BC, *Seyer* 1982).

Human settlements were commonly situated very close to the water, especially at suitable river banks. This allowed *Goldmann* (1982) to plausibly derive first signs of significant hydraulic engineering in the Havel region for the Bronze Age, about 3500 BP: artificial fosses for navigation at Spandau. Further, the change to a wetter climate with higher water levels and inundation of the large floodplain was indicated by the situation of the settlements: about 0.5-1 m above the Havel floodplain during the Bronze Age in contrast to on average 2 m above during the pre-Roman Iron Age as a response to increased flooding (*Seyer* 1982).

In the Havel region the construction of first mills and dams to use hydropower started already in the

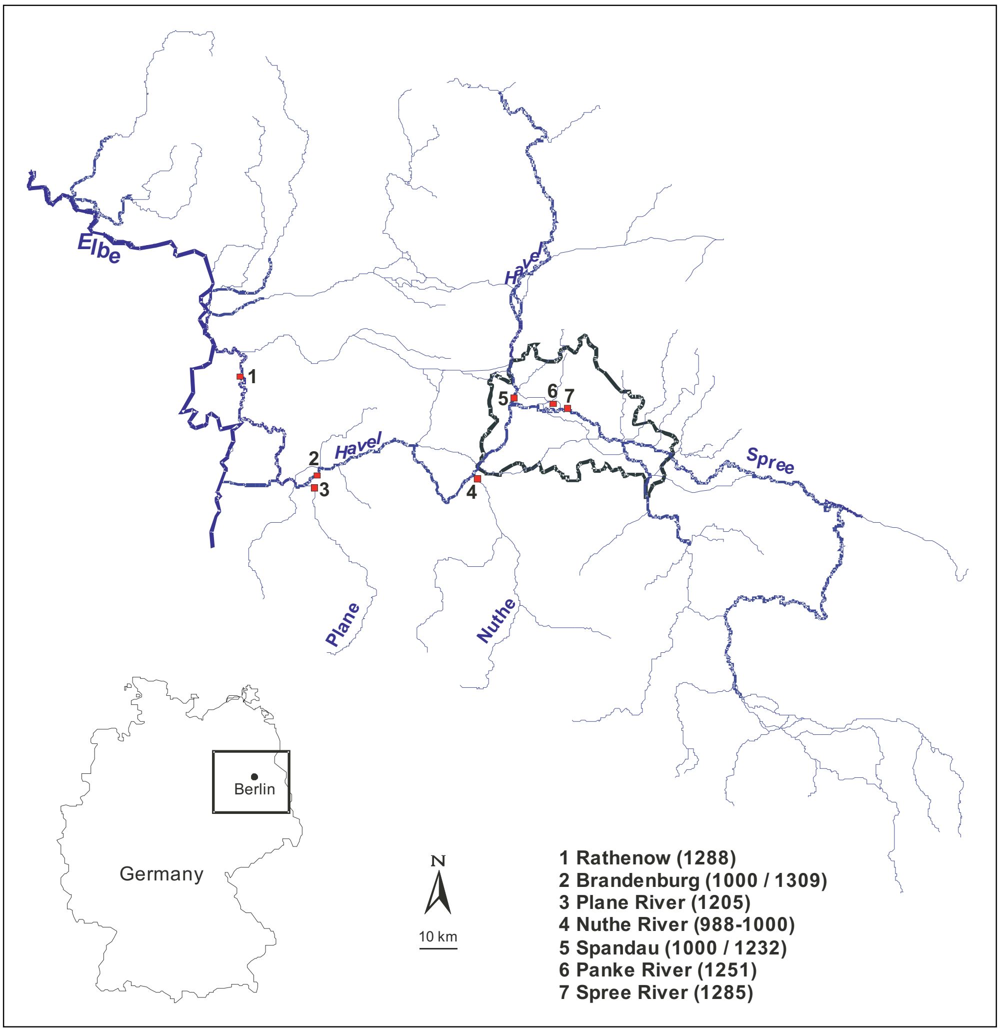

Fig. 1 First mill dams (year) along the course of the lower Havel River and its tributaries
Erste Mühlendämme (Jahr) an der Unteren Havel und ihren Zuflüssen

10th century (*von Müller* 1986, *Driescher* 2003), e.g. in Brandenburg and Spandau (*von Müller* 1986, *Fig. 1*). In 1180, the castle and town of Spandau were relocated 1.5 km upstream the Havel River due to an increased flood frequency resulting from the dams near Brandenburg (*von Müller* 1995). At the same time, around 1100, the first flood protection works, dams and levees, were constructed along the Elbe River and the lower Havel River (*Simon* 1994). Numerous obviously already existing weirs were first documented close to Spandau in 1232, Rathenow in 1288 and Brandenburg in

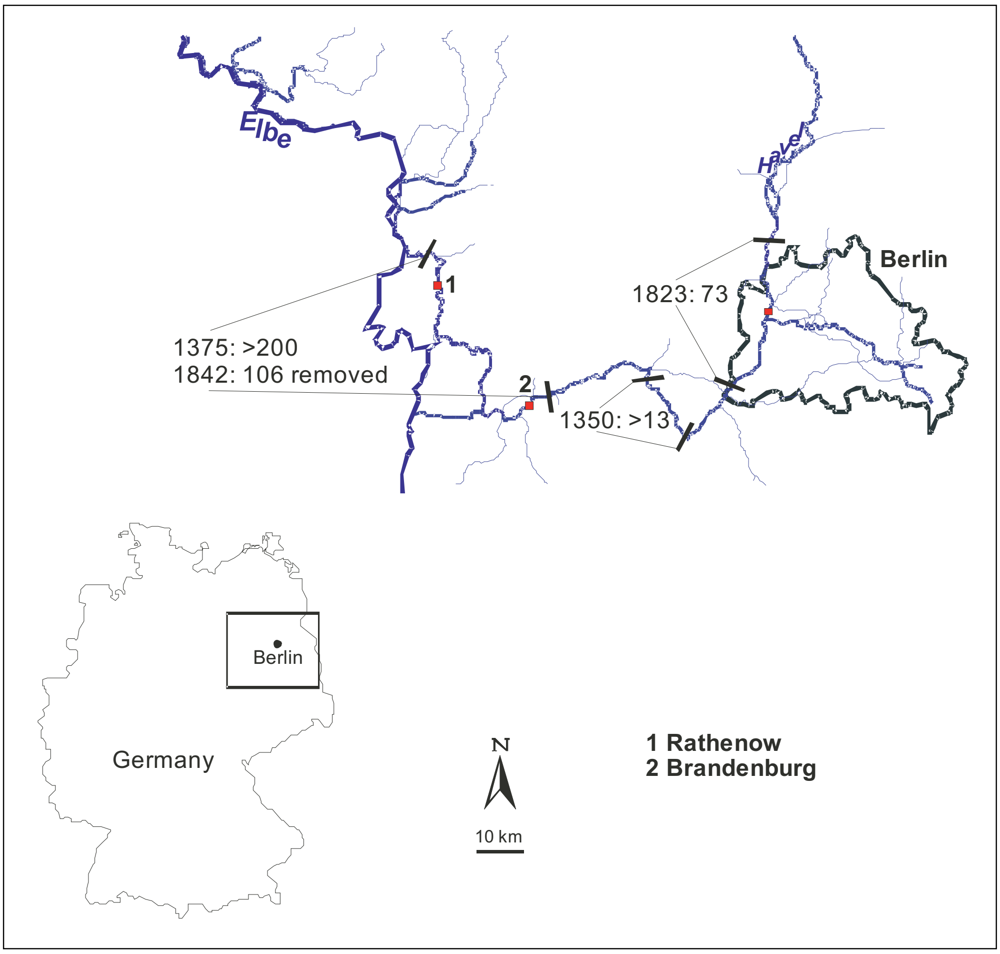

Fig. 2 Medieval fish weirs along the course of the lower Havel River and its tributaries
Mittelalterliche Fischwehre an der Unteren Havel und ihren Zuflüssen

1309 (*Natzschka* 1971, *Uhlemann* 1994, *von Müller* 1995, *Driescher* 2003). Further, several faster-flowing tributaries of the lower Havel River were blocked very early (*Fig. 1*): the Nuthe River at its mouth between 988 and 1000 (*Driescher* 2003), the Plane River mouth, additionally relocated after 1205 (*Driescher* 2003), the Panke River near Wedding in 1251 (*von Müller* 1968), and the Spree in Berlin in 1285 (*Natzschka* 1971). These dams may have existed as well long before their first documentation. Beside the mill dams, extensive weir fishing peaked in the Middle Ages causing large-scale water level increase and river fragmentation (*Bestehorn* 1913, *Arand* 1932). Fish weirs were constructed from wood posts, wattle fences and large stones as barriers, mostly completely blocking the river channels. Usually, these weirs had openings behind which baskets were positioned to catch the fish. Fish weirs were first documented in 1187 when margrave Otto II assigned the fishing rights on large Havel stretches including all fish weirs to minster at Brandenburg cathedral (*Bestehorn* 1913).

