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Forces at Play – Hydrosocial Infrastructuring and the Making of the Modern Rhine

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ABSTRACT: Rivers like the Rhine are embedded in complex hydrosocial entanglements. They serve as vital, though often latent, infrastructures that provide essential services and resources and underpin a wide array of situated sociomaterial practices. Yet their close relationship with societies is marked by a profound duality, as indicated by the increasing frequency of flood events and droughts. This article introduces a sociological account of rivers as hydrosocial infrastructures, that acknowledges heterogeneity, materiality and fluidity, alongside technical rationality and issues of control. Drawing on Bennett's "thing-materialism", the paper develops a theoretically grounded, process-sociological heuristic that reconceives "thing-power" as a relational capacity and systematises (hydrosocial) infrastructuring across six dimensions. Applying this framework to the historical case of the Rhine rectification in the 18th and 19th centuries enables a deconstruction of the engineering work as the product of a heterogeneous assemblage, while highlighting the multifaceted forces at play in the river's gradual transformation into a hydrosocial infrastructure. The paper shows how the Rhine's "modern" infrastructural character emerges from long-standing transformations that inscribe particular ontologies, values, expectations and relations to nature into the river's form – patterns that remain embedded within ongoing sociomaterial processes. While emerging from hydrosocial inquiry, the framework offers a perspective that may extend to other sociomaterial contexts that are shaped by infrastructured relations.

KEYWORDS: Infrastructure, hydrosocial, thing-power, modern water, sociology of water, Rhine straightening

INTRODUCTION

Today, the Rhine is Europe's most heavily used river. It flows through Switzerland, Liechtenstein, Austria, Germany, France and the Netherlands, and serves a wide array of functions including navigation, transport, drinking water supply, hydroelectric power generation, wastewater disposal, agriculture, recreation, sports and (non-commercial) fishing (FGG Rhein, 2026). Taken for granted within the fabric of everyday life, the river emerges as a vital infrastructure that underpins a range of sociomaterial practices along its course. Yet these close entanglements of rivers and societies are marked by a profound duality, which is particularly evident in the significantly rising frequency of extreme weather events such as floods and droughts (Newman and Noy, 2023). Rivers may exert destructive forces on socio-ecological systems. In the context of the Rhine, this is particularly exemplified by the 100-year flood of 1993 in the

Middle and Lower Rhine regions (Rottler et al., 2023), as well as the devastating floods of several tributaries within the Rhine catchment in 2021 (Wolf et al., 2024). Accordingly, political debates are focusing on water-related issues (WBGU, 2024; European Parliament, 2025; Madani, 2026), and discourses about the Anthropocene emphasise the growing recognition of the extent of human interventions in Earth's systems and the inextricable link between "social" and "natural" processes. Rivers are now coming to the fore (Latour, 2017) of this perceived "intrusion of Gaia" (Stengers, 2015).

A sociological inquiry into (the infrastructuring of) rivers must consider, first, the relative thinness of sociological engagement with water despite the growing impact of hydrological extremes on daily life and, second, the increasing prominence of infrastructure discourses. To address the first gap, Schulz and Gros (2024) recently outlined a "sociology of water"; nevertheless, genuine sociological contributions to the study of rivers remain scarce. Existing studies focus on governance (Losekann and Milanez, 2023), alongside more specialised topics such as the societal construction of landscapes and species (Scoville, 2019), the emergence of river-related knowledge (Heimann et al., 2024), or how risks of water extremes are addressed (Franke and Mühlenbrock, 2026). "Maritime sociology" (Poole, 1981) or the "sociology of oceans" (Hannigan, 2017) relies on a land/sea distinction and examines maritime practices such as deep-sea shipping and resource extraction without adequately addressing the rivers that run (through) society. An overarching sociological approach to the study of rivers remains absent.

