

Review

On the Way to the Fluvial Anthroposphere—Current Limitations and Perspectives of Multidisciplinary Research

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Abstract: Floodplains represent a global hotspot of sensitive socioenvironmental changes and early human forcing mechanisms. In this review, we focus on the environmental conditions of preindustrial floodplains in Central Europe and the fluvial societies that operated there. Due to their high land-use capacity and the simultaneous necessity of land reclamation and risk minimisation, societies have radically restructured the Central European floodplains. According to the current scientific consensus, up to 95% of Central European floodplains have been extensively restructured or destroyed. Therefore, question arises as to whether or when it is justified to understand Central European floodplains as a ‘Fluvial Anthroposphere’. The case studies available to date show that human-induced impacts on floodplain morphologies and environments and the formation of specific fluvial societies reveal fundamental changes in the medieval and preindustrial modern periods. We aim to contribute to disentangling the questions of when and why humans became a significant controlling factor in Central European floodplain formation, and how humans in interaction with natural processes and other chains of effects have modified floodplains. As a conclusion, we superimpose emerging fields of research concerning the onset of the Fluvial Anthroposphere and provide 10 specific thematic objectives for future multidisciplinary work.

Keywords: preindustrial floodplains; fluvial societies; path dependencies; socionatural site; early anthropogenic forcing; natural and cultural heritage



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1. Introduction—Floodplains as Hotspots of Socioenvironmental Changes

We understand floodplains as the natural area of a river system that is or has been characterised by episodic or periodic flooding during periods of higher discharge [1,2]. Floodplains comprise the active riverbed and palaeochannels, and roughly correspond to the distribution of Holocene flood sediments. Highly specialised river civilisations developed worldwide thanks to a specific mix of socionatural benefits and hazards. Floodplains and the associated alluvial landscapes represent some of the most dynamic parts of the cultural landscape and represent hotspots for natural and cultural heritage [3–5]. Although, at present, up to 50% of the world population live in natural or modified floodplains, these areas have been poorly investigated to date [6]. Little work has been undertaken to examine either buried archaeological remains within floodplain stratigraphies or the rich palaeoecological and geomorphological archives resulting from the excellent preservation conditions [7]. A deeper understanding of this highly sensitive spatial entity is of both scientific and public relevance, given the need—which is expected to become keener with climate change—for floodplain management [8,9].

Many floodplains have been hotspots of socioenvironmental dynamics and affected by significant anthropogenic modifications such as land reclamation and flood protection. These modifications could be so substantial that former floodplains are no longer recognisable. According to Tockner et al. [6], up to 95% of the Central European floodplains have been significantly modified or destroyed. Irrespective of the modification level, all floodplains and fluvial societies have been shaped by climatic and hydrosedimentary, as well as anthropogenic, impacts and interactions. Therefore, the questions are (1) whether the perception of specific floodplains and fluvial societies as forming a Fluvial Anthroposphere is justified, and if it is, (2) when particular Fluvial Anthropospheres come into being. To answer these questions successfully and to identify chronological as well as regional variants and similarities, the need to compare specific river systems has been underlined [10–12]. For this review, we focus on a comparative discussion of the onset of the Fluvial Anthroposphere in the three river systems of the Danube, Rhine and Elbe (Figure 1), which cover major parts of Central Europe and feature rather different natural (e.g., geology, hydrology, topography) and cultural (e.g., settlement and land-use history, technological traditions, forms of government) conditions.