Along the lower Havel River there must have been an incredible number of fish weirs in the Middle Ages, totaling about 200-400 at the end of the 14th century (*Bestehorn* 1913, *Arand* 1932, *Driescher* 2003, *Fig. 2*). Although in 1771 Frederick the Great had those fish weirs removed which were hampering navigation on the Havel River most, nearly 100 remained until the beginning of the 19th century (*Bestehorn* 1913). Between 1837 and 1842 a total of 106 large fish weirs were removed from the Havel River around Brandenburg and Rathenow (*Fig. 2*), at the expense of 225,000 Mark, to improve the discharge capacity of the river and inland navigation (Verwaltung der Märkischen Wasserstraßen 1905).

The ascent of inland navigation finally brought an end to the weir fisheries. Inland navigation on the Havel River was first documented in 789 (*Schich* 1994, *Molkenthin* 2006). In the 13th and 14th century the Havel belonged to the most important waterways of Central Europe (*Schich* 1994). Accordingly, the first recorded navigation locks north of the Alps were constructed here, near Brandenburg and Rathenow 1548-1550 (*Uhlemann* 1994) and in Spandau 1556 (*Schich* 1994).

The foundation of the German Tariff Union on January 01, 1834 marked the beginning of industrialisation. After that, the navigation paradigm has shifted completely from the historical adaptation of numerous vessel types to the specific river conditions to an adaptation of the rivers to the continuously increasing number of vessels. The first regulation of the entire Havel River for navigation purposes was conducted between 1875 and 1890 aiming to establish a fairway of 55 m width and 2-2.5 m depth at mean discharge and of 45 m width and 1.25-1.5 m depth at low discharge (*Natzschka* 1971). The second regulation between 1897 and 1902 further increased the fairway cross section and enabled 600 t vessels to reach Berlin (*Uhlemann* 1994). Thereafter the vessel transport increased to 400 vessels on average per day and a total volume of 6.3 million tons per year (*Natzschka* 1971). The doubling of the river profile dramatically increased the discharge capacity of the river, and thus a third regulation by dams became necessary to safeguard the water levels required for navigation. Between 1907 and 1913 three new weirs were constructed and the river was fully channelised and embanked up to Berlin (*Uhlemann* 1994). Today the average grade of the lower River Havel at low discharge conditions is 0.002 ‰ and the water body is nearly stagnant.

The long history of human pressures has had dramatic impacts on the fish community. First of all the long-distance migratory species disappeared from the system. These species depend on regular migration between marine and freshwater habitats to complete their life cycle. Interrupting their spawning migrations and blocking access to potential spawning sites in the headwaters as well as in the tributaries will inevitably result in failing reproduction, decreasing populations and extinction. Correspondingly, in Berlin the last salmon (*Salmo salar*) was caught on February 12, 1787 (*Krünitz* 1792: 212), the last sea lamprey (*Petromyzon marinus*) and the last sturgeon (*Acipenser sturio*) in 1868 (*Friedel* 1869, *Friedel* and *Bolle* 1886), and the last river lamprey (*Lampetra fluviatilis*) around 1875 (*Wittmack* 1875).

Further typical riverine species disappeared (barbel *Barbus barbus* and vimba *Vimba vimba*) or decreased dramatically due to the large-scale loss of lotic habitats caused by damming and regulation (*Wolter* et al. 2003, *Wolter* 2007). Riverine fish have special adaptations to the environmental conditions of flowing waters like gravel spawning, benthic larvae stages, or higher oxygen demand, which will fail in conditions of artificially lowered flow velocities, increased siltation and clogging of substrata. Today, the lack of suitable spawning substrate is the most significant limitation for rehabilitating river fish communities (*Wolter* et al. 2003). It might be argued that most lowland rivers were never gravel-dominated; in their reference state, however, they maintained substantial amounts of rheophilic, i.e. lotic conditions preferring species (*Wolter* et al. 2005, *Wolter* 2007). There is strong evidence that in particular the first weirs and water mills were constructed in the narrower, faster flowing river sections with stabilised beds and banks to use the maximum hydro power (*von Müller* 1968, 1986, 1995, *Cunliffe* 1996) – the same sites historically providing the most suitable spawning substrata for river fish. It will never be fully explored which changes or losses in the local fish composition must be attributed to these habitat losses. Whilst the first weirs may have had a rather local impact, the large-scale regulation of the lower Havel River destroyed most of the suitable spawning grounds and caused a highly significant loss of river fish (*Wolter* et al. 2003).

3.2 River regulation and landscape drainage

3.2.1 Land use and fluvial dynamics

Historic modifications to river channels and adjacent floodplains are illustrated using the example of the Spree River. The Spree originates in the Lusatian Highlands near the German-Czech border, but in its middle and lower courses it represents a typical lowland river. In total, the Spree is 398 km long, draining a total catchment of 10,100 km², with an average discharge of 37 m^3s^{-1} at its mouth to the Havel River.

The section of the Spree River that flows through Brandenburg and Berlin mostly represents a typical meandering river. River meanders migrate slowly through the floodplain, as erosion takes place at the outer bank of the meander, and sediments are deposited near the slip-off slope. These fluvio-morphological processes leave characteristic traces in the floodplain. Hence, ancient meander structures can be recognised in many parts of the floodplain using aerial near-infrared photographs which document the former dynamics of the river (*Fig. 3*). Interestingly these meanders vary considerably in their radii. While most meanders that are currently flown through by the 'Müggelspree' east of Berlin have a radius of 60-120 m, ancient meanders may vary from only 30 m to more than 300 m. As meander size is related to river discharge, this range provides a first insight into the variation of flow the Spree has seen during the post-glacial and holocene periods. While the largest meanders were formed by melting waters from the huge glaciers during the postglacial period, the smallest ones are found at the same level of altitude as the recent river channel, and thus must be much younger. Their formation may be linked to drier climatic conditions, but also to the facts that in its pristine state the river catchment was densely forested so that runoff from the catchment was reduced by high evapotranspiration of these forests (*Schönfelder* and *Steinberg* 2004), and that the Spree may have used several (anastomosing) channels crossing alder swamp.