The growing salience of infrastructure discourses is equally crucial and despite its broad usage the term's importance in public perception continues to rise (Edwards et al., 2009). Infrastructures dominate societal debates, driven by demands for expanded transportation and communication networks, and for the reliability of critical infrastructure in response to recent crises.¹ They have become key targets of political action, ranging from localised disruptions such as the "Extinction Rebellion" blockades in London (Kountouris and Williams, 2023), to national movements such as the French "Yellow Vests protests" (Martin and Islar, 2021), and international incidents such as the Nord Stream pipeline attacks of September 2022 (Sanderson et al., 2023). These examples illustrate the degree to which the societal expectation placed on infrastructure is crucial in shaping and enabling social life; at the same time, its viability is increasingly being questioned in the face of growing socio-ecological and geopolitical challenges. The previously unquestioned, background-operating "enabling structures" are suddenly emerging as "inhibition structures" (Barlösius, 2019: 38-39, translated), and the once-opaque "black box" of infrastructure is gradually opening up. Infrastructures studies are also experiencing a renaissance in academia. Traditionally explored in the context of human geography, political science and urban studies, infrastructure research has expanded into the disciplines of philosophy, media and cultural studies (Sellami, 2020); similarly, in recent years sociology has witnessed an increase in infrastructure-related research (see, for example, Kropp, 2023; Clot-Garrell and Wagner, 2025).

This paper addresses water as a subject of sociological inquiry, while also contributing to infrastructural research. Conceptualising rivers as infrastructure is not entirely new. The EU's green infrastructure initiative, for example, seeks to establish strategic networks that provide ecosystem services while enhancing biodiversity (Chatzimentor et al., 2020). In contrast to the management and governance perspectives that define rivers by the services they (are expected to) provide, recent social science scholarship has introduced an infrastructural lens that emphasises the co-constitution of humans and "natural infrastructures" beyond purely technical meanings (see Carse, 2012; Edgeworth, 2018). Building on this shift, the paper aims to introduce a genuine sociological account of rivers as hydrosocial infrastructures; it acknowledges heterogeneity, materiality and fluidity alongside technical rationality and control.

In the first step, we outline a sociological approach to rivers by examining existing approaches to the societal dimensions of water and rivers. Second, drawing on Bennett's (2004, 2005) thing-materialism,

¹ In Germany, experts estimate that modernising (drinking) water infrastructure and adapting it to climate change will require 800 billion euros over the next 20 years (VKU, 2025).

we develop a theoretically grounded, process-sociological heuristic that reconceives thing-power as a relational capacity and systematises (hydrosocial) infrastructuring across six dimensions. Its applicability and analytical value are illustrated in a third step where we revisit the historical rectification of the Rhine in the 18th and 19th centuries. We trace how the "modern" configuration of the river emerges from the straightening project, which sought to convert the Upper Rhine from a meandering watercourse into a regulated infrastructural system. The article offers a transferable heuristic for analysing hydrosocial infrastructuring beyond the Rhine, foregrounding sociological dimensions of power and sociomaterial entanglement.

HOW TO (SOCIOLOGICALLY) UNDERSTAND RIVERS AS INFRASTRUCTURES

The complex dynamics of infrastructuring processes are particularly evident in relation to water. Lakes and rivers² have always been prime locations for human settlement. The facilities developed to harness, transport and drink water, and to protect against its imponderability, are among the oldest (socio)technical systems (Nützmänn et al., 2011). In human history, water always transcended spatial and temporal scales, pervading material spaces, practices and discourses while establishing connections between (non-)human entities, as captured within the idea of the "hydrosocial cycle" (Linton and Budds, 2014).

Water is also characterised by its unique materiality and temporalities. Seasonal rhythms dictate agricultural processes; transportation and mobility depend on water levels and weather; and everyday routines are affected by water's quantitative, measurable (floods, droughts, pollution) and qualitative changes (drying up of old river branches, technocratic river design, deterioration of water bodies) (Schmitt, 2022: 291-292). Water is thus best understood as a societal relationship with nature through which water and society emerge in continuous co-production.