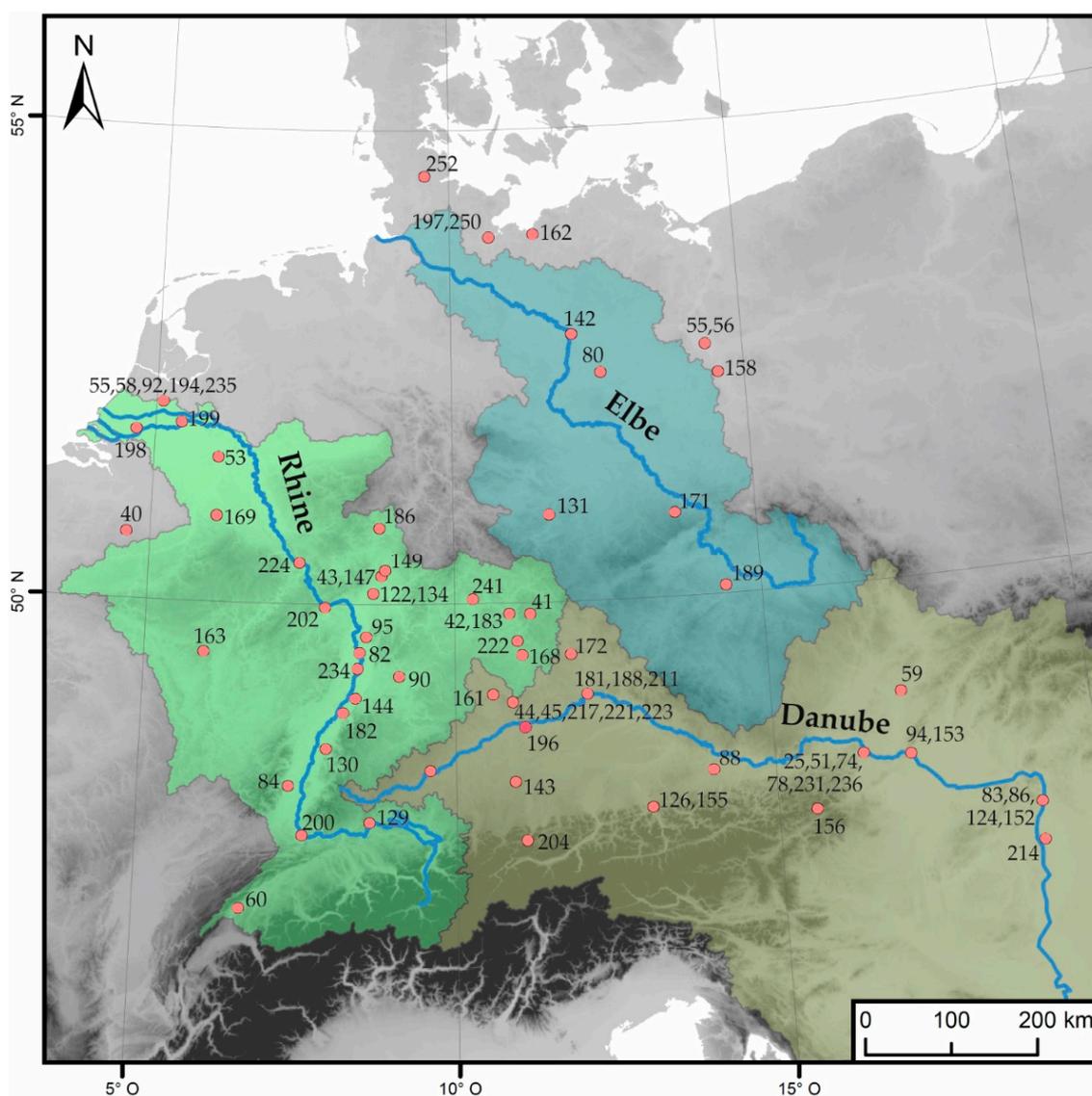


Figure 1. The Central European river catchments of the Danube, Elbe and Rhine with study locations, ranging from local to regional, mentioned in the text. The numbers refer to the list of references.

1.1. The Fluvial Anthroposphere in the Context of the Global Anthropocene

Over the last decade, the Anthropocene has become a key scientific concept. It can be considered as a geological time scale that features significant and synchronous anthropogenic-induced changes in climate and material cycles, as well as species invasion and mass extinction at a global scale [13–17]. Further, socioecological perspectives in the humanities consider the Anthropocene a powerful new narrative that radically revises the ‘meaning of nature and even the nature of humanity’ [18]. However, the varied historical pathways to the Anthropocene as a global phenomenon (‘Early Anthropocene’, see [18]) are comparatively unexplored.

Worldwide, floodplains represent particularly sensitive socioenvironmental systems concerning anthropogenic impacts—with resulting effects on global freshwater balance [19] and land-use, aquatic and riparian biodiversity [20], material balances and greenhouse gas emissions. In contrast with the ubiquitous Anthropocene concept, anthropogenic forcing and the resulting feedback mechanisms in floodplains have to be considered as spatially and chronologically asynchronous. In this context, we understand the geomorphological, ecological and socionatural setting of anthropogenic forcing in specific floodplains on a more local-to-regional scale as a Fluvial Anthroposphere (Figure 2).



Figure 2. The Fluvial Anthroposphere as a series of socionatural processes in and along a floodplain. Thematic fields, such as the human impact on biodiversity, floods and flood-control measures, channel engineering, hydropower, legal frameworks and mechanisms of conflict management, land use and land reclamation, river crossings and floodplain pollution might have seen profound qualitative and quantitative changes during the medieval and preindustrial periods. Human-induced changes in floodplain environments and the formation of specific fluvial societies justify the understanding of Central European floodplains as a Fluvial Anthroposphere.

Here, increasing anthropogenic impacts can be traced through an artificial change in the magnitudes and frequencies of ‘natural’ processes. This includes flood hazards, sediment imbalance, chemical contamination and eutrophication. They can also be seen through the direct modification of ‘natural’ floodplain structures resulting from floodplain colonisation, water regulation and river fragmentation [21]. These processes run alongside changes in the involved socionatural systems and feedback mechanisms. Societies acted as agents of change, but were also shaped by the river systems in terms of their economic activities, sociopolitical structures and even their religious ideas. While most changes in natural processes can be measured by indicative measurements, the sociocultural factors required for changes can only be described relationally and determined semiquantitatively. The different search variables in the natural and sociocultural spheres are based on different material (e.g., sediments, pollen) and immaterial sources (e.g., ideas, norms, practices) and

require a combined analysis of the archives of nature as well as of society. They enable a targeted search for the specific beginning, course and dynamics of the path to a Fluvial Anthroposphere in a given area of investigation.

The onset of the Fluvial Anthroposphere might be understood as a gradual transition from nature-dominated to human-dominated processes in floodplains [22], which is an integral part of the ‘Early Anthropocene’. There are strong arguments for perceiving most Central European floodplains as having been a Fluvial Anthroposphere since at least the beginning of the industrial period. However, the human impact on many floodplains and the formation of specific fluvial societies began much earlier due to the long-lasting and intense cultural history in Central Europe [7,23]. In our review, we focus on the medieval and preindustrial modern periods as a game-changing time of transition, but we do consider both earlier and later developments depending on the specific floodplain. The onset of the Fluvial Anthroposphere is a global research desideratum due to the spatial and temporal asynchrony of the dynamics of fluvial societies [9,21]. However, there is a gap in the systematic availability and understanding of both the quantitative environmental and semiquantitative and qualitative socioeconomic parameters describing this great transition in a multidisciplinary way [24–26].

1.2. Current Limits from the Fluvial-Geomorphological and Palaeohydrological Perspective

European floodplain research has produced important geomorphological and geoscientific knowledge in recent decades. The International Union for Quaternary Research (INQUA) project ‘Hydrological EXtreme Events in Changing Climate’ [27], the radiocarbon chronologies of fluvial archives [28], the Deutsche Forschungsgemeinschaft (DFG-German Research Foundation) Priority Programme ‘Changes in the Geo-Biosphere during the Last 15,000 Years’ [29], the RheinLUCIFS project [30,31] and the DFG Graduate School on ‘Paleoecosystems and History’ [32] can be highlighted here (Table 1). In recent years, the potential of fluvial sediment sequences on shallow continental shelves for floodplain research has also been emphasised [33,34]. Accordingly, the long-term geomorphological development of Central European floodplains can be summarised as follows: covering early to mid-Holocene wetlands and secondary channels, the onset of loamy overbank deposition transformed floodplains in the course of the middle to late Holocene [7,35,36]. The onset and intensification of land use correspond with catchment-scale soil erosion and subsequent flood loam deposition [37,38]. Although this aggradation process differs between individual floodplains due to nonsynchronous catchment clearings [39,40] and cascade effects [29,41], flood loam deposition must be seen as a first, but indirect, human impact on floodplain evolution.