This smooth flow regime of the pristine Spree was presumably profoundly changed with the immigration of the Germans starting in the second half of the 12th century. The Germans developed agriculture at a rapid pace, and for that purpose cleared the major portion of the forests in the Spree catchment within a few generations. As a result, large pristine woodland was transformed into an agricultural landscape in the 14th century in Brandenburg. The massive shrinking of the forest which then only covered less than 20 % of the landscape (*Bork* et al. 1998), which is much less than today's 37 %, must have led to a massive increase of catch-

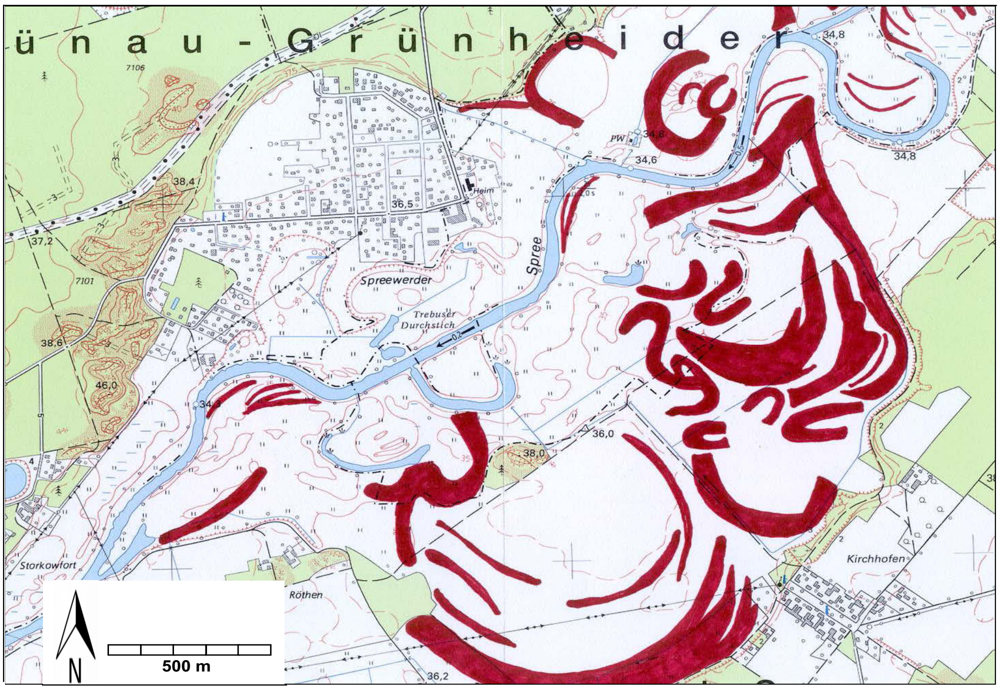

Fig. 3 Patterns of fossile meanders in the floodplain of the Spree near Mönchwinkel east of Berlin (study by *R. Carls*, in *Pusch* et al. 2001) / *Muster fossiler Mäander in den Auenbereichen der Unteren Spree bei Mönchwinkel, östlich von Berlin (Studie von R. Carls, in Pusch et al. 2001).*

ment runoff and river discharge. Moreover, deforestation led to an increase in the range of flow extremes, i.e. in the severity of droughts and floods. In July 1342 one of the heaviest floods of the whole millennium occurred that affected large areas of Central Europe (*Bork* et al. 1998, *Mudelsee* et al. 2004). It washed away much of the topsoil from crop fields that had been established on hill slopes, so that many villages had to be abandoned subsequently (*Dotterweich* and *Bork* 2007).

This event during the medieval climate optimum constitutes an early and impressive example for the interactions between over-exploitation of land, hydrological extremes and socio-economic conditions. Soil erosion resulting from deforestation and floods must also have been accompanied by a huge release of nutrients. This may have initiated a first temporary eutrophication phase in the Spree and Havel rivers (*Schönfelder* and *Steinberg* 2004). Their tributaries as well as the lakes of the region must have been similarly affected, too.

3.2.3 Mill weirs and groundwater levels

During the German colonisation, an increasing need for the use of hydropower emerged for the grinding of harvested grain, as well as for saw mills and iron hammers. Hence water mills were built along nearly every tributary of the Spree, e.g. in Müllrose (first mentioned 1275, *Peschke* 1934). The Spree itself was also used in several sections to drive mills, e.g. in Berlin (first mentioned in1285), Fürstenwalde (1298, *Eckoldt* 1998), Burg/ Spreewald (1315) and for the iron hammer in Schlepzig (1385, *Bayerl* and *Maier* 2002). The construction of the mill weir in the city of Beeskow (first mentioned in 1385) raised the water level of upstream Lake Schwielochsee considerably (*Driescher* 2003). By the end of the 19th century, 67 hydropower facilities existed along the middle section of the Spree (*Bayerl* and *Maier* 2002).

The demand for hydropower was not easy to meet in Brandenburg, as the stream network only exhibits a coarse mesh due to the geological setting. Hence even streams with low difference in head had to be used. These were often impounded in order to generate enough potential to drive mill-wheels, and to store water for the time of high demand after grain harvest. In the 16th century the 21-km 'Hammergraben' canal was built between Cottbus and Peitz in order to provide hydropower for the iron works in Peitz (*Kalweit* 1998). The development of streams for hydropower finally resulted in the use of most of the available potential, and in the impoundment of a large number of streams by 1-3 m (*Driescher* 2003).

The removal of a large share of the forest and the widespread construction of mill weirs together resulted in a transformation of the water regime even at landscape level. Groundwater levels were raised, the levels of many lakes rose by 1-2 m, and even new lakes emerged in hollows of the glacial landscape (*Driescher* 2003). Interestingly, this large-scale alteration of the water regime also resulted in an accelerated growth of peat layers in marshes. The growth of these peat layers has probably influenced the hydrological and biogeochemical balance of the landscape in Brandenburg until today. Peat layers effectively store water, thus mitigating runoff dynamics and stabilising groundwater levels. Growing peat also efficiently traps nitrogen and phosphorous, which form macronutrients for the plants that produce peat. Presumably, the growth of peat bogs in a large proportion of the former glacial valleys of Brandenburg led to a reduction in nutrient loads to rivers and lakes (*Schönfelder* and *Steinberg* 2004).

3.2.4 Conflicts of milling with other uses of surface waters

The extensive use of the available small hydropower resources by millers, who received the sought-after water rights and mill privileges from the sovereign, produced a vast number of legal disputes with other users of the surrounding land or of the surface waters, like farmers, fishermen, boatmen and raftsmen. Farmers were forced to abandon the use of valley marshes due to rising groundwater, boatmen were not able to pass by mill weirs, fishermen lost yields due to obstructed fish migration and competing fisheries, and finally millers located downstream complained because of the arbitrary retention of water by the upstream miller. Complaints on raising water levels became more frequent, especially from the late 16th until the 18th century during the 'Little ice age' (*Driescher* 2003). On the other hand, millers and farmers were both interested to drain small lakes and bogs located in the catchment of 'their' stream.

3.2.5 Drainage of wetlands transforms marshes and wetlands

As draining efforts rely on coordinated planning, the existence of good maps, on-site surveys, the solution of judicial conflicts arising from changing land and water rights, and on technical equipment, major artificial drainage networks were only established since the 18th century, when the hydrological regime was again profoundly altered in large parts of Brandenburg, supported by

