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MODELLING PRE-MODERN FLOW DISTANCES OF INLAND WATERWAYS – A GIS STUDY IN SOUTHERN GERMANY

MODELADO DE DISTANCIAS DE REDES FLUVIALES PREMODERNAS - UN ESTUDIO SIG EN LA ALEMANIA MERIDIONAL

Lukas Werther[a,*], Tanja Menn[b], Johannes Schmidt[c], Hartmut Müller[b]

[a] Department of Medieval Archaeology, Eberhard Karls University Tübingen, Schloss Hohentübingen, 72070 Tübingen, Germany. lukas.werther@uni-tuebingen.de

[b] Institute for Spatial Information and Surveying Technology, University of Applied Sciences, Lucy-Hillebrand-Straße 2, 55128 Mainz, Germany.menn.tanja@gmail.com; hartmut.mueller@hs-mainz.de

[c] Institute for Geography, Leipzig University, Johannisallee 19a, 04103 Leipzig, Germany. j.schmidt@uni-leipzig.de

Highlights:

- Systematic comparison of old maps and modern geodata to deduce river-specific length correction values to improve supra-regional network models of pre-modern inland navigation.
- Large-scale analytical approach and transferable GIS workflow for flow distance reconstruction with case studies in Southern Germany.
- Length changes of navigated fairways result in pre-modern period travel times up to 24% higher in corrected models.

Abstract:

Rivers form major traffic arteries in pre-modern Central Europe and accurate regional to supra-regional network models of inland navigation are crucial for economic history. However, navigation distances have hitherto been based on modern flow distances, which could be a significant source of error due to modern changes in flow distance and channel pattern. This paper anlyzes results of a systematic comparison of vectorized old maps, enlightening the fluvial landscape before most of the large-scale river engineering took place, and modern opensource geodata to deduce change ratios of flow distance and channel patterns. The river courses have been vectorised, edited and divided into comparable grid units. Based on the thalweg, meandering and braided/anabranching river sections have been identified and various ratios have been calculated in order to detect changes in length and channel patterns. Our large-scale analytical approach and Geographic Information System (GIS) workflow can be transferred to other rivers in order to deduce European scale change ratios. The 19th century flow distance is suitable to model pre-modern navigation distances. As a case study, we have used our approach to reconstruct changes of flow pattern, flow distance and subsequent changes in navigation distance and transportation time for the rivers Altmühl, Danube, Main, Regnitz, Rednitz, Franconian and Swabian Rezat (Southern Germany). The change ratio is rather heterogeneous, with main channel length and travel time changes of up to 24% and an extensive transformation of channel morphology in many river sections. Based on published travel time data, we have modelled the effect of our change ratios. Shipping between the Ulm and Regensburg commercial hubs, to name an example, was up to 5 days longer based on pre-modern distances. This is highly significant and underlines the necessity for river-specific correction values to model supra-regional networks of pre-modern inland waterways and navigation with higher precision.

Keywords: digital archaeology; historical geography; pre-modern inland navigation; historic transport time; fluvial morphology; Geographic Information System (GIS)

Resumen:

Los ríos forman las principales arterias de tráfico en la Europa central premoderna y los modelos precisos de redes, tanto regionales como suprarregionales de navegación fluvial, son cruciales en la historia económica. Sin embargo, las distancias de navegación se han basado hasta ahora en distancias de redes modernas, lo que podría ser una fuente significativa de error debido a los cambios modernos en la distancia de la red y en el patrón del canal. Este trabajo analiza, por una parte, una comparación sistemática de mapas antiguos vectorizados, que ofrecen datos del paisaje fluvial antes de que se llevara a cabo la mayor parte de la ingeniería fluvial a gran escala; por otra parte, se estudian geodatos modernos de código abierto que permiten deducir las relaciones de cambio de las distancias de las redes y los patrones de los canales. Los cursos de los ríos se han vectorizado, editado y dividido en unidades de cuadrícula comparables. A partir de la línea de vaguada, se han identificado secciones de río serpenteantes y trenzadas/ramificadas y se han calculado varias proporciones para detectar cambios en la longitud y en los patrones de

*Corresponding author: Lukas Werther, lukas.werther@uni-tuebingen.de

los canales. Nuestro enfoque analítico a gran escala y el flujo de trabajo seguido con el Sistema de Información Geográfica (SIG) son transferibles a otros ríos, a escala europea, para deducir proporciones de cambio. La distancia de la red del siglo XIX es adecuada para modelar distancias de navegación premodernas. Como caso de estudio, hemos utilizado nuestro enfoque para reconstruir los cambios en el patrón de la red, la distancia de la red, así como los cambios posteriores en la distancia de navegación y el tiempo de transporte en los ríos Altmühl, Danubio, Main, Regnitz, Rednitz, Franconian y Swabian Rezat (sur de Alemania). La proporción de cambio es bastante heterogénea, con variaciones de longitud y tiempo de viaje de hasta un 24% en el canal principal, además de una transformación extensa de la morfología del canal en muchas secciones de los ríos. Basándonos en los datos publicados de tiempos de viaje, hemos modelado el efecto de nuestras proporciones de cambio. La navegación entre los centros comerciales de Ulm y Regensburg, por ejemplo, duraba hasta 5 días más según las distancias premodernas. Esto es muy significativo y subraya la necesidad de determinar valores de corrección específicos de los ríos, que permitan modelar con mayor precisión tanto las redes suprarregionales de vías navegables fluviales premodernas como la navegación.

Palabras clave: arqueología digital; geografía histórica; navegación fluvial premoderna; tiempos de transporte histórico; morfología fluvial; Sistema de Información Geográfica (SIG)

1. Introduction

Rivers form major traffic arteries in pre-modern Central Europe and have been used intensively for navigation (Campbell, 2012; Eckoldt, 1980; Eckoldt, 1998). In recent years, a particular research focus in history and archaeology lay upon inland harbours, vessels and canals, which form the infrastructural backbones of inland navigation in Antiquity as well as in the Middle Ages (Ettel & Hack, 2019; Foucher et al., 2019; Mirschenz et al., 2019; Werther, Müller & Foucher, 2018-2020; Wollenberg et al., 2019). First attempts have been done to model regional and supra-regional networks of inland navigation, taking into account navigation distances based on modern flow distances as well as different efforts for transportation upstream and downstream (Foucher et al., 2019; McCormick, 2012; Preiser-Kapeller & Werther, 2018; Scheidel, 2014; Scheidel, 2020). Nevertheless, a crucial unknown in all such models is the ratio of pre-modern changes in flow distance in specific navigated river sections, which could be triggered by natural processes as well as anthropogenic impact. This unknown could have tremendous effects on modelling results and therefore network properties (Foucher et al., 2019; McCormick, 2012; Preiser-Kapeller & Werther, 2018). To enlighten this unknown and to improve digital models of waterways and inland navigation is not only fundamental for economic history and archaeology (McCormick, 2012), but also e.g. for advanced modelling of the spread of diseases such as plague along navigable rivers in pre-modern Europe (Siuda & Sunde, 2021; Yue et al., 2016).