Direct human impact on floodplain evolution followed from the historical period onwards, characterised by a significant increase in hydroengineering constructions with weirs, dams, bridges and canals [42–46]. This process was accompanied by riparian forest clearings that are reflected in floodplain toponyms [47]. As shown by fluvial geomorphological studies, hydroengineering infrastructure such as watermills impacted floodplain morphology and stratigraphy due to its direct influence on river flood regimes and their hydrosedimentary connectivity [43,48,49]. Starting in the early 18th century, channel engineering for navigation, flood protection and the prevention of avulsion represent a massive intervention in Central European floodplains as well [50–52].

The onset of overbank silt–clay deposition (German: ‘Auelehm’), which often began in prehistory, is probably the most striking sedimentological marker of human impact in Central European floodplain history. However, this transition does not form the focus of our review report, as we aim to identify anthropogenic activities within the floodplain itself and their consequences, whereas the beginning of overbank silt–clay deposition was due primarily to catchment-scale intensification of land use and not human activity within the floodplain. Still, subsequent increases in the magnitude of overbank silt–clay deposition may be far more significant for the genesis of the Fluvial Anthroposphere [35,53]. These probable increases in fluvial dynamics need to be explained through multidisciplinary

research into human activities within the floodplain and are far less researched. Similarly, although numerous medieval and early modern construction works led to changes in flood regimes, little work has done on these mechanisms to date.

1.3. Current Limitations from an Archaeological Perspective

Central European floodplains are key areas of cultural heritage, and the archaeological preservation is often exceptional, but this heritage is constantly being destroyed [5,54]. In recent decades, several multidisciplinary projects have focused on archaeological remains at a river-catchment scale, but rarely in the floodplain itself and very few projects have on the late medieval and postmedieval periods. The cutting-edge project ‘Mensch und Umwelt im Odergebiet in ur- und frühgeschichtlicher Zeit’ [55,56], which dealt with the socio-natural interplay from the Neolithic to the early medieval period, concluded that human impacts on the environment were mostly apparent from the late medieval period onwards. Other projects have focused on isolated river sections or periods such as the lower Rhine River [57,58] or the March River in the 1st millennium AD [59]. There are local case studies that yield spatially restricted insights into floodplain modifications [60–62]. However, attempts to make a cross-catchment synthesis of archaeological features in floodplains are rare [63]. Furthermore, documentary sources (e.g., texts and old maps) have rarely been investigated in a systematic way to complement and contrast the archaeological record.

As far as we know, the initial exploitation of European floodplains ‘in their natural state’ for grazing and the use of aquatic resources dates back to prehistory. In the Roman and early post-Roman periods, floodplain modification for drainage and navigation, among other purposes, is mainly documented at the local scale. However, it is only from the medieval period onwards that large-scale landscape engineering and systematic floodplain reclamation can be observed in many catchments [64–66]. Embankments, dykes, artificial channels, milldams, fishponds and weirs, bridges and systematic levelling and waste disposal from this era are typically encountered archaeological features [9,62,67–69]. The impact of these anthropogenic features on floodplain sedimentation and fluvial morphodynamics has been discussed [43,49,70], but the features themselves have rarely been the target of specific research, so they usually serve to tell a rather simplistic background story. This follows from the fact that research-focused excavations are generally rare and the archaeological potential to enhance our understanding of past floodplain transformation remains unexplored. This is especially true for the later medieval and early modern periods. Furthermore, the archaeological perspective has often been too narrow, neglecting to pay closer attention to ecological and hydrological consequences and feedback loops.

1.4. Current Limitations from an Historical Perspective

From the historical perspective, river history is a classic topic. The historiography has evolved from the early study of the Rhine by the annalists [71] to an ‘histoire totale’ in the *longue durée* [72], the ‘urban history’ of rivers [73–75], the economic and environmental history of rivers [76–78] and the history of the network of rivers and canals as transport routes and infrastructure [79–81]. Increasingly, interest has been focused on the floodplains of the great European rivers [82–86]. Regional studies have examined environmental dynamics and human activities in river deltas, fens, swamps and lagoons [87–90] from England [91] to the Netherlands (as an ‘amphibious culture’ [23]) to the Venetian lagoon [92].

However, analysing rivers in the sense of environmental history as resources, sociotechnical drivers and specific habitats [91,93,94], focusing on floodplains as cultural landscapes and studying rural societies shaped by the waterscape, represent new directions in academic research [6,10]. Scholars are asking questions about groups of actors and the agency of increasingly specialised professions (e.g., millers, tanners, engineers) in transforming the landscape, and the conflicts that these have created [95]. In recent years, a methodological consensus has been suggested, whereby the common history of rivers and society is analysed not as a dichotomy of nature and culture, but as the complex interplay within a specific ‘socio-natural site’ [4,25,51,96,97]. This means a reciprocally working

combination of natural and anthropogenic structures resulting from long historical processes of interaction between nature, technology and society, which shaped the floodplain specifically as an instance of colonised nature [98,99]. However, many questions regarding the onset of and the way towards the Fluvial Anthroposphere remain unanswered due to the underdeveloped interplay between natural science and the humanities: Which natural and human-induced material flows, interactions, feedback loops, tipping points and cascade effects have to be considered? To what extent do these dynamics reflect human intentionality and to what extent do they not? As a research perspective, there is now the unique opportunity to combine the recent spatial and material turn of cultural studies with the cultural turn of natural sciences in a meaningful way [8,100–102]. Moving beyond the old and simplistic theses on hydraulic societies [103], a more bottom-up approach is proving to be promising, helping to conceptualise the interplay of society and nature as a kind of ‘empowering interaction’ [84,104], which led to epoch- and space-specific cultural landscapes. This requires close multidisciplinary cooperation.