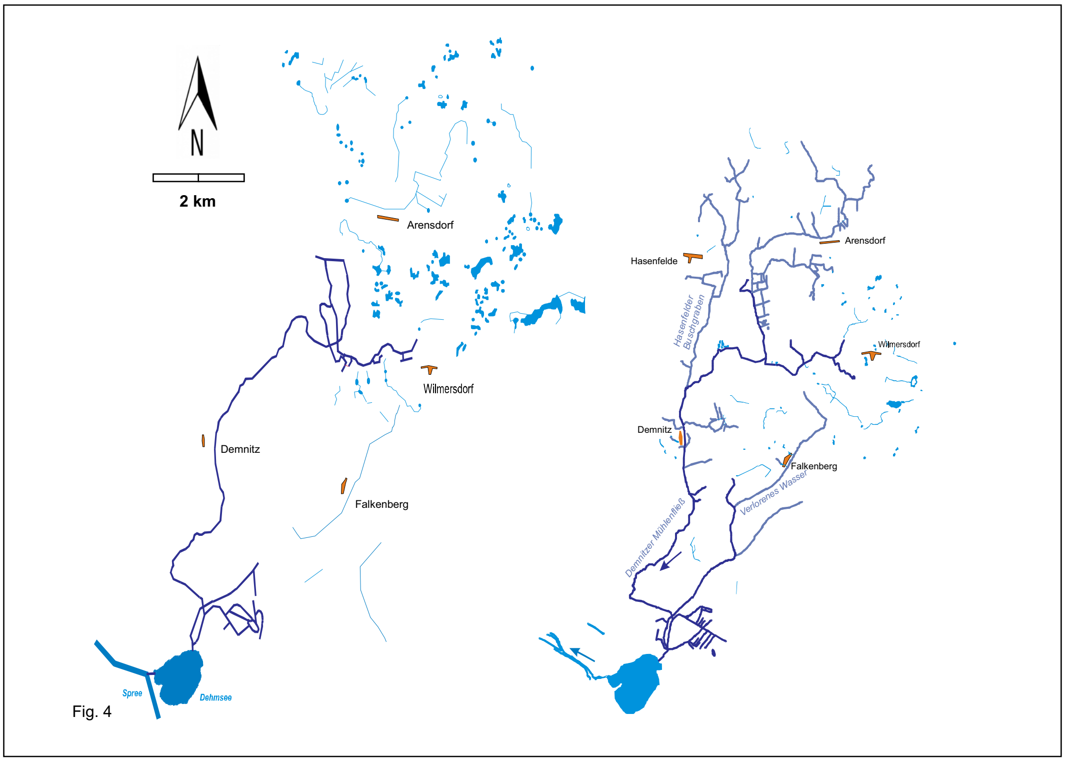

Fig. 4 Artificial expansion of the stream system of the Demnitzer Mühlenfließ (a right tributary of the Spree near Fürstenwalde) by connection of glacial hollows without surficial outflow (*Gelbrecht* and *Opitz* 2000). Stream channels running to the Spree are given in dark blue. Left: Historic stream system around 1780 (Schulenburg's map) with 20 km total channel length. Right: Recent stream system (present-day topographical map 1:25,000) with 88 km total channel length / *Künstliche Ausweitung des Flusssystems des Demnitzer Mühlenfließes (eines rechten Spreezuflusses in der Nähe von Fürstenwalde) durch die Verbindung eiszeitlicher Hohlformen ohne oberirdischen Abfluss (Gelbrecht und Opitz 2000). Die zur Spree führenden Kanäle sind dunkelblau dargestellt. Links: Historisches Flusssystem um 1780 (Schulenburgische Karte) mit 20 km Fliesslänge. Rechts: Heutiges System (Topographische Karte 1: 25 000) mit ca. 88 km Fließlänge.*

the immigration of Dutch specialists in hydraulic construction. Many lakes, ponds and swamps which are located in glacial hollows (with 'closed catchments') were artificially connected to the next drainage system, thus gaining new arable land and increasing water resources for mills (*Fig. 4*). On a large scale such drainage was performed in the 18th century in the floodplains of the Havel, Oder (Odra), Warta (Warthe) and Noteæ (Netze) rivers following the policy of King Frederick William I of Prussia and his successor Frederick II to "colonise" and "populate" the country.

The drainage of peatland resulted in a release of nutrients that led to a new increase in the trophic state of surface waters. While the settlers in the newly drained land benefitted from the release of nutrients from degrading peat, later generations faced growing problems aris-

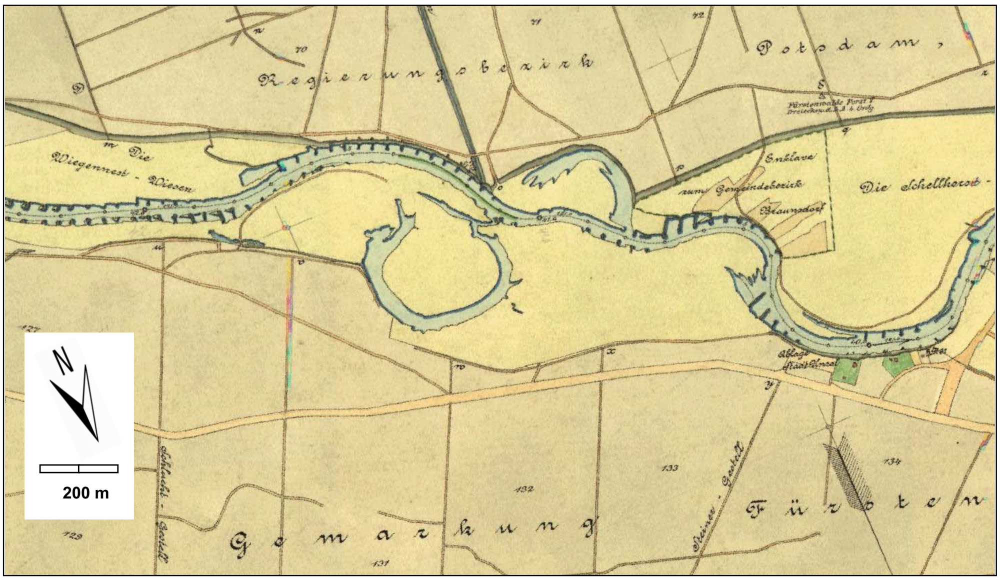

Fig. 5 River training of the "Müggelspree" section of the Spree west of Fürstenwalde. The groynes represented along the river course aimed to stabilise river margins, to confine the navigable water, and thus to increase usable depth for the barge traffic that passed the river section until 1890. Extract from Kartenwerk Müggelspree by Wasserbaudirektion Kurmark of 1921 (Survey 1916/17), Wasser- und Schifffahrtsamt Berlin / *Flussverlauf der „Müggelspree" westlich von Fürstenwalde. Die Buhnen dienen zur Stabilisierung des Flusslaufes und sollten seit 1890 die Befahrbarkeit mit Binnenschiffen sichern. Auszug aus dem Kartenwerk Müggelspree der Wasserbaudirektion Kurmark von 1921 (Ausgabe 1916/17), Wasser- und Schifffahrtsamt Berlin*

ing from the settling of drained peat land (up to 1 cm/year), as the gradient to receiving waters decreased virtually completely, and drained areas were flooded again. This effect could be only solved by the installation of costly pumping stations that pumped drained waters up to the higher water level of the adjacent river. Also, with progressive degradation of peat, its famous storage capacity is lost, so that paradoxically, in former swamp areas like the Havel floodplain, installations for irrigation in dry summers were built after WW II (*Kalweit* 1998).

Drainage by construction of drainage ditches was complemented by the mid of the 19th century by the invention of subsurface tile drainage. By tile drainage, water retentivity in the respective sub-catchment is further reduced. With the application of artificial fertilizers in the 20th century, these areas developed into strong sources of eutrophication of surface waters, as tile drainages function like 'short-cuts' for nutrients from the fields to rivers and lakes.

3.2.6 Navigation on the lower Spree River as part of a key east-west route

The Spree River served as an important waterway both for the transport of wood and other

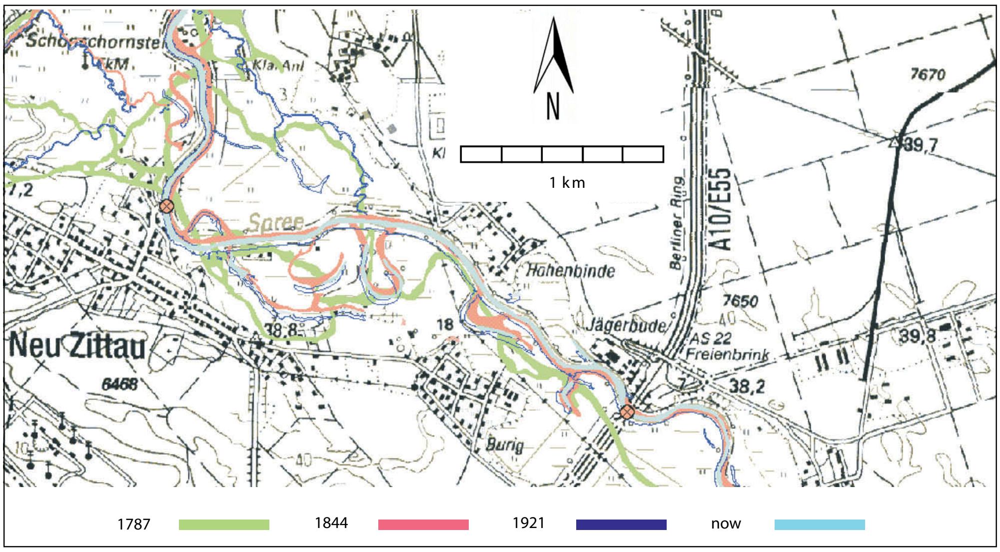

Fig. 6 River courses of the "Müggelspree" section of the Spree near Neu Zittau east of Berlin in three historic stages (1787: green; 1844: rose; 1921: blue) as well as according to the recent topographic map (light blue). Deviations of the channel may be either due to channel migration or due to cartographic imprecision. / *Flussverlauf der „Müggelspree" in der Nähe von Neu Zittau, östlich von Berlin, in drei historischen Abschnitten (1787: grün; 1844: rosa; 1921: blau) sowie im heutigen Zustand (hellblau). Abweichungen im Verlauf des Hauptkanals lassen sich durch die hydrodynamische Entwicklung des Flussverlaufs oder durch kartographische Ungenauigkeiten erklären.*