On a local to regional scale, changes in flow distance and river morphology have been analysed intensively and in great detail by means of fluvial geomorphology as well as geoarchaeology (e.g. Brown et al., 2018 and references within). Concerning the human impact on fluvial systems, especially in the modern period, Hoffmann et al., 2010 conclude, that numerical models could provide detailed data, but validation approaches are crucial. However, upscaling local information to larger areas is often difficult (Schlummer et al., 2014) and a data gap on the regional to supra-regional scale, which is particularly important for the analysis of networks of navigation, could be observed. This lack of information could not be solved by fieldwork and upscaling of small-scale fieldwork results from our point of view, but only by a large-scale approach based on old maps and tools and methods provided by digital humanities.

In this paper, we would like to present a comparative case study in Southern Germany. Our comparison of river morphology and flow distance is based on modern opensource geodata-sets (OpenStreetMap, FOSSGIS e.V., 2017) and early 19th century georeferenced maps (Bayerische Staatsbibliothek, 2020), which document flow patterns with sufficient spatial precision before most of the modern large-scale river engineering took place.

Our aims are: 1) To detect changes in river morphology through time-based on widely available geodata; 2) To reconstruct regional to supra-regional changes of flow distances and subsequent changes in navigation distance and transportation time; 3) To discuss the effect of flow distance changes on historic traffic systems and networks of inland navigation; 4) To present a transferable GIS workflow for flow distance reconstruction, which could be adapted for other regions in order to deduce change ratios for modelling historical networks of navigation on a European scale.

2. Study area

Our study area in Bavaria (southern Germany) encompasses the rivers Altmühl and Danube (Danube catchment) as well as the river Main (Rhine catchment) and a cluster of southern tributaries (Regnitz, Rednitz, Franconian and Swabian Rezat), which have been analysed collectively (Fig. 1). This study area is particularly targeted on the waterway between Regensburg (Danube) and Würzburg (Main), which has been navigated in 793 AD by emperor Charlemagne in one of the most enigmatic voyages of the European Middle Ages according to written sources and formed a particular focus of our research in recent years (Ettel, 2015; Werther et al., 2018; Werther et al., 2020; Werther & Kröger, 2017).

The river Main, which flows into the Rhine, has an actual flow distance of 524 km from source to the mouth of which 406 km are located in Bavaria and therefore in the study area. The mean annual discharge at the confluence (Frankfurt) is 225 m³/s. The river is characterised by strong winter floods with a high discharge (Bayerisches Landesamt für Umwelt, 2020; Generaldirektion Wasserstraßen und Schifffahrt, 2020; Uehlinger et al., 2009). Significant river engineering and straightening did start in the 1840s in order to form a waterway for large cargo vessels (Eckoldt, 1998; Mälzer, 1986). Therefore, despite local modifications, the river morphology could be assumed to be close to its natural state when the respective map sheets of the

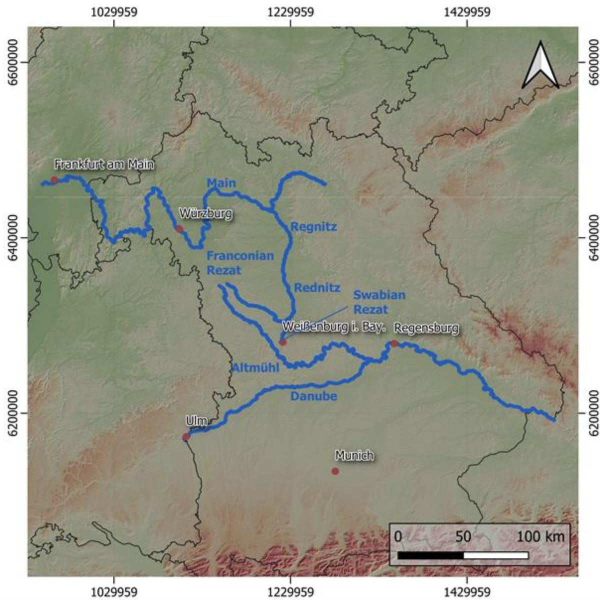

Figure 1: Supra-regional overview of the study area and analysed river sections. (DEM data: SRTM 90 m; U.S. Geological Survey 2015).

Topographical Atlas of Bavaria were surveyed in the field from 1812 onwards. The river Main has been navigated intensively from Antiquity onwards at least from the mouth of the river Regnitz near Bamberg to the confluence with the Rhine, which is documented by written sources, shipwrecks and archaeological remains of harbour infrastructure (Gunzelmann, 2009; Kröger, 2018; Werther & Kröger, 2017). Regnitz, Rednitz, Franconian and Swabian Rezat are southern tributaries of the river Main with a current length of 45-70 km each. Their mean annual discharge differs significantly from smaller upstream tributaries such as the Swabian Rezat (Mühlstetten: 2.11 m³/s) to the downstream section of the Regnitz (Pettstadt: 52.6 m³/s) (Bayerisches Landesamt für Umwelt, 2020; Eckoldt, 1980; Generaldirektion Wasserstraßen und Schifffahrt, 2020). Significant river engineering for flood protection did already take place in the second half of the 18th century and canalization for mill channels much earlier, so that it is difficult to assess the state of anthropogenic modifications of river morphology in general when the Topographical Atlas of Bavaria has been surveyed. Nevertheless, as these rivers have not been used for navigation on a significant scale upstream of Forchheim from the Late Middle Ages onwards, anthropogenic modifications of river morphology have always most likely been rather local (Eckoldt, 1998; Gunzelmann, 2009; Uehlinger et al., 2009). The river Regnitz has been navigated downstream of Forchheim in the Medieval and Post-Medieval period. Furthermore, there is proof for at least occasional navigation and navigability of the upstream section, too as well as for parts of the southern tributaries Rednitz, Franconian and Swabian Rezat, which gave access to the portage bridging the Main European Watershed towards the Danube catchment (Gunzelmann, 2009; Werther & Kröger, 2017).