Water ontologies and epistemologies differ across eras, societies and contexts. While, theoretically, there coexists a "multiplicity of water-related worlds", Western societies are shaped by a "hegemonic ontology of water-as-resource" (Yates et al., 2017: 798, 803). Unlike holistic conceptions of "water-as-lifeblood" (ibid: 802), this "modern water" (Linton, 2014) is conceptualised as H₂O: an abstract, measurable and quantifiable substance that is external to society and extracted from the totality of nature. It is inscribed in laws and is reproduced in institutional arrangements (Harris, 2006), technical paradigms and forms of water governance which subsequently determine societal engagement with water as a resource (Yates et al., 2017).

The image of natural rivers has little in common with 21st century realities. In Europe, no landscape has remained untouched by extensive human reshaping (cf. Folke et al., 2021). Human (direct and indirect) manipulation of rivers has a long history that extends from the weirs and dams of medieval water mills (Buchty-Lemke and Lehmkuhl, 2018) to the large-scale alterations of morphology in the industrial era (Edgeworth, 2018: 246). These interventions range from subtle changes to radical transformations such as the reversal of the Chicago River's flow direction (Edgeworth and Benjamin, 2017) or the concretisation of the Los Angeles River (Gandy, 2006). Rivers are thus better understood as hybrids of natural and cultural forces (Edgeworth and Benjamin, 2017).

These intricate assemblages arise from the reciprocal and iterative interactions between humans and rivers that have accompanied human settlement near water (Gandy, 2006: 136). To fully understand

² Rivers are typically perceived as part of the landscape, long studied by disciplines such as geography and archaeology, which is one reason why sociology has largely overlooked them. Ipsen (2006: 71) attributes this marginalisation of landscape to sociology's focus on urbanisation (particularly in the Chicago School) and the deliberate separation of landscape and nature as an 'outside' within its historical development. Simmel, however, already saw the subconscious perception of one's environment as 'landscape' as a defining characteristic of 'modern' humans. He described this construction of landscape as a cognitive act extracting elements from nature as a "unity of a whole" to create a new "wholeness" (Simmel, 2007: 22).

them, it is essential to account for their relationality and historicity. Edgeworth (2018: 252) refers to constructed transverse structures (such as weirs) as material "river heritage". This line of thought can be extended beyond individual built structures to rivers as such, accounting not only for their material but also for their immaterial dimensions. Each generation 'inherits' rivers as prolonged processes of adaptation and transformation encompassing both material characteristics such as river courses, water conditions, ecosystems and structures, and immaterial aspects such as understandings of nature, water ontologies, and epistemologies. These elements are inscribed in the river or in the water itself. They are stabilised, transmitted and reproduced through institutions and forms of governance and in symbolic associations and narratives. Rivers thus serve as repositories where the past, present and future converge. Shaped by past generations, they "enable and constrain what can be done in the future" (ibid: 245).

PROCESSUAL PATTERNS OF INFRASTRUCTURING

Grasping the heterogeneous (im)material hydrosocial entanglements of rivers requires a differentiated analytical perspective. We therefore bring current hydrosocial approaches into dialogue with existing interdisciplinary infrastructure research. Defining "infrastructure" in a way that adequately fits its complexity has long posed a challenge. Traditionally, infrastructures were defined as stable technical systems or material artefacts supporting social life. Recent work, however, has shifted attention from infrastructures as fixed objects towards the ongoing sociomaterial processes through which they are continuously produced, maintained and transformed (Star and Ruhleder, 1996; Anand et al., 2018). In this section, we present a conceptual framework that guides analyses of infrastructural phenomena in general and rivers in particular.