1.5. Research Perspectives within a Multidisciplinary Framework

Beyond the disciplinary limitations outlined above, we aim to highlight multidisciplinary research perspectives with regard to Central European floodplain development:

(a) Mills, fisheries, irrigation, draining, levelling for land reclamation, bridges, pathways, dykes and artificial channels have immediate effects on floodplains. The use of floodplain resources such as water, gravel, fish, wood and meadows also led to significant modifications to floodplains. Anthropogenic features in the floodplain are rarely isolated, but always entangled with and embedded in natural features and processes. Therefore, they have been defined as a ‘fluvio-cultural unit’ that forms a complex structure. Small changes can initiate ‘path dependencies’ that shape the development of a floodplain into its modern-day state [9,10,12,76]. This is exemplified by the considerable impact of medieval milldams on recent hydropower potential [7,105]. However, precisely when and why human activity became a significant controlling factor in specific floodplains, and how socioeconomic structures were influenced by riverine environments, has not yet been examined in a multidisciplinary and comparative way [8,9,25]. A particular deficit regards the long-term socioecological perspectives, which would not only aim to understand the environmental and geomorphological history in the floodplain, but also the inherent changes within the corresponding societies.

Macklin and Lewin [11] use the term ‘river civilisation’, and they and others [106–109] have called for multidisciplinary research that includes historical approaches across domains. However, the impacts of the fluvial environment on societies have not really been highlighted to date. These are of particular importance, because the highly dynamic interaction has produced very specific socioecological systems in many areas, and fluvial or even amphibious cultures and societies [23,47,110], the members of which have both extensively adapted their way of life to the particular conditions in and around floodplains and intensively altered those conditions. On a granular level, however, it is often unclear how social activities at the local, regional and supraregional scales influenced or even excluded each other. These are key issues for understanding of the formation of the Fluvial Anthroposphere as a network of effects of floodplain and society in a socionatural site (Figure 3).

(b) Knowledge of natural palaeohydrological conditions underpins any attempt to pinpoint the transition towards the Fluvial Anthroposphere. This means that even if the palaeohydrological focus of floodplain research relates to the medieval and preindustrial modern period, the full Holocene floodplain history needs to be considered in order to identify and quantify anthropogenic changes. In this context, geoscientific floodplain research approaches must develop quantitative parameters and related Holocene boundary levels. These parameters will be useful for past and current socioecological risk assessments in the context of the Anthroposphere debate and current Global Change [16,17,19,24,111–113].

(c) The transition from nature-dominated to human-dominated processes can be detected in many environmental archives for the historical period [17,22] and there are indications from fluvial archives as well [26,114]. The detection of ‘natural’ climatic imprints within fluvial archives will help to distinguish between climatic and anthropogenic forcing mechanisms in floodplain genesis. Here, signals of Holocene ‘Rapid Climate Changes’ (RCCs) [115–118] within floodplain chronostratigraphies play a key role. The most recent RCC is known as the ‘Little Ice Age’, for which Central European lake-level reconstructions [119] point to wet intervals. However, although late Holocene flood loams might also have an extraordinarily high potential for the detection of climate-induced flood periods [120,121], those of Central European floodplains are still under-investigated.

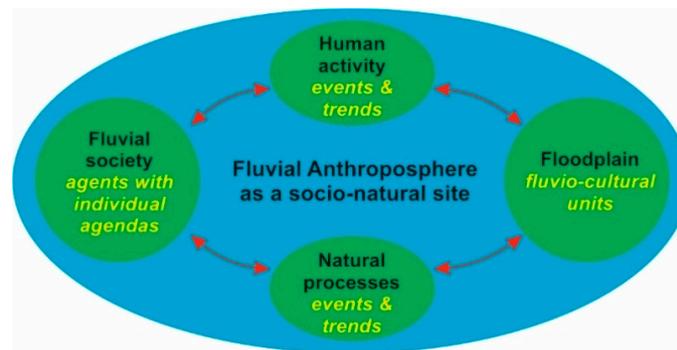


Figure 3. The Fluvial Anthroposphere as a socio-natural site.

Table 1. Joint research projects mentioned in the text.

Joint Research Project	Project Aims
Hydrological EXtreme Events in Changing Climate	This INQUA-funded project aimed to reconstruct past and supraregional hydrological activity in the context of climatic variability using an approach based on a meta-analysis of data sets of chronological control (¹⁴ C and luminescence dating) [27,28].
Changes in the Geo-Biosphere during the Last 15,000 Years	The DFG Priority Programme aimed to reconstruct environmental conditions and geomorphological processes in Central Europe by combining catchment-scale case studies [29].
RheinLUCIFS	The RheinLUCIFS project investigated the effects of land use and climatic forces on sediment fluxes at Rhine catchment and subcatchment scales [30,31].
Paleoecosystems and History	The Regensburg Graduate School on ‘Paleoecosystems and History’ aimed to reconstruct historical human–environmental interaction in Germany [32].
Harbours from the Roman Period to the Middle Ages	The DFG Priority Programme 1630 aimed to construct a complex understanding of Roman and Medieval harbour systems in Europe and their ecological, logistical, economic, social, legal, military and religious subsystems [44,45].
Mensch und Umwelt im Odergebiet in ur- und frühgeschichtlicher Zeit	This project of the Volkswagen Foundation investigated socio-natural interplay along the River Oder from the Neolithic to the early medieval period [55,56].
The Dark Ages in an interdisciplinary light: people, landscape and climate in the Netherlands between AD 300 and 1000	This project, funded by the Netherlands Organization for Scientific Research, aimed to reconstruct the Dutch riverine landscape and its human occupation in the first millennium AD [58].
ENVIEDAN. Environmental history of the Viennese Danube 1500–1890	This project, supported by the Austrian Science Fund investigated the long-term dynamics, patterns and side effects of the colonisation of rivers, focusing on the Viennese Danube [25,51].
Historical disaster research with a view to comparative cultural study	This DFG project undertook an historical investigation of disasters such as flooding and droughts [84].

2. Specific Thematic Fields and Major Challenges

We now present 10 specific thematic fields that we identify as critical to the understanding of the transition to the Fluvial Anthroposphere in Central Europe.