The Danube has currently a flow distance of 2826 km from source to mouth, of which 380 km, the Upper Danube, are located in Bavaria and therefore in the study area. The mean annual discharge at Kelheim is 331 m³/s (Bayerisches Landesamt für Umwelt, 2020; Generaldirektion Wasserstraßen und Schifffahrt, 2020; Sommerwerk et al., 2009). From the Iller confluence downstream, the Upper Danube is characterised by strong meltwater floods controlled by large Alpine tributaries. Significant river engineering and straightening did already start in the Medieval period, but mainly on a local scale. Large-scale corrections and straightening of the Bavarian part of the river for navigation did start in 1806, but major engineering took only place from the second half of the 19th century onwards. Therefore, large parts of the river morphology could be assumed to have been still close to its natural state when the Topographical Atlas of Bavaria has been recorded from 1812 onwards (Eckoldt, 1998; Longoni & Wetter, 2019; Schielein, 2010; Schielein, 2012; Sommerwerk et al., 2009). Anyway, from 1806 to 1888, the flow distance of the Danube Thalweg between the mouth of the river Iller and Kelheim has been reduced artificially from 211 km to 172 km or 18.4% according to Eckoldt 1998, which gave a first specific idea of ratios of flow distance change for our study. The Danube has been navigated in Antiquity as well as in the Middle Ages at least downstream from Ulm and therefore on its whole length within the study area (Eckoldt, 1980; Eckoldt, 1998; Höckmann, 2003; Werther & Kröger, 2017). The river Altmühl is one of the major northern tributaries of the Danube in the study area and gives access to the portage bridging the Main European Watershed from the South. It has a modern length of 224 km from the source to the confluence with the Danube near Kelheim. The annual discharge at Treuchtlingen, until where the river has been navigable at least in the Early Middle Ages, is 5.72 m³/s (Bayerisches Landesamt für Umwelt, 2020; Eckoldt, 1980; Generaldirektion Wasserstraßen und Schifffahrt, 2020). Large-scale corrections and straightening of the river section downstream of Kelheim for navigation did start in 1836 and further upstream for flood protection between 1910 and 1920 (Eckholdt, 1998; Klein, 2010; Wasserwirtschaftsamt Ansbach, 2014; Werther & Kröger, 2017).

3. Material and methods

3.1. Data and data quality

In order to compare morphology and flow distances of modern and pre-modern rivers in the whole study area, two major datasets have been used to create an accurate and consistent base: first, 19th century maps which enlighten the fluvial landscape before most of the large-scale river engineering took place and second, modern OpenStreetMap (OSM) data.

The 19th century fluvial pattern has been captured based on the "*Topographischer Atlas vom Königreiche Bayern*". This series of 112 map sheets to scale 1:50000 has been produced gradually between 1812 and 1867, when the full and at that time groundbreaking volume has been published (Bayerische Staatsbibliothek, 2020; Habermeyer, 1993; Seeberger, 2001). The map series is the first high-resolution map of the whole study area, which has been surveyed based on triangulation and does allow for a homogenous spatial analysis of river morphology. Further, the whole map series has been provided to our working group as a high-resolution georeferenced Web Map Service (WMS) by the "Bayerische Staatsbibliothek" in the framework of research cooperation. Therefore, it is most suitable for our supra-regional analytical approach with regard to representativity, resolution and availability. There are of course older maps such as the so-called "Stromatlas" (stream atlas) of Bavaria, which has been surveyed by Adrian von Riedel and published in 1806, which would have been more suitable than the "*Topographischer Atlas vom Königreiche Bayern*" to analyse river morphology before large scale river engineering started from 1806 onwards (Eckoldt, 1998; Seeberger, 2001; Schielein, 2010; Schielein, 2012). However, this series of maps does not cover the whole study area but only the Danube and some of its major southern tributaries (Riedel, 1806) and it was not available in a georeferenced version. Furthermore, other medium-scale pre-19th century maps of the study area are generally not suitable for quantitative analysis due to their lack of spatial precision (Schielein, 2010).

The modern fluvial pattern has been captured based on OSM topographical raster-data, which has been available for the whole study area via WMS, mainly on a scale of 1:25000-1:50000 and therefore comparable with the "Topographischer Atlas" concerning spatial accuracy (FOSSGIS, 2017; Terrestris, 2014). In this paper, we are not using aerial photographs and satellite imagery.

3.2. Methodology

Our methodological approach builds upon the methodology presented by Schielein, 2010, which we have adapted and developed further. In a first step, the river courses of the Main and selected southern Main tributaries as well as Altmühl and Danube have been vectorised based on the two WMS raster datasets in ArcGIS v. 10.5. A manual vectorising process has been chosen as it turned out to be the fastest and most reliable approach to ensure a consistent data basis. As the 19th century "*Topographischer Atlas*" consist of many map sheets which have been georeferenced separately by GISCON engineering company via ArcGIS based on the originally measured grids and as the spatial precision is limited in general, offsets in the range of tens of meters, especially at the edges between different map sheets, are inevitable (Schielein, 2010). The modern OSM dataset, in contrast, is much more accurate, but smaller branches of the river are sometimes not (yet) visualised. Based on the modern and pre-modern maps, the main channel as well as all significant secondary channels/bifurcations, islands and branches have been digitised as polygon layers.

In a second step, based on the vectorised river courses, the main channel has been identified and tagged via ArcEditor. This step has been carried out manually, too, as the shortest route is not necessarily the main current and therefore automated approaches are not suitable.