supplies to the growing city of Berlin and as an important section on the east-west large-distance trade route from the Elbe River to Poland. For that purpose, the river was continuously maintained, i.e. local sand and gravel bars were removed, erosive shores were protected e.g. by groynes, secondary channels were cut off, and meanders were cut through (*Fig. 5* and *Fig. 6)*. As barges had to be towed, the use of the river as a waterway required the removal of riparian trees and the establishment of a continuous trail along the banks, which also contributed to the modification of the river morphology. Conspicuous changes in the course of the river occurred between Erkner and Neu Zittau (*Fig. 6*), where the Spree originally split into several channels that headed to the following lakes: Wernsdorfer See, Seddinsee and Müggelsee (by-passing Dämeritzsee), respectively (*Driescher* 2003).

The natural east-west waterway of the 'Müggelspree' section of the river ends near the city of Fürstenwalde, where goods had to be transferred to carriages to reach the city of Frankfurt on the Oder River. Several German emperors and sovereigns of Brandenburg planned to join both river systems by a canal, but their attempts failed, partly because of the resistance of the city of Frankfurt which feared that trade would no longer pass through the city (*Driescher* 2003).

Hence, it was not until 1668 when Frederick William I, Elector of Brandenburg, succeeded to finish the first complete canal, which was 22.6 km long, with a difference of the water level in the highest canal section to the water level of the Oder of about 20 m (*Uhlemann* 1994). The locks were initially built from wood, and 300 oak logs were needed for each lock. This 'Friedrich-Wilhelm Canal' served until 1890, when it was replaced by the Oder-Spree Canal, which included a separate canal route west of Fürstenwalde, so that the Müggelspree was no longer needed for cargo transport by barges.

3.2.7 River training with questionable success

The section of the Spree upstream of Fürstenwalde to Beeskow, Lake Schwielochsee, and the subsequent river section of the 'Krumme Spree' never attained a similar importance for inland navigation as the 'Müggelspree' section. The 'Krumme Spree' therefore kept its extensively meandering river course until 1906, when an extensive canalisation campaign started to improve flood protection, but also drainage and navigation. Until 1912 forty meanders were cut through, so that the river course was shortened by 45 %, and a standardised and deepened river channel was constructed (*Uhlemann* 1994, *Eckoldt* 1998).

However, shortly afterwards it became obvious that the significant efforts undertaken to channelise that river section could only partially reach its goals, and produced undesired side-effects. Inland navigation never developed on this section, as the region had been connected to the railway network through a station in Briescht in 1901. Concerning agricultural use, it turned out that the benefits gained by the improved use of the floodplain were counterbalanced by a loss of usability in vast areas outside of the floodplain. Adverse effects on agriculture were seen even at 4 km distance from the river. The lowering of the river had led to a drop of groundwater levels by up to 1.5 m, which afterwards continued to drop by about 1 cm per year, as the shortening of the river produced a continuous incision of the river bed. As a consequence, groundwater levels dropped beneath the level that would still have allowed the further use of agricultural areas located outside the floodplain (*Andreae* 1956).

3.2.8 Mitigation of flood events

The risk of disastrous floods by the Spree has decreased since the afforestation of large areas in the Spree catchment in the 19th century, which has resulted in today's relatively high forest share of 37 %. The high proportion of Scots Pine trees (*Pinus sylvestris*) in these forests has contributed to a further decrease of groundwater levels in landscapes dominated by pure pine plantations. In the 19th century the discharge regime of the Spree was characterised by a relatively predictable seasonal pulsation of flow, with regularly occurring floods in late winter and spring and seasonal amplitude of the water level of about 1.1 m (*Berghaus* 1854). Later the discharge dynamics of the Spree was additionally mitigated by the construction of the reservoirs in Spremberg (1965), Quitzdorf (1972) and Bautzen (1975). The Dahme-Umflutkanal near Leibsch built in 1908-1912 enables the redirection of up to 30 m^3/s of river discharge to the Dahme River, thus reducing the flooding risk in the lower Spree catchment. Similarly, the Oder-Spree Canal may function as a flood relief for the 'Müggelspree' section. In the glacial valley of the Spreewald flooding risk was reduced since the beginning of the 19th century by repeated straightening and merging of meandering Spree channels, as well as by the construction of levees. However, in dry years drainage of the area resulted in considerable losses for agriculture due to drought. Hence, a system of weirs was built in the 1930s that enabled to regulate water levels, but impounded river channels (*Kalweit* 1998).

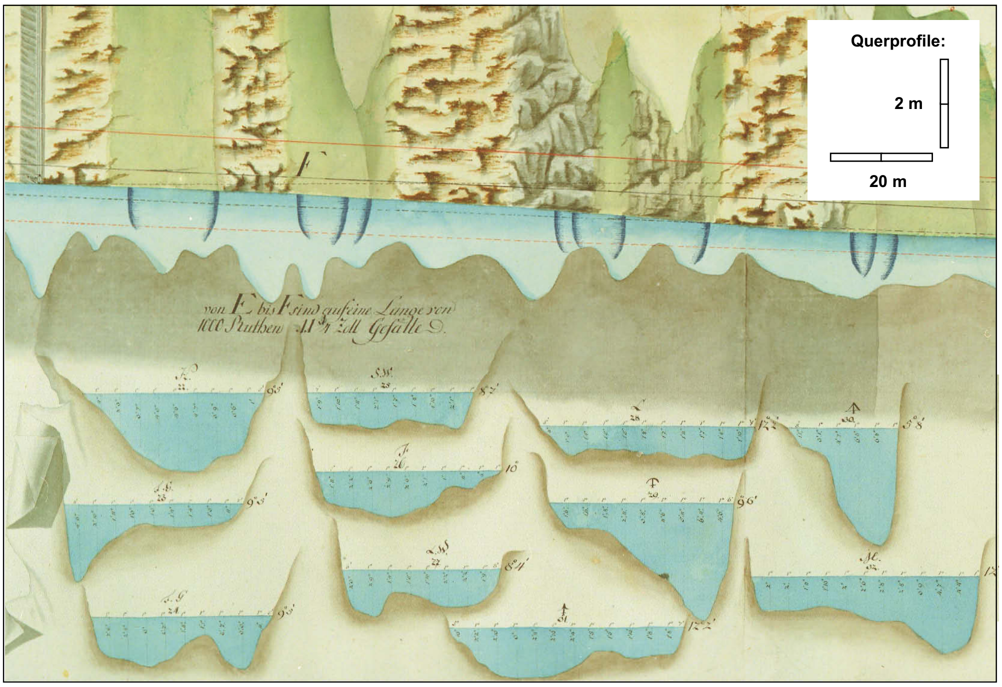

Fig. 7 Vertical breakdown and some cross-sections of the Spree downstream of Beeskow in the 18th century. It is only because this section of the Spree was used for navigation that these cross-sections are so well documented. Extract from the "Nivellements Plan des Spree Strohms von Beeskow bis Fürstenwalde" of 1791 (Geheimes Staatsarchiv Preußischer Kulturbesitz in Berlin-Dahlem)
Vertikalschnitt und Querprofile der Spree hinter Beeskow im 18. Jahrhundert. Nur weil dieser Abschnitt der Spree für die Schifffahrt genutzt wurde, sind diese Profile gut dokumentiert. Auszug aus dem „Nivellements Plan des Spree Strohms von Beeskow bis Fürstenwalde" von 1791 (Geheimes Staatsarchiv Preußischer Kulturbesitz in Berlin-Dahlem)

3.2.9 Pollution of river waters

With growing population density and industrialisation, the water quality of the Spree deteriorated by dumping waste water since the second half of the 19th century, especially in the upper course in Saxony, and downstream of major cities in Brandenburg. With the extension of lignite mining activities after WWII, water quality in the middle section of the Spree was additionally affected by the discharge of groundwater pumped from the mining pits, which partly contained high amounts of iron oxide flocs staining some river sections red. After 1990 the treatment of urban wastewaters was improved, and also the rapid shift to phosphorus-free detergents resulted in a significant decrease of the concentrations of phosphorus and nitrogen in river water. Together with the concomitant reduction of discharge this was probably the main reason for the shift of the lower Spree from a green, plankton-dominated status to more transparent waters dominated by aquatic macrophytes (*Köhler* et al. 2002).