2.1. Construction, Maintenance and Socio-Natural Effects of Flood Control Measures

Ice drift, disastrous floods [122], channel displacement [123] and droughts [95,124] have a remarkable impact on fluvio-cultural units [125]. Riverine societies have developed techniques to control and exploit extreme events and protect (agri)culture from floods: damming, river straightening and canalisation [42,52,69,79], drainage systems and plantings against erosion [87,90]. Situations in the upper courses of rivers [93] and on smaller rivers, for which the term ‘flood culture’ has been suggested, seem to be particularly dynamic [126]. Additionally, disastrous ‘normal’ flood events have been the focus of research in recent years [86,87,127–131]. An initial interest in reconstructing such events and the perception and interpretation of them has shifted the examination of topics such as coping strategies, societal learning from recurring flood events and river management practices [85,89,132,133]. However, the relationship between extreme events such as floods, long-term structural changes due to hydro-climatic fluctuations and societal adaptation strategies has only recently been questioned [134]. Furthermore, there is a lack of systematic and comparable studies on different river systems and sections, especially for second- and third-order tributaries (e.g., Neckar, Main, Havel, Altmühl), for which we have a poor knowledge of adaptation strategies, preparedness and prevention during different periods of sociocultural transformations and climatic change.

2.2. Long-Term Social Responses to Changing Flood Dynamics

The responses, adaptations and varying vulnerability of riverine societies to hydrological changes have been globally recognised [132,133,135,136]. In the context of long-term riverine changes, the coupling of robustly dated floodplain chronostratigraphies [110] and medieval place names enables an understanding of the impact of longer-term floodplain dynamics on society [47]. Place names provide information on the values, constraints and threats of water over time and across space [137–139]. However, regarding long-term periods of up to several centuries, our knowledge of the societal responses to hydrological changes is still scarce, although it is known that climatic changes modified flood regimes, floodplain surfaces and floodplain ecosystems, bringing about, for example, the emergence of malaria [140,141], which influenced accessibility to fluvial wetlands before c. 1000 AD.

2.3. Floodplain Land Use and Modification of Riparian Vegetation

Floodplain palaeoecological studies show a rich biodiversity during phases of low anthropogenic impact, consisting of habitats that have become very rare in temperate Central Europe [142], e.g., fens in fluvial settings [143] and large oak-rich riverine woodlands [144]. Early and middle Holocene floodplains were densely forested with birch (*Betula*), willow (*Salix*), poplar (*Populus*), alder (*Alnus*) and oak (*Quercus*) [7,144–146]. Due to intensified land use in the catchments, flood loam deposition led to a shift from multichannel rivers towards late Holocene single-channel and meandering rivers [7]. This indirect human impact on floodplain habitats started at different regional times [39], but ultimately corresponds with more homogeneous floodplain morphologies, a reduction in riverine biodiversity and a significant decrease in *Quercus–Ulmus*-hardwood floodplain forests [29,147]. Regarding the onset of direct human impact, river systems are important natural corridors for the distribution of arable plants. The edges of floodplains may be among the oldest agricultural areas in the world [148]. Riparian forest clearings, pastoralism and meadow cultivation are detectable in middle to late Holocene pollen records from Central European floodplains [144,149]. The establishment of managed water meadows is one of the additional remarkable human impacts [150].

2.4. Effects of Fishing and Hunting

Worldwide, river ecosystems have seen the largest decline in large vertebrates [20], with the human threat to biodiversity emerging long before the modern period. Despite legal regulations from the medieval period onwards, overfishing, pollution and hydro-engineering have resulted in a dramatic decline of the allis shad ('Maifisch', *Alosa alosa*) in the Rhine, as well as the sturgeon family ('Stör/Europäischer Hausen', *Acipenseridae*) in the Danube [151–153]. Written sources, artefacts and environmental data have been studied to investigate the exploitation of such riverine fish species, but rather sporadically and not from a cross-disciplinary perspective. Additionally, modern scientific approaches such as aDNA analyses are still infrequently employed [154]. Furthermore, changes in fish communities were mainly reconstructed for the modern period, without utilising archaeological material from earlier periods [94,155]. Medieval fish remains are rarely utilised and interdisciplinary syntheses contributing to fish ecology hardly exist. Human intervention in riverine ecosystems (hunting, habitat drainage, clearances) also has significant impacts on other wild animal species, such as the European pond turtle (*Emys orbicularis*) [156] and beaver (*Castor fiber*) [157,158]. A challenging issue is the mismatch of source categories. Mentions of fish weirs and traps are abundant in written sources from the early medieval period onwards [159]. However, there is only very limited archaeological evidence for them in floodplains [160,161]. Hence, the hydro-sedimentary effects of such installations remain largely unknown, and our knowledge of conflict associated with their use is patchy [10,63]. Archaeological research on fishing and its ecological effects or on the impact of hydraulic structures (mills, dams, etc.) on fish migration and populations of both fish and wild animals is hampered by the scarcity of scientific wetland excavations utilising on- and off-site methodologies of a good standard.

2.5. Construction, Maintenance and Hydro-Sedimentary Effects of Mills and Hydropower Installations

Hydropower installations with water wheels, ponds, diversion channels and dams had a significant impact on sediment flux, flow rate, water temperature, groundwater tables and fish migration, as well as navigability [10,36,43,52,162]. In the early medieval period, vertical undershot constructions with no need for large dams prevailed in Central Europe [163]. After a fundamental transformation from the 11th–12th centuries onwards, overshot wheels requiring large-scale damming and water-table modifications had significant geocological effects on floodplains [164,165]. Hydro-energy was now frequently used for many craft purposes and instead of mainly for grinding grain. There are clear signs of a significant rise in the numbers of mills, as well as a spatial diffusion and relocation. Large numbers of mills clustered in small urban and monastic areas, accompanied by significant modifications to the primary riverbed [43,139,162]. These changes have been ascribed to the 'medieval industrial revolution' [166,167], a concept that requires reassessment. A second period of intensification and differentiation, accompanied by serious water pollution, can be observed in the 15th–16th centuries, when, for example, paper mills spread all over Europe [168]. However, our knowledge of the complex interplay between hydro-energy exploitation, fluvial and ecological feedback (e.g., sediment flux, fish populations), socio-economic transitions and long-term path dependencies [105,169] is still patchy. From the historiographic and archaeological perspectives, late and postmedieval installations have been rather neglected. Further, the choice of locations in the context of competing interests in floodplains has never been analysed in a comparative and diachronic way.