In a third step, the river courses have been divided into smaller, comparable units which could be further processed and compared more easily. As modern and pre-modern river courses have different lengths, a division based on predefined sections with a specific length has not been appropriate. Therefore, grids have been used to split the vector layers of the entire pre-modern and modern river courses as well as the pre-modern and modern main channels at the grid edges by using Fishnet and Intersect (combined via Model Builder) in ArcMap. The resulting attribute tables contain river name, grid ID as well as segment length within each grid. As grid sizes are crucial for the outcome, different sizes have been evaluated. Larger grids lead to generalization and therefore inaccurate simplification, but at the same time, they can help to eliminate falsely classified sections. Smaller grids are more detailed, but also more vulnerable to miss-classification. Based on an evaluation with grid sizes of 10x10 km, 20x20 km and 30x20 km, we decided to focus on 10x10 km grids.

In a fourth step, the thalweg has been determined, which is necessary to identify meandering and braided/anabranching river sections. As automated approaches require vector-based floodplain areas, which have not been available, the thalweg has been mapped manually via ArcEditor based on the modern topography visible in OSM data as well as Shuttle Radar Topography Mission (SRTM, U.S. Geological Survey, 2015) digital terrain models.

In the fifth step, various ratios have been calculated for each grid in order to classify channel patterns (meandering, braided/anabranching, straight) and to detect changes in length and channel patterns. For the calculation, all attribute data from step 3 have been merged into one table for further analysis. Changes in length have been deduced by using percentages based on the quotient between the lengths of present and historic entire river courses as well as main courses. To identify meandering river sections, sinuosity based on Leopold & Wolman, 1957 has been used, which describes the ratio of thalweg length to valley length and is therefore easy to calculate (on limits of the method see e.g. Dey, 2014; Leopold & Wolman, 1957; Schielein, 2012; Williams, 1986). To identify braided/anabranching river sections, the "braid channel ratio" of Friend & Sinha 1993 has been used, which puts the length of all the different branches and the length of the main river course in a direct relation (Friend & Sinha, 1993; Schielein, 2012). To detect straight river sections, the sinuosity and the braid channel ratio can be used, based on the simple conclusion, that if a river that is neither meandering nor braided/anabranching has to be straight. As there is a certain uncertainty between the values 1.1 and 1.5, only 1.0-1.1 have been classified as straight (Dey, 2014; Leopold & Wolman, 1957).

In the sixth and final step, the calculated ratios have been categorised in order to interpret the results based on conditional formulas in Microsoft Excel:

1. For channel patterns, using critical values of 1.5 and 1.2: =IF(AND(Sinuosity >= 1.5; Braid-Channel Ratio < 1.5); meandering; IF(AND(Sinuosity < 1.5; Braid-Channel Ratio >= 1.5); braided; IF(AND(Sinuosity < 1.2; Braid-Channel Ratio < 1.2); straight ; other)))
2. For changes in channel patterns: =IF(category present = category historic; "no changes" ; IF(category present = straight; "change to straight"; IF(category historic = meandering; "meanders straightened"; IF(category historic = braided; "braids disbanded"; "no changes"))))
3. For changes in length, 1.0 has been defined as 100% of historic length and 0.9-1.1 have been defined as "no changes", taking offsets, etc. into account: =IF(AND(ratio main current > 0.9; ratio main current < 1.1; ratio complete current > 0.9; ratio complete current < 1.1); "no changes"; IF(OR(ratio main current < 0.7; ratio complete current < 0.7; ratio main current > 1.3; ratio complete current > 1.3); "significant changes"; "small changes"))

All ratios and categorisations have been merged in a master table, which contains river name, grid number, length [km] within the grid, sinuosity, braid-channel-ratio, length difference main course [%], length difference complete course [%], channel pattern, changes in channel pattern and finally changes in length. This master table has been re-imported into ArcGIS and joined with subsequent vector layers in order to visualise the data and analyse it spatially.

4. Results

For each river, the ratios of length change between the pre-modern and modern river course have been calculated (Tab. 1, Fig. 3). The calculation has been made for the entire course (including all secondary channels) and the main course only.

Table 1: Length changes: overview of results.

	Main	*Regnitz, Rednitz & Rezat*	*Danube*	*Altmühl*
Modern main course (km)	448.7	213.7	379	228
Pre-modern main course (km)	466.3	227	440.4	242
Change ratio (%) main course pre-modern vs. modern	-4	-6	-16	-6
Modern entire course (km)	460.2	237.4	411.4	256.8
Pre-modern entire course (km)	520.2	252.8	796.9	274.7
Change ratio (%) entire course pre-modern vs. modern	-13	-7	-94	-7

4.1. Main

For the river Main, the pre-modern main course is 4% (17.6 km) longer than the modern main course. Including all secondary channels, the pre-modern flow distance is 13% higher than the modern one. The table of pattern (Table 2) changes does clearly show, that this reduction is mainly due to the transformation of meandering sections (- 40%) to straight sections (+ 40%). Further, a significant number of secondary channels, which contributed to the pre-modern flow distance, must have been abandoned, as the modern entire course is 60 km shorter. Nevertheless, more than 50% of all sections do not show detectable changes at all, so the general ratio of change is rather moderate.

4.2. Main tributaries (Regnitz, Rednitz, Swabian and Franconian Rezat)

For the Main tributaries (Regnitz, Rednitz, Swabian and Franconian Rezat) the pre-modern main course is 6% (13.3 km) longer than the modern main course. Including all secondary channels, the pre-modern flow distance is 7% higher than the modern one. The table of pattern changes (Table 2) does clearly show, that –similar to the river Main– this reduction is mainly due to the transformation of some meandering sections (-80%) to straight sections (+167%). In contrast to the river Main the smaller tributaries do not have a significant number of abandoned secondary channels, as the pre-modern and modern flow distance of the main channel and the entire course do not differ significantly. More than 50% of all sections do show detectable changes, but only for a small number of significant changes could be observed.

Further, changes of river morphology between meandering, braided/anabranching, straight and unspecific sections have been calculated for each grid (Table 2, Fig. 4). Additionally, the number of sections with no significant changes, moderate changes and significant changes have been calculated, too.

4.3. Danube

For the Danube, the pre-modern main course is 16% (61.4 km) longer than the modern main course. Including all secondary channels, the pre-modern flow distance is 94% higher than the modern one. The table of pattern changes (Table 2) does clearly show, that this reduction is mainly due to the transformation of a large number of braided/anabranching sections (-94%) and some meandering sections (-80%) to straight sections (+520%) (Fig. 2). Further, a huge number of secondary channels, which contributed significantly to the pre-modern flow distance, must have been abandoned, as the modern entire course is 385.5 km shorter. Almost two-thirds of all sections do show significant changes and less than 10% no detectable changes, so the general ratio of change is very high.