3.2.10 Consequences of historic human modifications for today's status and management of the Spree

The various channelisation measures, together with the regulation of discharge, have profoundly altered the ecology of the Spree. Based on studies of the ancient meanders, it seemed that the river channel of the Müggelspree originally had a width that was not very much larger than today. However, original depth (incision depth into the floodplain level) was only about 0.9 to 1.5 m in straightened sections, with deeper pools in the river bends (*Pusch* et al. 2001), in contrast to a mean depth of 2.7 m today (*Fig. 7*). The protection of the shores against erosion reduced sediment transport, which led to a homogenisation of channel morphology and channel incision. Together with the artificial mitigation of the dynamics of river flow, the loss of typical fluvial features, like e.g. sand and gravel bars has had severe effects on the flora and fauna of the Spree. Some of the most abundant and typical fish species of the Spree – the barbel (*Barbus barbus*) and the burbot (*Lota lota*) – have now become extinct or rare for several decades. Formerly burbot was so abundant that this fat fish was lit and used as torch. The artificial uniformity of the discharge regime of the Spree has favoured the massive growth of macrophytes, which have to be removed by water authorities each year.

Besides the ecological effects of alterations of its morphology, the Spree suffers from a substantial reduction of its discharge. During the period of intensive lignite mining in the catchments of the Spree and Schwarze Elster rivers before 1990, groundwater had been lowered by 2 m and more in an area of 2500 km^2, producing a hydrological deficit of 9 km^3. This groundwater was discharged into the Spree during several decades, which again resulted in local enlargements of the channel profile in order to prevent flooding by increased river discharge. In the 1990s mining activities dropped sharply, and a number of former lignite pits started to be filled by Spree river water, in order to prevent acidification of the future lakes by infiltrating ground water. As a consequence the discharge of the Spree ceased sharply during the 1990s (*Pusch* and *Hoffmann* 2000). In the dry years 2000, 2003 and 2006 river discharge downstream of the Spreewald nearly stopped for several weeks during high summer. In the artificially deepened channel of the Krumme Spree, the daily minimum concentration of dissolved oxygen strongly depends on river discharge (*Köhler* et al. 2002). Cessation of flow thus has recently resulted in a depletion of fish fauna, and in severe losses of riverine invertebrate fauna, especially in the disappearance of dense mussel populations.

As a consequence, today's management of the Spree has to cope with the facts of receding mean discharge, an artificially increased channel cross-section, and increased probability both for droughts and floods. Knowledge on the historical transformations the Spree catchment has seen will facilitate to further develop a combined strategy of retention of water in small catchments, improved discharge capacity during flood events, and a near-natural shallow channel that supports significant flow velocity even during periods of low flow.

3.3 Increased nutrient emissions by urbanisation

In 1850, Berlin's population was about 300,000 inhabitants; it increased to 1 mill. inhabitants by the beginning of the 20th century and to the maximum size of 4.5 mill. in 1939. During WW II the population decreased to 3 mill. inhabitants and has remained at a level of 3.5 mill. residents ever since. With growing population density and industrialisation in the second half of the 19th century, the demand of drinking water increased in Berlin and the water quality of the Spree and the Havel rivers was strongly affected by waste waters. With

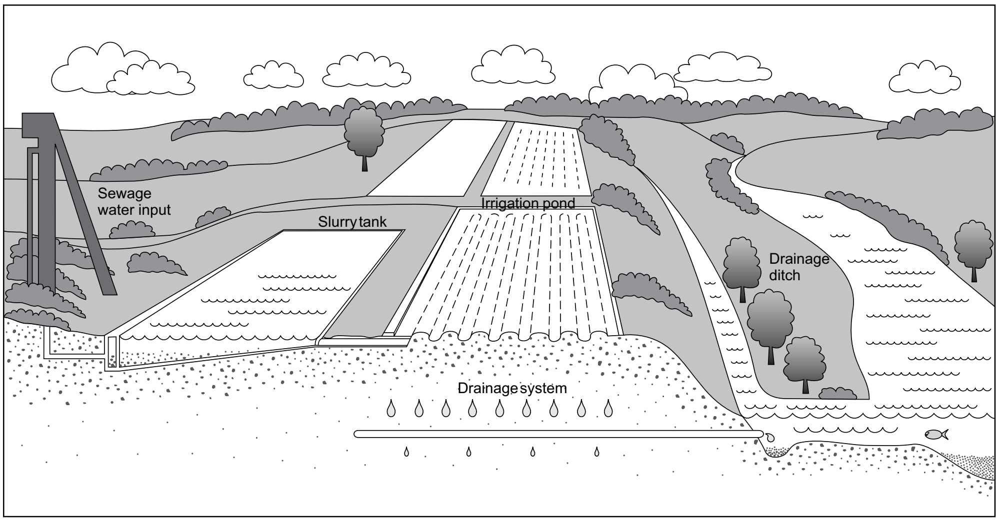

Fig. 8 Schematic diagram of a former "Rieselfeld" (sewage farm). Source: http://www.berliner-rieselfelder.de/geschichte/gFunktion.html, modified / *Schema zur Funktion eines Rieselfeldes. Quelle:verändert nach http://www.berliner-rieselfelder.de/geschichte/gFunktion.html*

the introduction of the water closet and related substantial changes in the water supply system in 1856, both the amount and composition of domestic waste water changed as well as its collection and the treatment system. Before 1875, all waste water of Berlin had been released into the Spree River and other water bodies via an open gutter system, without any treatment.

The introduction of the so-called *Rieselfelder* (sewage farms; *Fig.* 8), areas of sewage treatment by infiltration of waste water into soils, represented a substantial progress in urban waste water management and sanitation (*Nützmann* et al. 2002). In the first half of the 20th century the industrial waste water volume was growing followed by a contamination of soils and groundwater in these waste water treatment areas. Beside heavy metals and organic pollutants the amounts of nitrogen and phosphorus are important, especially for the ecological status of Berlin's surface waters.

Since 1887, the separate sewer system has been installed especially in the new urban area of Greater Berlin (SenStadtUm 2001, *Bärthel* 2003). In the extension parts of Greater Berlin almost all areas became drained by the separate sewer system. The impervious area in the extension parts of Greater Berlin rapidly developed from 1850 to 1920.

In the area of Berlin the first two waste water treatment plants (WWTP) were constructed in 1927 and 1931 in Waßmannsdorf and Stahnsdorf respectively, due to the overloading of the sewage farms. Before this, the larger proportion of waste water was treated in sewage farms. During the first 35 years of operation of the waste water treatment plants, their treatment capacity as well as nutrient removal efficiencies were very limited (*Mohajeri* 2005). At the beginning the waste water was treated only mechanically, while later biological treatment was added (BWB 2000, *Bärthel* 2003).