2.6. Floodplain Pollution from Craft, Manufacturing and Mining

Mining, craft and floodplain colonisation have led to floodplain pollution, eutrophication, changes in aquatic biodiversity and social responses worldwide [20,21]. Historic mining has been one of the most far-reaching human interventions in European river systems since at least the Middle Ages [21,170]. Mining activities were carried out alongside large-scale forest clearing [171]. As a result, preindustrial flood loam aggradation

and floodplain pollution occurred [107,172,173]. Floodplains served as a depository for inorganic and organic pollutants, which were rich in nitrogen, phosphorus and heavy metals [174,175]. From the 13th century onwards, one can observe an awareness of water pollution in floodplains and various attempts to reduce this pollution. The problem of how and where to dispose of effluents became a major topic of legislation [176,177]. Despite a few sophisticated exceptions (e.g., isotopic tracers [178], multi-tracer approaches [179]), there is a lack of systematic and comparative research on pollution processes within fluvial sediments, and previous studies lack ground-truthing and detailed consideration of a socio-natural variety. Although major sources of pollutants, such as mines and tanneries, are well known, it is difficult to assess their contribution to pollution [10,172]. Furthermore, path dependencies and the effects on biotic subsystems have been rather neglected [180].

2.7. Construction, Maintenance and Socio-natural Effects of River Crossings

Ferries, fords and bridges are essential elements of floodplains [181–183], but there is a great need for further research, especially from a historical perspective [74]. All river crossings have impacted floodplains, not only in terms of solid built structures but also as a mobile and connective element of societies in and on rivers. Bridges have been studied as an important part of the built infrastructure, as well as a factor for cultural, economic and political life [184–187]. Outstanding examples, such as stone bridges, have been comprehensively examined [188], although usually from a disciplinarily limited focus [189,190]. As multifunctional sites for punishments, markets and defensive facilities, the number of specific studies is high, but only a few multidisciplinary studies [191] have considered the effects of river crossings as a formal element for the artificial fixation of watercourses, as a compulsory point for settlements, or in terms of path dependency from a ferry to a bridge. Furthermore, the financing and maintenance of expensive bridges has also been poorly examined in relation to the possible climatic impacts ('bridge death' [134,192]).

2.8. Construction, Maintenance and Hydro-Sedimentary Effects of Land Reclamation

Human interventions in floodplains include draining and embankments for land colonisation or animal husbandry. From the 11th to 12th centuries and onwards, [193,194] drainage measures increased [195]. During the 18th century, large-scale land reclamation measures ('ameliorations') were introduced, e.g., in the Donaumoos, which coincided with significant ecological changes [196]. Opposition to drainage evolved from irrigation (e.g., floodable meadows), which was widely overlooked as a feature of premodern European floodplain management [90,150]. Although scattered projects to rural land reclamation have been carried out, multidisciplinary approaches are infrequently employed. Especially in the late medieval and early modern periods, knowledge of ecological and sociocultural consequences and feedback loops remains limited.

Regarding urban land reclamation in floodplains, archaeological findings point to a tipping point around 1200 A.D., with a high number of large-scale construction schemes, which are not usually documented in written sources. An outstanding example of this is Lübeck, where, in the early 13th century, the urban settlement expanded into the Trave floodplain [197]. Similar transformations have been seen in the Rhine river system, all dating to the 12th and 13th centuries [198,199]. Such modifications were sometimes ended with flood catastrophes [200]. There is a general lack of comparative analyses of urban land reclamation schemes and their corresponding socio-natural impacts. Municipal administrative records, iconographic sources and maps have rarely been used to answer the questions of who initiated, financed and coordinated urban land reclamation in floodplains.

2.9. Environmental and Socioeconomic Effects of Channel Engineering and Inland Navigation

Inland navigation from antiquity to the High Middle Ages has recently been studied quite thoroughly, especially as part of the DFG Priority Programme 1630 'Harbours from the Roman Period to the Middle Ages' [63,201,202]. However, the impacts of navigation and rafting on the fluvial landscape from the 13th century onwards are rather unknown,

despite the higher number of available sources [4,203–205]. Many river sections were not suitable for navigation or rafting due to natural (e.g., cataracts) and man-made (e.g., dams and weirs) obstacles, resulting in frequent conflicts of use. Decisions enhancing or degrading trafficability often implemented long-lasting economic, social and environmental path dependencies [10,165]. From the 11th to 12th centuries onwards, canalisation, bank revetment and river diversion, as well as the extraction and dumping of a ship's ballast, transformed European floodplains on a hitherto-unseen scale [65,162,206–208], embedded in the complex interplay between exploitation rights, exploitation interests and material legacies [25,52,165,209]. There is much archaeological proof of stream works and, from the 14th century onwards, written and pictorial sources do also allow for further insights, but they have hardly ever been analysed systematically [49,67,210,211]. The dynamics and socio-natural consequences of medieval and early modern stream engineering have been neglected by multidisciplinary research, and the path dependencies are unknown.

2.10. Legal Framework, Power Structures and Conflict Management in the Context of Floodplain Use

Floodplains have been spaces of overlapping and competing rights and interests arising from the connection between the changeability of the fluvial landscape and the need for perpetual readjustments to the legal framework, individual rights and claims [212]. Major conflicts are documented between groups of agents, for whom a continuous water flow has been essential (e.g., shipowners) and groups for whom damming has been desired or inevitable (e.g., millers). Further conflict lines have been between those in need of watercourses for waste disposal (e.g., tanners) or for clean water (e.g., brewers), as well as between agents with a high general water demand [10,87,126,165,212,213]. Land loss due to shifting channels has been another major cause of conflicts [205]. Since watercourses form territorial borders, they have been the subject of power conflicts [214]. From the 12th to 13th centuries onwards, we can observe the development of highly specialised water rights and fluvial confraternities [215]. In the Late Middle Ages, guild orders of fishery- and floodplain-related craft contributed to specifications in legal frameworks [52,176]. However, a comparative and cross-period analysis of floodplain-specific interest groups, rights, orders and codifications as part of a socio-natural site is a challenging undertaking. Consequently, the spatial distribution and overlap of different interests, and the specific conflict potential within individual sections of rivers, has not been analysed in the *longue durée* [63].