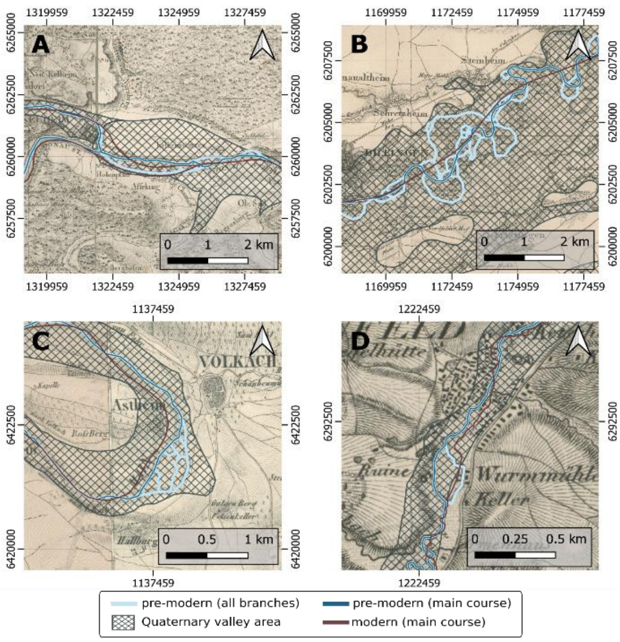

Figure 2: Spatial comparison of the pre-modern and modern fluvial patterns; a) Confluence of Altmühl and Danube, b) Danube, c) Main and d) Swabian Rezat. Quaternary valley area derived from the hydrogeological map of Germany (HÜK250). In the background: “Topographischer Atlas vom Königreiche Bayern”, 1812-1867 (1:50000; Bayerische Staatsbibliothek 2020).

Table 2: Pattern changes – overview of results.

Pattern changes - results (grid size 10 km, number of sections)	*Main*	*Regnitz, Rednitz & Rezat*	*Danube*	*Altmühl*
Meandering sections - modern	6	1	1	1
Meandering sections - pre-modern	10	5	5	4
Change ratio “meandering sections” pre-modern to modern	-40%	-80%	-80%	-75%
Braided/anabranching sections - modern	0	0	1	2
Braided/anabranching sections - pre-modern	0	0	18	1
Change ratio “braided sections” pre-modern to modern	0%	0%	-94%	100%
Straight sections - modern	21	8	31	8
Straight sections - pre-modern	15	3	5	2
Change ratio “straight sections” pre-modern to modern	40%	167%	520%	300%
Unspecific sections - modern	17	16	12	12
Unspecific sections - pre-modern	19	17	17	16
Change ratio “unspecific sections” pre-modern to modern	-11%	-6%	-29%	-25%
No significant changes	24	11	4	11
Moderate changes	12	10	12	8
Significant changes	8	3	29	4

4.4. Altmühl

For the river Altmühl the pre-modern main course is 6% (14 km) longer than the modern main course. Including all secondary channels, the pre-modern flow distance is 7% higher than the modern one. The table of pattern changes (Table 2) does clearly show, that –similar to Main tributaries north of the Main European watershed– this reduction is mainly due to the transformation of some meandering sections (-75%) to straight sections (+300%). Like Rezat, Rednitz, Swabian and Franconian Rezat, the river Altmühl does not have a significant number of abandoned secondary channels, as the pre-modern and modern flow distance of the main channel and the entire course do not differ significantly. 50% of all sections do show detectable changes, but only a small number of significant changes could be observed.

5. Discussion

5.1. General remarks

In general, Table 1 and Table 2 as well as Fig. 3 and Fig. 4 do clearly show, that the ratio of change in length and river morphology is significantly different between the analysed rivers. The most significant changes by far could be observed for the Danube due to the anthropogenic transformation of numerous braided/anabranching sections into straight channels suitable for modern navigation (Fig. 4). The length difference of the main channel of more than 60 km is quite noteworthy for pre-modern navigation conditions. The change ratio of the main channel of 16% is a little bit lower than 18.4% according to Eckoldt, 1998, which is most likely due to the fact that upstream sections, which have never been navigated and therefore have been less transformed, have been included in our study, but not in Eckoldts calculation.

The river Main, which is also a major waterway of supra-regional importance (Eckoldt, 1998; Werther & Kröger, 2017), has not been transformed with the same intensity as the Danube. The reduction in length of the main river course is the smallest of all analysed rivers, despite the fact that the river Main has also been transformed to a modern waterway in the 19th and 20th centuries (Eckoldt, 1998; Gunzelmann, 2009). Cutting several large meanders did obviously have only a minor effect on the overall flow distance – and there has never been a large number of active secondary channels, which have been abandoned in the modern period.

The smaller tributaries Altmühl, Regnitz, Rednitz, Swabian and Franconian Rezat are rather similar concerning their change ratios. Many river sections have passed through significant changes in length and

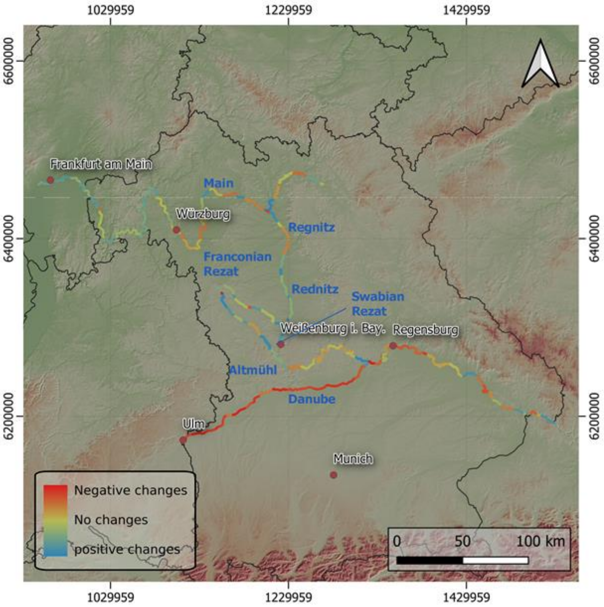

Figure 3: Changes of river lengths of the entire courses of the studied rivers. Negative changes are losses in length, positive changes are gains in length. (DEM data: SRTM 90m; U.S. Geological Survey 2015).