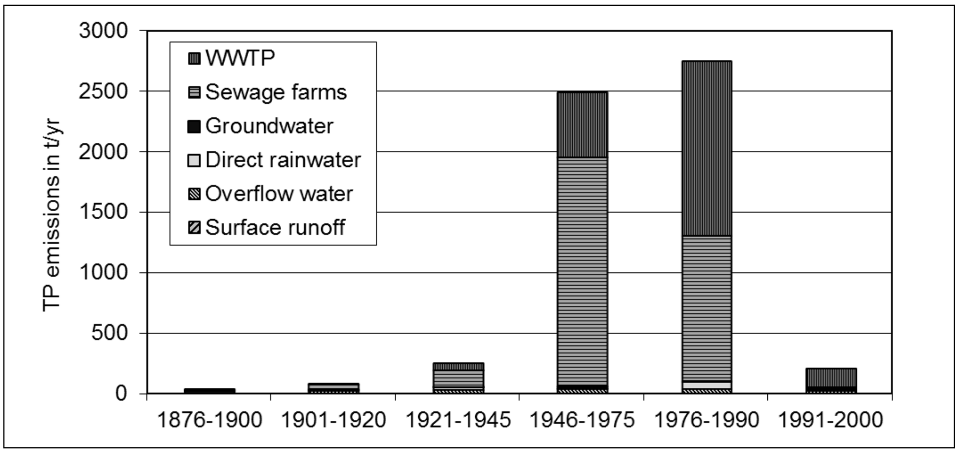

Fig. 9 Phosphorus emissions to Berlin's surface water bodies via different pathways and their emergence over the last 150 years (*Le* 2008) / *Phosphateinträge in Berlins Oberflächengewässer über verschiedene Eintragspfade und ihre zeitliche Entwicklung seit den letzten 150 Jahren (Le 2008)*

The low nutrient loads from WWTPs in the period of 1931-1962 were mainly caused by a low waste water volume. Although several sewage plants were constructed, the domestic and industrial waste water volume increased faster than the treatment capacity of Berlin's WWTPs and the nearly exhausted sewage farms.

A decreasing trend in loads from waste water treatment plants was found since the beginning of the 1980ies. This was mainly caused by an increase of the treatment capacity and the introduction of new technologies to eliminate nitrogen and phosphorus from the waste water (*Klose* 1985, *Leymann* 1991, SenStadtUm 2001, BWB 2005). However, this change was different for nitrogen and phosphorus as technological improvements of WWTPs mainly focused on phosphorus elimination. Nitrogen removal, however, has only been applied since 1990.

A strong population expansion demanded an intensification of agricultural practices, consequently followed by an overuse of fertilizers. Increasing agricultural activities played an important role for the development of emissions. Until the second half of the 19th century fertilizers had not been used widely for agricultural activities. After 1913 ammonia fertilizers were produced on the basis of the Haber-Bosch approach. But even commercially produced fertilizer was still expensive and not widely used until after WW II. After that both the production and large-scale use of fertilizers increased exponentially. With economic change after reunification of the two German states, the total livestock numbers in eastern Germany declined sharply, by 50 %, in the period of 1990-1993 (*Nitsch* and *Osterburg* 2004).

This decrease could also be found in the nitrogen surplus on arable land and its emissions to the surface waters. Demographic change, intensified agriculture and especially the introduction of sewage farms and their subsequent replacement by WWTPs dominantly influenced the local distribution and source apportionment of nutrients (and heavy metals) emissions in

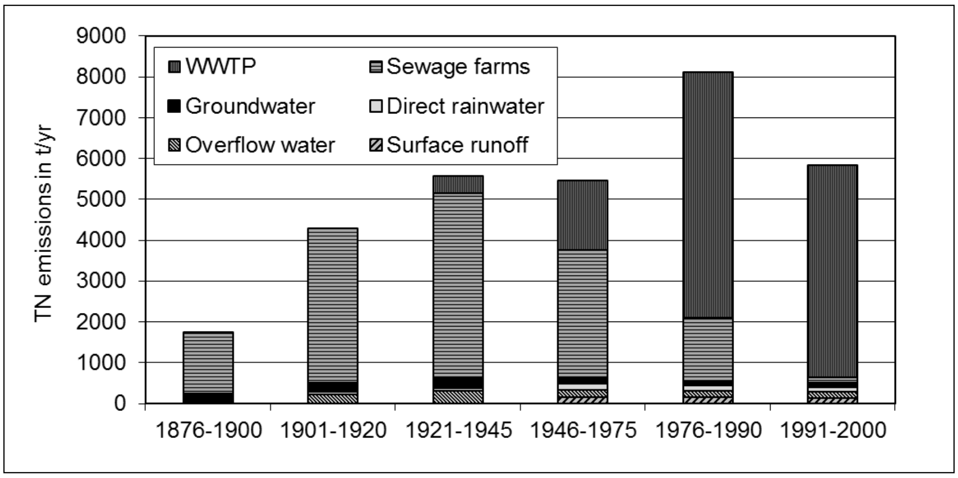

Fig. 10 Nitrogen emissions to Berlin's surface water bodies via different pathways and their emergence over the last 150 years (*Le* 2008) / *Nitrateinträge in Berlins Oberflächengewässer über verschiedene Eintragspfade und ihre zeitliche Entwicklung seit den letzten 150 Jahren (Le 2008)*

Havel and Spree. Although often driven by the same processes, different trends have been identified in the development of Total Nitrogen and Total Phosphorus emissions.

Le (2008) conducted a detailed study on the sources and total amount of nitrogen and phosphorus emissions in the area of Berlin. The amount of Total Nitrogen and Total Phosphorus emissions into surface waters of Berlin and the apportionment of sources and pathways changed significantly during the last 150 years. An overview of the total phosphorus emissions via different pathways and their contributions to the surface water bodies of Berlin over the last 150 years is given in *Figure 9.*

In general, P-emissions into surface waters in Berlin have developed very dramatically over specific periods. Total P-emissions increased from 34 t TP/a in 1876-1900 to 250 t TP/a in the period 1921-1925. After WW II, total P-emissions increased tremendously, to 2480 t TP/a (1946-1975) and reached the peak of 2790 t TP/a in the period 1976-1990. The decreasing trend in total P-emissions was recognised since 1975 and reached the level of 190 t TP/a in the period of 1991-2000. Effluents from sewage farms and WWTPs were the dominant sources of P-emissions into surface waters in Berlin in the period of 1921-2000. From the years 1946-1990 to the years 1991-2000, the share of point sources was reduced from 97 % to 76 %. Discharges from combined sewer overflow played an important role for total P-emissions, especially in the period of 1876-1920 (33 %) and 1991-2000 (12 %). P-emissions via direct deposition and groundwater had very limited importance for total P-emissions (*Fig. 9*).

In the last century, TN-emissions did not change as much as TP-emissions. They increased from 1770 t TN/a in the period of 1876-1990 to around 4276 t TN/a in the following 20 years and stayed at the level of 5700 t TN/a in the period of 1991-2000. As shown in *Figure 10*, the highest TN-emissions (more than 8100 t TN/a) occurred in the period of 1976-1990. Among the different pathways, point sources played a dominant role for TN-emissions with an average share of 90 % over the last 150 years. Among point sources, sewage farms played the dominant role in the period of 1876-1976 and have been replaced by WWTPs subsequently. Nitrogen load via surface runoff from urban areas in the separate sewer system show an increasing trend in the contribution on the total N emissions, while nitrogen emissions via groundwater and combined sewer overflow and direct atmospheric deposition have very limited importance in total N-emissions (*Fig. 10*).

Before the intensive use of fertilizers, atmospheric deposition was an important source for nitrogen and phosphorus emissions. Anthropogenic atmospheric nitrogen and phosphorus mainly originate from fossil fuel combustion and agricultural activities. With increasing industrial and agricultural productivity, atmospheric deposition of nitrogen and phosphorus increased, too. The implementation of upgraded catalytic converters in cars and the installation of particle filters since the 1980s resulted in a substantial decrease of atmospheric deposition (*Kahn* 1996, *Bartnicki* 2006). This process was delayed by 10 years in eastern Germany.

4. Conclusions

According to our hypotheses we identified specific stages of anthropogenic impact on the freshwaters in the Berlin-Brandenburg region, which consequently led to a transformation of the hydraulic and the ecological status of lakes and rivers. And moreover, the transformation process is still going on. In the past, the installation of small-scale structures in rivers and streams, the development of longitudinal navigability combined with the large-scale landscape drainage, and the direct and diffuse pollution of surface waters are substantial effects, which result in both an alteration of freshwater resources in terms of quantity and quality and a change of traditional use of surface waters. Moreover, we addressed topics that exemplarily summarised the challenges for a sustainable management of freshwater systems in this region from an ecohydrological point of view: restoration of fluvial dynamics and related habitats and structures, and a modification or adaptation of the traditional objectives of water management, which will be illustrated in the following.