3. Methodological Challenges

In this review, we identify several methodological challenges that are critical to understanding the transition to the Fluvial Anthroposphere.

3.1. Advances in Geophysical Prospection Techniques and Remote Sensing in Fluvial Geomorphology and Geoarchaeology

Floodplain chronostratigraphies with intercalated human-influenced deposits are suitable archives for the reconstruction of cause–effect mechanisms in socio-natural systems [216]. Floodplain deposits are valuable geoarchaeological archives, because anaerobic conditions foster the excellent preservation of palaeoecological and geomorphological proxy parameters, and of archaeological remains [217]. However, floodplain stratigraphies also present difficult exploration conditions that require complicated and costly excavation techniques due to the impact of groundwater and unstable sediments [218]. Therefore, we recommend scale-overlapping geoscientific approaches, including large- and medium-scale remote-sensing techniques, LiDAR modelling approaches [219–222] and noninvasive geophysical prospecting [223], as well as combined medium-, small- and micro-scale, minimally invasive direct push-sensing approaches, drilling campaigns and excavations [217,224–227].

3.2. Advances in Multidisciplinary Big Data Sciences

Digital humanities, remote-sensing and manifold database tools offer fundamentally new approaches to integrative floodplain research [47,57,63,228–230]. They enable the systematic integration of heterogeneous cultural and natural data such as texts, maps, place names, archaeological finds and geoscientific data [221,231–233], and allow for analyses of different spatial and chronological scales, from events to the *longue durée* [51,234–238]. The mandating of consistent standards for data quality, as well as homogeneous thematic thesauri, could enable the analysis of a range from local to supraregional floodplains as socio-natural sites beyond the limitations of specific disciplines and sources [239–242]. However, tapping the full potential of the digital humanities for a systematic modelling of human impacts on fluvial environments, as well as fluvial impacts on riverine societies, is essential.

3.3. Progression of DNA Technology

The rapid progression of DNA technology has brought about a quantum leap in approaches to research on modern and past biodiversity in rivers and wetlands. Regarding modern aquatic habitats, successful DNA technology applications in aquatic ecosystems include biotic screenings of environmental DNA on superficial river bottom samples. This enables, for example, the reconstruction of fish stock [243,244] or the detection of invasive species. Regarding fluvial environments in the past, the emergence of studies of ancient DNA from aquatic sediments has opened up new possibilities for the reconstruction of past biotic inventories, because species that do not leave distinct morphological fossils, including microbiota, can also be determined [245,246]. Topics related to past aquatic environments include ecological reconstructions via plant metabarcoding [247], past fish population dynamics [248] and the spread and ecological effects of invasive species [249]. A methodological innovation is the use of DNA analysis in (geo)archaeological and historical contexts [245,250,251]. An established approach that holds promise for further development is the reconstruction of traded species provenances and trading networks through DNA analyses of ancient fish remains [252]. This approach can be applied to migratory fish remains [253], which might provide new insights into the dynamics of such species in the context of mill weir constructions and hunting during the preindustrial period.

4. On the Way to the Fluvial Anthroposphere—Superimposed Emerging Fields

Based on our review of the state-of-the-art, and the research limitations and perspectives we identified, we suggest six superimposed emerging fields to be further researched regarding the onset of the Fluvial Anthroposphere in Central Europe.

4.1. Recovery and Understanding of Early Anthropogenic Forcing towards a Fluvial Anthroposphere

Floodplains represent a global hotspot of sensitive socioenvironmental changes and early human forcing mechanisms with exceptional (geo)archaeological preservation conditions and high cross-disciplinary data availability and accessibility in archaeology, the geosciences and history. This might provide an opportunity to fundamentally improve the knowledge of socionatural relations in floodplains, and to reconstruct, understand and model the onset and transition from nature-dominated floodplains towards a Fluvial Anthroposphere, as well as their spatiotemporal variability.

4.2. Studying and Understanding of Socionatural Sites within a Multidisciplinary Framework

The material culture of past fluvial societies should be analysed and contrasted with historical, archaeological and geoscientific sources for the build-up of coevolutionary processes and models. Here, spatial quasi-fixed positions of floodplains as socio-natural sites encourage diachronic research strategies and the recovery of multicausal socionatural path dependencies. A multidisciplinary research approach provides a unique opportunity that combines the recent spatial and material turn of cultural studies with the cultural turn of the natural sciences.

4.3. Chronological Focus on the Medieval and Preindustrial Modern Periods

The significant premodern transitions and developments of fluvio-cultural units towards the onset of the Fluvial Anthroposphere were probably fixed during the medieval period. Although the temporal research focus should, therefore, be on the medieval and preindustrial modern periods, the entirety of Holocene floodplain dynamics should be considered to quantify natural boundary levels, as well as onsets and peaks in anthropogenic forcing.

4.4. Focus on Comparative and Diachronic Floodplain Studies

Multidisciplinary studies should focus on the short-term (events) and long-term socio-natural processes and feedbacks that take place in floodplains themselves, including second- and third-order floodplains in tributary subsystems. Due to the spatial and temporal asynchronies of past and contemporary socioenvironmental dynamics in floodplains, human forcing and the resulting feedback mechanisms should be investigated in comparative and diachronic studies.