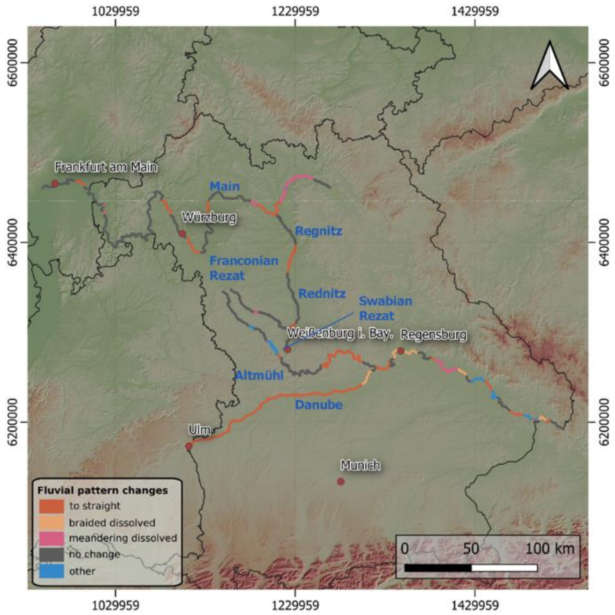

Figure 4: Changes of fluvial patterns for the entire courses of the studied rivers. Colours indicate specific changes of the fluvial pattern from the 19^{th} century to present. (DEM data: SRTM 90m; U.S. Geological Survey 2015).

morphology and the pre-modern main course is 6% on average longer than the modern one. General straightening of the river course is clearly visible, but the overall effects have been limited.

To sum up, some of the analysed rivers have been affected by significant changes in length and morphology from the 19^{th} century to the modern period (Fig. 3 and Fig. 4). Anyway, based on our quantitative and qualitative results three crucial questions for further interpretation must be discussed: 1) How likely is it, that the flow distance represented by 19^{th} century maps is comparable to the flow distance of earlier periods –and how robust is, therefore, the length correction value?; 2) How likely is it that the river morphology represented by 19^{th} century maps is similar to earlier periods –and, if not, what are the consequences on flow distance and length correction values?; 3) How significant in general are the changes in flow distance for pre-modern navigation?

Concerning the first two key questions, it has to be stressed, that floodplains and flow patterns of almost all European rivers have heavily been transformed during the late Holocene, especially due to flood loam deposition, but also due to hydro-engineering (Beauchamp et al., 2017; Brown, 1997; Brown et al., 2018; Hoffmann et al., 2009; Hoffmann, 2010; Houben et al., 2013; Longoni & Wetter, 2019; Notebaert et al., 2018). In general, a decrease of channel sinuosity during the last two millennia has been observed for many European rivers (Erkens et al., 2009), which tends to result in higher pre-modern flow and navigation distances. However, the dynamics of medieval and early modern hydro-engineering beyond the local scale have been neglected by multidisciplinary research and path dependencies are virtually unknown. Further, significant spatial and chronological heterogeneity should be taken into account. Therefore, in order to evaluate the reliability of our results in greater detail, each river has to be treated separately and available ground-truthing has to be discussed.

5.2. Main and Main tributaries

The river Main has been a typical meandering river all over the Holocene. Nevertheless, from the so-called Unterbrunn phase of fluvial activity (c. 260-550 AD, dated by dendrochronology) onwards, there has been a major shift in channel morphology. The river became more shallow, the channel base rose and more secondary channels, sand- and gravel banks did occur. This general trend and fluvial pattern remained rather stable until modern river engineering took place in the 19^{th} and 20^{th} centuries (Gerlach, 1990; Schirmer, 2007; Schirmer et al., 2005). Therefore, on a regional to supra-regional scale, the general morphological pattern and flow distance of the main channel recorded in the earlier 19^{th} century "*Topographischer Atlas*" before large-scale river engineering could be assumed to be rather similar to the medieval and early modern period. Nevertheless, as small-scale river engineering and straightening on a local scale have to be reckoned at least from the later Middle Ages onwards, the flow distance in Antiquity and in the Early Middle Ages might have been slightly higher than our correction values based on 19^{th} century patterns do suggest.

The southern Main tributaries Regnitz, Rednitz, Swabian and Franconian Rezat are meandering watercourses in their natural state, too. However, due to intense use for hydro-energy and accompanied river engineering at least from the 14^{th} - 15^{th} centuries onwards (Eckoldt, 1980; Gunzelmann, 2009; Hanemann, 2009; Rössler, 2000), it is impossible to evaluate the reliability of our results in general without further research. Anyway, the fact that a rather high ratio of unspecific morphological sections (17) and a rather low ratio of meandering sections (5) have been observed on 19^{th} century maps (Table 2) suggests, that a significant level of straightening did already take place before the first half of the 19^{th} century, as more meandering sections are to be expected in a natural state of Holocene river morphology. This is underlined by the fact, that e.g. the course of the Swabian Rezat south of Weißenburg had already been partially straightened in 1801 (Note du général, 1801), that is, before map sheet no. 46 of the "*Topographischer Atlas*" was surveyed in 1830 (Bayerische Staatsbibliothek, 2020; see also Schmidt et al., 2018; Rabiger-Völlmer et al., 2020). Therefore, it is likely that the overall flow distance before the 19^{th} century was higher than observed and our correction value has to be adjusted based on further research.

5.3. Danube and Altmühl

The river morphology of the Danube in the study area is much more heterogeneous compared to the river Main, which is underlined by the fact, that braided/anabranching, meandering and unspecific sections (Table 2) are represented in our 19^{th} century map series (Schellmann, 2010; Schielein, 2010; Schielein, 2012). Based on a detailed regional study of the confluence area of Lech and Danube (Schielein, 2010) it could be assumed, that the high ratio of braided/anabranching sections is a particular phenomenon of the early 19^{th} century in specific areas, whereas the general morphological pattern of the Danube has always been meandering. The meandering sections in the 19^{th} century "*Topographischer Atlas*" are part of the H6- and H7-terraces, which have been developing from the 16^{th} to the early 19^{th} centuries

(Schellmann, 2010). Similar to the river Main, the Danube channel became more shallow and wider from the Early Middle Ages (H5-terrace) onwards (Schellmann, 2010). Further, it has to be stressed that Schielein, 2010 did not observe channel engineering beyond occasional local exceptions in his Danube study area before the 19th century, which points to a rather low level of large-scale sustainable river engineering. Overall it seems likely, that on a supra-regional scale the flow distance of the meandering main channel, which we have mapped based on the "*Topographischer Atlas*", is quite similar to the flow distance in the medieval and early modern period. That does also count for the river Altmühl, which did preserve its predominant meandering morphology during the late Holocene (Hilgart, 1995; Hilgart & Nadler, 2005; Kirchner et al., 2018), so that the 19th century overall flow distance should be comparable to earlier periods.