Regarding fish biodiversity in the Berlin-Brandenburg region it has to be mentioned that the last river regulations and improvement of dams did not only affect sensitive fish species. Channelisation, profile enlargement, embankments and the substantial loss of former floodplain areas (*Simon* 1994) caused a significant decline in fishing productivity. As a result, only along an 80 km long Havel stretch 1100 fishermen gave up their family businesses after the regulations of 1907-1913 (*Kotzde* 1914). The total damage for the local fisheries was estimated to one million Mark annually (*Kotzde* 1914). This former productivity is probably irreversibly lost with the floodplain area. Today, river management increasingly addresses the conservation of aquatic biodiversity. The rehabilitation of rheophilic fish, which are an essential element of the native fish communities even in lowland rivers, requires the restoration of fluvial dynamics and related habitats and structures.

The drainage of landscapes and the channelisation of streams and rivers in the Spree basin from the 17^{th} until the mid 19^{th} century were performed under the conditions of the 'Little ice age', with increased runoff. The drainage system created at that time as well as in following decades did not account for long-term effects of drainage on hydrology and agriculture, on groundwater resources, and thus on the fertility of crop fields in higher areas, on fisheries and biodiversity. Also at that time natural changes of climate were hardly analysed systematically. The drainage system of Brandenburg with a length of 33,000 km, of which 80 % are constructed artificially, and with 20,000 installations for water management (Data: Landesumweltamt Brandenburg), today constitutes a legacy that more and more develops into a burden. Growing knowledge on the functioning and vulnerability of natural systems, as well as the challenge of rising global and regional temperatures give strong arguments to modify – or partly even reverse – traditional objectives of water management.

A historic analysis of the current situation with 83 % of the original swamps in Brandenburg having disappeared, falling levels of groundwaters and lakes, receding discharge of most rivers in Brandenburg as well as of the Spree in Berlin, river sections lacking riverine fauna, with concomitant intensive efforts addressed to water management, leads to the conclusion that the water management in Berlin and Brandenburg has to be adapted to new conditions. Potential adaptation measures could be the reduction of the length of the artificial drainage systems, scaling down again artificially deepened river channels, and re-developing simple measures that support water retention in the catchments, with a priority for natural retention systems over costly technical systems. By the construction of the mill weirs all over the country in the 14th to 18th centuries it was shown unintentionally that the multitude of single measures may result in a significant raise of water levels even at landscape level – which may be taken as an encouragement for the future success of the re-orientation of traditional water management in the region.

Since the beginning of the 1990s, significant efforts were made to further decrease water contamination by nutritive and noxious substances, through eliminating almost all direct discharges. The long-lasting problem of the effect of diffuse discharges into ground and surface water can, in contrast, still be treated as relevant. To solve this problem it is necessary to introduce measures in the drainage areas, like e.g. changing land use in general and especially in agricultural exploitation. The expected droughts specifically in the north-east of Brandenburg resulting from predicted climate change, pose an additional challenge (*Nützmann* 2007). In contrast to this, the following question arises for the urban centre of Berlin: How can the water supply – generally gathered from bank filtration – be secured, considering climate change and the lowering of the discharges of the Spree River while at the same time it is to be expected that the chemical ingredients change (*Möller* and *Burgschweiger* 2008)? Finally, new approaches in river basin management aim to improve the structural diversity of rivers as basis for rehabilitating and conserving aquatic biodiversity.

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Summary: Historical Patterns of Anthropogenic Impacts on Freshwaters in the Berlin-Brandenburg Region

Since people started settling on flood plains they influence the freshwater systems more or less intensely. In the Berlin-Brandenburg region, the role of rivers and lakes for the development of the region can hardly be over-estimated. The first signs of anthropogenic impact in the Berlin-Brandenburg region are approximately 3000 years old; already back then first dams were built in order to control the Havel River. In the beginning rivers were used for fishing and to operate mills, in the early Middle Ages the passability of rivers was important for shipping. Wide spread drainages and river regulations were performed even before the industrialisation in former Prussia. But afterwards the massive extension of the rivers, the waste water disposal and later on the diffusive nutrient input in the water bodies, caused by intensive farming, played an even more important role from the ecological point of view. Effected by the growing changes of the water body landscape, the stock of fish was reduced and the importance of the commercial fishery dropped. The fishing resources and commercial fishing became less important. The challenge for the future will be to improve the structural diversity of riverine habitats to form the basis for a sustainable development and to assertain a high aquatic biodiversity.

Zusammenfassung: Historische Muster anthropogener Einflüsse auf das Gewässernetz in der Region Berlin-Brandenburg

Seit der Mensch am Wasser siedelt, beeinflusst er das Gewässernetz und damit die Abflüsse sowie die Qualität und die Ökologie der Gewässer. In der Region Berlin-Brandenburg sind erste Zeichen von anthropogenen Eingriffen ca. 3000 Jahre alt; schon damals versuchte man, durch Dammbauten regulierend auf die Havel einzuwirken. Erste Zeugnisse für die Nutzung der Havel als Wasserstrasse gehen auf das Jahr 789 n. Chr. zurück. Der Beginn fischereilicher Nutzung dieser Gewässer dagegen wird auf 5000 v. Chr. datiert. Während zu Beginn menschlicher Einflussnahme neben dem Fischfang die Ausnutzung der Strömung zum Betrieb von Mühlen stand, rückte bereits im frühen Mittelalter die Durchgängigkeit der Gewässer für eine möglichst ungehinderte Schiffbarkeit in den Vordergrund. Aus dieser Zeit stammen auch die ersten Gewässerum- und Verbauungen. Großflächige Trockenlegungen und Flussbegradigungen fanden schon vor der Industrialisierung im ehemaligen Preußen statt, danach allerdings spielten aus gewässerökologischer Sicht der massive Ausbau der Flüsse, die Abwasserbeseitigung und später die infolge intensiver Landwirtschaft entstehenden diffusen Nährstoffeinträge in die Gewässer eine vorrangige Rolle. Mit zunehmender Veränderung der Gewässerlandschaft gingen die Fischbestände zurück und die kommerzielle Fischerei nahm an Bedeutung ab. Neben der Verringerung der Gewässerbelastung mit Nähr- und Schadstoffen besteht heute die Aufgabe darin, die Strukturvielfalt der Fließgewässer weitgehend zu verbessern, um die Grundlage einer nachhaltigen Entwicklung der aquatischen Biodiversität zu sichern.

Résumé: Aspects historiques des influences anthropiques sur le réseau d'eau dans la région de Berlin-Brandebourg

Depuis que l'homme s'installe au bord des fleuves et rivières, il influence leur cours ainsi que la qualité écologique de leurs eaux. Dans la région de Berlin-Brandebourg, les premières traces de modification des cours d'eau par l'homme remontent à environ 3000 ans; les riverains essayaient alors déjà de réguler l'écoulement de la Havel par la construction de barrages. Les premiers documents certifiés pour l'utilisation de la Havel comme voie navigable datent de 789 ap. J.-C. Les débuts de la pêche organisée sont datés de 5000 av. J.-C. Au début, les rivières étaient surtout utilisées pour la pêche et pour faire tourner les moulins au fil du courant, mais dès le début du moyen âge, la nécessité d'une navigation sans entraves pour les bateliers est devenue un enjeu prioritaire. Les premières modifications connues du lit des rivières en vue de réguler les écoulements datent d'ailleurs de cette époque. Le drainage à vaste échelle des plaines alluviales et la régulation des cours d'eau a commencé en ancienne Prusse avant même l'industrialisation. Puis, le recalibrage massif des rivières, le déversement des eaux usées et plus tard, les rejets diffus d'éléments nutritifs en provenance de l'agriculture intensive ont joué un rôle majeur dans la dégradation de la qualité écologique des écosystèmes fluviaux. Affectés par la modification progressive des plaines alluviales, les stocks de poisson ont diminué et les rendements de pêche commerciale ont chuté. Tout en continuant de s'attacher à réduire les rejets de polluants ou de nutriments, le challenge aujourd'hui consiste à restaurer la diversité structurelle des cours d'eau afin de favoriser la conservation de la biodiversité dans le cadre d'un développement durable.

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