4.5. Quantifying and Modelling of Natural and Anthropogenic Processes

Increasing human impact can be recovered within the diversity of socio-natural sites through artificial changes in the magnitudes and frequencies of geomorphological, hydrological and ecological processes, through direct anthropogenic modifications of 'natural' floodplain structures and developments of and changes in specific fluvial societies, as well as the feedback mechanisms occurring in socioecological models. Archaeologists, historians and geoscientists should jointly develop targeted research strategies and methodological concepts to build up quantitative and semiquantitative parameters and models of gradual transitions, abrupt tipping points and socioecological interactions. The aimed-for recovery and identification of natural boundary levels from floodplain archives under the consideration of multi-centennial 'Rapid Climate Changes' provide a high potential to distinguish between hydro-climatic and anthropogenic forcing mechanisms in floodplain genesis.

4.6. Socioecological Risk Assessments

These newly generated quantitative and semiquantitative parameters and models will support socioecological risk assessments, in accordance with the recovery of 'great transitions' towards a human-dominated Anthroposphere and in relation to the current Anthropocene debate and Global Change.

5. Conclusions: Specific Thematic Objectives for Future Research

Recalling the 10 specific thematic fields (Section 2), we recommend 10 specific thematic objectives to be considered in future research on the onset of the Fluvial Anthroposphere:

The **first objective** to consider is the recovery and modelling of social response mechanisms to abrupt events in floodplains. We particularly recommend systematic research that identifies and makes use of palaeohydrological and sociocultural key control variables. These will increase fundamental knowledge of the perception of and social responses to abrupt floodplain ecosystem changes due to extreme flood events, ice drift and droughts (e.g., artificial channel capturing, flood protection, societal adaptations).

The **second objective** to consider is the recovery and modelling of long-term social responses towards medium- and long-term changes in flood regimes and floodplain accessibility. We recommend research that will deepen the understanding of social adaptation and wetland colonisation strategies with regard to hydro-climatic variations and attendant changes in flood regimes and floodplain ecosystems, as well as probable emergences of or declines in diseases such as malaria.

The **third objective** we recommend is the reconstruction and modelling of floodplain land use and potential modification of riparian vegetation by new multiproxy approaches. This will expand the breadth of research strategies beyond the common approaches: palynological records should be combined with dendrochronological data from buried riparian

trees, fluvio-geomorphological data, geochemical proxy data and biomarkers and aDNA. This will produce a fuller understanding of overlapping and asynchronous patterns of climatic forcing, flood dynamics, riparian vegetation changes and direct human impact on floodplains.

The **fourth objective** to consider is the reconstruction and modelling of the effects of fishing, hunting, hydroengineering and floodplain habitat destruction on faunal biodiversity. We recommend research that diachronically synthesises chemical analytics, aDNA, (geo)archaeological data and written sources for the reconstruction of changes in migratory fish communities and faunal biodiversity.

The **fifth objective** we recommend is a cross-period synthesis of the history of hydro-energy exploitation and related socio-natural sites. We recommend a range from local to supraregional research approaches in order to synthesise the complex interplay between hydro-energy exploitation, floodplain morphology, socioeconomic transitions and path dependencies such as the long-term impacts of medieval mill weirs, hydro-sedimentary connectivity, floodplain ecosystems and floodplain colonisation.

The **sixth objective** to consider is the reconstruction and modelling of the impacts of craft, manufacturing and mining on floodplain dynamics and pollution. Innovative analytical approaches might enable a geochemical sink-to-source reconstruction of preindustrial contaminants. Furthermore, we recommend future research that couples geoscientific big datasets with archaeological and historical inventories.

The **seventh objective** to consider is the recovery of the socioecological and environmental significance of river crossings (bridges, fords, ferries). We recommend multidisciplinary research strategies that recover the diachronic history and path dependencies of river crossings and corresponding socionatural processes with regard to floodplain environments, material flows and land-use practices.

The **eighth objective** we recommend is a cross-period synthesis of the history of land reclamation and related socionatural floodplain sites. We recommend multidisciplinary research approaches that focus on the recovery of the history, involved agents, socionatural dynamics and the short- to long-term consequences of land reclamation in floodplains.

The **ninth objective** to consider consists of the cross-period synthesis of the history of channel engineering and inland navigation and related socio-natural floodplain sites. We recommend multidisciplinary and big data research strategies that recover the interplay between inland navigation, floodplain environments and socioeconomic strategies, as well as conflicts of interest.

The **tenth objective** to consider is the recovery of the interaction between legal rights and conflict management within the cross-period history of fluvio-cultural units. We recommend the use of systematic and comparative research concepts that investigate floodplain evolution and the involved fluvial societies in relation to Roman law, customary law and the formation of 'national' codifications.

6. Outlook: The Establishment of New Avenues of Research and Potentials for Scientific Transfer

Research into the onset of the Fluvial Anthroposphere will have a strong link to highly relevant topics of social significance. The Early Anthropocene/Anthropocene debate [18,26,254] with a focus on fluvial landscapes [36,121,255–259] is particularly notable, and the question of how to deal with natural resources and concomitant conflicts of use [7,9]. Furthermore, the response to river-related disasters, including subsequent strategies in environmental planning [260], could be improved.

In most temperate regions worldwide, the dominant models of natural lowland rivers are incised-meandering channels with flood loam deposition [261], which form the dominant template for floodplain restoration [7,262–264]. Hence, in most cases, these models are based on anthropogenic preconditions that are inappropriate for natural river systems. Nevertheless, this is an important factor in the context of riverine ecosystem services and floodplain rewilding based on European legal frameworks [7,265]. Future research on the onset of the Fluvial Anthroposphere will pave the way for a much more

systematic exploration of emerging stages of the Fluvial Anthroposphere in Central Europe and, therefore, provide a tool for the better understanding of preanthropogenic, i.e., natural, floodplain stages.

Research on the onset of the Fluvial Anthroposphere in Central Europe will support the establishment of a floodplain archaeology and the ‘Way to the Fluvial Anthroposphere’, particularly as a general research topic and long-term field of research for heritage management. The current large-scale rewilding of rivers based on the European Water Framework Directive [5,54] is not only a further major step forward in anthropogenic floodplain modification, but also a forms considerable threat to the fluvial cultural heritage, as it largely neglects archaeology.

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