5.4. Reliability of length correction and pattern reconstruction

To sum up, despite significant gaps of knowledge for some of the analysed rivers concerning our key questions, there are strong indications that the 19th century flow distance and our length correction value are suitable and robust to model pre-modern navigation distances more precisely. For all the analysed rivers, the pre-modern flow and navigation distance of the main course has been 4-16% higher compared to modern hydrological datasets. This range could therefore be understood as a minimum ratio of correction and pre-modern navigation distances could be re-modelled accordingly. Anyway, as the rivers Danube and Main have been subject to profound hydrological and morphological transformations between Late Antiquity and the Early Middle Ages (Schirmer, 2007; Schellmann, 2010) our correction value might have higher uncertainties for and before these periods. Further, referring to Hoffmann et al., 2010, our numerical approach could work as a validation step for late Holocene floodplain development reconstruction, as our methodology allows for the identification of river morphology patterns, too.

5.5. Significance for pre-modern navigation models

Our analysis resulted in an overall correction value of modern flow distances in the range of 4-16% to approximate and model the pre-modern hydrological situation. Based on this value, it has to be discussed how significant this difference is for pre-modern navigation practice and which role regional differences do play.

We would like to use a specific historical case study and two further examples to outline the significance and regional variability. In 793 AD, emperor Charlemagne went by boat from Regensburg to the construction site of the Fossa Carolina, upstream the river Danube to the Altmühl confluence and further upstream the river Altmühl to the Main European Watershed between Treuchtlingen and Weißenburg. After a longer stay at the site, he continued to travel downstream on the rivers Swabian Rezat, Regnitz and Main to Würzburg, where he celebrated Christmas (Hack, 2014; Werther et al., 2020).

Further, we have also carried out modelling of two random riverine route examples of similar modern length, Ulm–Regensburg (river Danube) and Frankfurt–Würzburg (river Main), which did both play an important role in medieval inland navigation (Eckoldt, 1998; Gross, 2001; Rothmann, 2010; Werther & Kröger, 2017).

In order to estimate travel times upstream and downstream, which could cover quite a wide range, we have collected published travel time data for inland navigation (Table 3). Based on written sources and experimental data (see also Scheidel, 2014; Scheidel, 2020), the average travel distance per day varies from 26–130 km downstream and 1–50 km upstream, depending on the current, cargo and weight of the boats, propulsion technique (e.g. hauling, rowing, punting), obstacles and many more unknown variables (see e.g. Ellmers, 1972; Bockius, 2006; Scheidel, 2014; Scheidel, 2020; Werther & Kröger, 2017). In general, the ratio between travelling downstream and upstream is 1:2 minimum and 1:15 maximum, the median is c. 1:4, so travelling upstream takes four times as long as downstream on most of the rivers.

Based on this data, we have been able to model travel distances and time for our three case studies and to determine the effect of calculation with pre-modern flow distance ratios (Table 4). In order to outline travel time, we have been using high-speed values (60 km downstream and 25 km upstream per day) as well as low-speed values (30 km downstream and 10 km upstream per day), based on Table 3.

The travel of king Charlemagne from Regensburg to Würzburg has a length of c. 440 km (modern flow distance) respectively c. 473 km (pre-modern flow distance), of which more than 1/3 has been upstream travel on the rivers Danube and Altmühl. If he and his court had been travelling fast, the modelled travel time is 11.2 (modern flow distance) or rather 12.13 days (pre-modern flow distance). If he had travelled slow, the modelled travel time would be 25.74 (modern flow distance) respectively 27.92 days (pre-modern flow distance). The difference in navigation distance and travel time by using modern or pre-modern length data is 8% or 1-2 days.

Travelling by boat between the important medieval centres of trade and commerce Ulm and Regensburg means to follow the river Danube on a length of c. 207 km (modern flow distance) respectively c. 257 km (pre-modern flow distance), either upstream or downstream. A fast boat could have covered the distance downstream in 3.45 (modern flow distance) respectively 4.28 days (pre-modern flow distance) and upstream in 8.3 (modern flow distance) respectively 10.28 days (pre-modern flow distance). A slow boat, heavily laden or with insufficient propulsion, may have needed 6.9 (modern flow distance) respectively 8.57 days (pre-modern flow distance) downstream and 20.69 (modern flow distance) or rather 25.71 days (pre-modern flow distance) upstream. The difference in navigation distance and travel time by using modern or pre-modern length data is 24% or up to five days, which is highly significant. Furthermore, this specific section of the river Danube is above the average of 16% length change for the whole Danube in the working area, which points to significant regional variability. Compared to late medieval and early modern written sources (Eckoldt, 1998), which testify a travel

Table 3: Selection of published travel time data for inland navigation upstream and downstream.

Bibliographic reference	*average distance downstream / day*	*average distance upstream / day*	*average overall distance*	*Time ratio downstream – upstream*
Baker & Brookes 2014 (Viking Age ships, inland)			4.1 km / h	
Brönnimann 1997 (alpine rivers)		10-15 km		1:3-6
Ellmers 1972 (early medieval period, Lower and Middle Rhine)		23 – 24 km		
Ellmers 1972 (late medieval and early modern period)	50 to 100 km	15 – 17 km		1:3 to 1:6
Escher & Hirschmann 2005 (inland navigation in the low countries, 11th – 15th cent.)	26 km	9 km		1:2.9
Franconi 2016 (lower Rhine, medieval period)				1:5 to 1:6
Fütterer 2019 (10th - 11th centuries, itineraries on rivers in Thuringia and Eastern Saxonia)			60 km / day	
Hack 2019 (fluvial itinerary of Frederic III., 15th century)			37 - 57 km /day	
McCormick 2012 (Po catchment, Early Middle Ages)	up to 130 km			1:2
Reinke 1987 (royal ships, inland waterways, 11th - 12th cent.			21 km / day (median)	
Salway 2004 (Diocletian´s price edict of 301 AD)				1:2
Scheidel 2014 (river Rhône, Avignon – Lyon, medieval period)				1:6 to 1:15
Scheidel 2014 (roman military row boats)	120 km	50 km		1:2.4
Scheidel 2020 (roman civilian boats, general)	45-75 km	10 – 30 km		mainly 1:4
Scheidel 2020 (roman civilian boats, Middle Danube)	55 km	20 km		1:2.75
Schmitz-Esser 2015 (medieval period)	up to 100 km	20 km		1:5
Weski 2014 (river Danube, 18th cent.)				1:6 to 1:10
Weski 2014 (river Elbe, 18th cent.)		1 – 11 km		
Weski 2014 (river Rhine, Mainz-Strasbourg, 18th cent.)				1:3.5 to 1:6
Weski 2014 (river Weser, 18th cent.)				1:2 to 1:3
Weski 2014 (Russia, 10th cent.)				1:3
				Minimum: 1:2 Median: c. 1:4 Maximum: 1 : 15

time of 13-22 days following the Danube upstream from Regensburg to Ulm, our calculation based on pre-modern flow distances (9-26 days) seems to be quite accurate. Nevertheless, our values for fast speed tend to be a little bit too high and the values for slow speed a little bit too slow, which results in a slight under- and overestimation of travel time towards the extrema.

Travelling by boat between the equally important medieval centres Würzburg and Frankfurt means to follow the river Main on a length of c. 218 km (modern flow distance) to c. 220 km (pre-modern flow distance), either upstream or downstream. The difference in navigation distance and travel time by using modern or pre-modern length data is not even 1% and therefore insignificant. Nevertheless, this specific section of the river Main is below the average of 4% length change for the whole Main in the working area, which points to significant regional variability, again.

In comparison, the three case studies underline, that changes in flow distance could have tremendous effects on time and effort for inland navigation – but with huge regional differences from river to river and even from river section to river section. Modelling travel time based on pre-modern flow distance resulted in travel time values up to 24% higher than based on modern flow distances. Nevertheless, this is only the case for rivers such as the Danube, which have heavily been transformed and straightened by modern river engineering. The river Main, in contrast, does not show any significant differences between travel time models based on modern respectively pre-modern flow distances. Therefore, individual and river-specific correction values are the only solid and promising way to improve network models of pre-modern inland waterways and navigation such as the Stanford Geospatial Network Model of the Roman World ORBIS (Preiser-Kapeller & Werther, 2018; Scheidel, 2020). Our methodological approach based on a comparison of vectorised flow distances extracted from old maps and modern opensource geodata allows for feasible and fast processing of such correction values for other rivers, too.

.**Table 4**: Modern and pre-modern navigation distances for case study 1-3 and calculations of estimated travel time and change ratios.

	Direction upstream / downstream	*Modern distance (km)*	*Travel days high speed (60 km downstream / 25 km upstream per day)*	*Travel days low speed (30 km downstream / 10 km upstream per day)*	*Pre-modern distance (km)*	*High speed (60 km downstream / 25 km upstream per day), travel days*	*Low speed (30 km downstream / 10 km upstream per day), travel days*	*Travel time variation modern to pre-modern flow distance*	*Length variation modern to pre-modern*
Charlemagne's fluvial itinerary Regensburg - Würzburg, 793 AD									
Danube Regensburg - Altmühl	up	30.56			35.19				
Altmühl confluence - Fossa Carolina	up	135.31			146.86				
Swabian Rezat Fossa Carolina - Rednitz	down	24.87			24.93				
Rednitz	down	46.78			47.22				
Regnitz	down	64.74			71.01				
Main Regnitz confluence - Würzburg	down	138.01			148.08				
total (km)		440.27			473.29				+8%
of which upstream		165.87	6.63	16.59	182.05	7.28	18.21	+10%	
of which downstream		274.4	4.57	9.15	291.24	4.85	9.71	+6%	
total (days)			11.2	25.74		12.13	27.92	+8%	
Other important riverine routes									
Ulm - Regensburg	down	206.94	3.45	6.9	257.09	4.28	8.57	+24%	+24%
Regensburg - Ulm	up	206.94	8.3	20.69	257.09	10.28	25.71	+24%	+24%
Frankfurt - Würzburg	up	218.39	8.74	21.84	220.29	8.81	22.03	+1%	+1%
Würzburg - Frankfurt	down	218.39	3.64	7.28	220.29	3.67	7.34	+1%	+1%

6. Conclusion

The ratio of pre-modern and modern changes in flow distance could have significant effects on modelling medieval and early modern inland navigation. For the first time, our study provides a large-scale analytical approach to evaluate this changing ratio based on a comparison of old maps and modern geodata by means of methods provided by digital humanities. Our transferable GIS workflow for flow distance reconstruction could be adapted for other regions in order to deduce change ratios and model historical networks of navigation on a European scale.

Our approach has been used systematically in a case study focussing on the rivers Altmühl, Danube, Main, Regnitz, Rednitz, Franconian and Swabian Rezat (Southern Germany). For these rivers, we have reconstructed regional to supra-regional changes of flow pattern, flow distances and subsequent changes in navigation distance and transportation time. The most significant changes have been observed for the river Danube, where the main channel did lose 16% in length from the pre-modern to the modern period (and even 24% between Ulm and Regensburg) due to vast flow pattern transformation and straightening by modern river-engineering. Based on a comparison of published travel time data for inland navigation, we came to the conclusion that this length change could result in a travel time up to 24% higher in the pre-modern period. However, other waterways such as the river Main do not show comparably significant differences in flow distance, channel pattern and travel time. Therefore, river-specific correction values on a regional scale are the only solid and promising way to improve supra-regional network models of pre-modern inland waterways and navigation. Finally, as small-scale river engineering and straightening on a local scale have to be reckoned with at least from the later Middle Ages onwards, the flow distance in Antiquity and the Early Middle Ages might have been slightly higher than our correction values based on 19th century patterns do suggest. To verify or reject this hypothesis, further research on a medium spatial scale has to be done.

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