The conceptual framework responds to two crucial reflections on sociological infrastructure analysis arising (mostly) from political ecology. First, while political ecology brings non-human entities into view, it tends to overlook the subtle, "latent" materialities – such as water and riverbeds – whose forces nonetheless shape infrastructures. We address this theoretical gap using Bennett's (2004) "thing-power" to examine latent *and noisy forces at play*. Second, political-ecological accounts tend to favour present-focused, single-location studies. To move beyond such isolated cases and enable comparison across assemblages, including inherent forces at play, we demonstrate the analytical purchase of our framework and its underlying dimensions.

Studying rivers in this way calls for a process-sociological understanding of infrastructure, one that conceives infrastructure not as a fixed object but as an ongoing and open-ended process. We therefore adopt the notion of *infrastructuring* (Björgvinsson et al., 2012; Karasti, 2014; Niewöhner, 2014), which holds that infrastructures are never complete, but instead emerge through the continuous alignment and reconfiguration of heterogeneous (non)human elements. Rather than asking what infrastructures are, this perspective asks how infrastructures are continuously brought into being, stabilised and reconfigured. The following sections develop a relational-processual heuristic for reconstructing changing material contributions across different dimensions of infrastructuring.

The analytical challenge: From *whether* to *how* materiality matters

While infrastructuring links natural and social processes, at first there seems to be a missing link between philosophical reflections on hydrosocial relations and a comprehensible set of analytical tools. If water is to be understood as a "total social phenomenon" (Orlove and Caton, 2010), the growing complexity of hydrosocial entanglements raises the question of how sociological research can adequately conceptualise and analyse these processes. Rivers and infrastructures alike are usually examined through political-ecological analyses of local case studies. This seems appropriate ever since the "ontological turn" (Hein and Thomsen, 2023) critical and relational approaches gained popularity across disciplines. Through their "flat ontology" they also highlight the materiality of rivers, that is, the presence and power of non-human

actants. Drawing on power-oriented analyses of hydrosocial infrastructures, political ecology theoretically requires taking into account "ontological politics" (Hein and Thomsen, 2023). These approaches thereby significantly expand the analytical framework to include "more-than-human" phenomena (Pötzsch, 2025) in micropolitical processes.

This analytical strength is accompanied by a particular empirical orientation. Political ecology is especially powerful in analysing situations in which materiality becomes politically articulated through controversies, conflicts, crises or catastrophes. It focuses on infrastructures that are part of "noisy" micropolitical contestations. As an "activist theory", it is particularly sensitive to moments in which heterogeneous entities draw attention to themselves (Stäheli, 2021). Consequently, analytical attention tends to gravitate towards moments of disruption and surprise. By contrast, "sedimented practices, materialised habits, *the functioning of infrastructures*, atmospheres" (Stäheli, 2021: 104) often remain less visible. It is thus easy to overlook long-term sociomaterial path dependencies, their reinforcement of subtle forces and structures, and creeping processes.

It follows that the analytical challenge is no longer whether material entities matter, but *how* their heterogeneous contributions to infrastructuring processes can be empirically reconstructed. Our heuristic is designed to capture the structure and composition of material heterogeneity as it is linked with – and through – hydrosocial infrastructuring, along with the constant processes of change and rearrangement within them: the forces at play. In line with political ecology, these processes are thoroughly political (Swyngedouw, 1999: 448). Rather than conceiving infrastructures as stable objects, we understand them to be intrinsically dynamic assemblages whose heterogeneous relations shift over time. This raises a methodological question that political ecology alone does not fully resolve: how can different material contributions within such assemblages be analytically distinguished without reducing them to either human intentionality or an undifferentiated notion of agency?

Operationalising assemblages through thing-power

To address this methodological challenge, we draw selectively on Jane Bennett's concept of thing-power. Rather than adopting her new materialism as a comprehensive ontology of hydrosocial relations, we use thing-power as an analytical concept that enables us to reconstruct how heterogeneous material entities contribute differently to the emergence, stabilisation and transformation of infrastructural assemblages. In doing so, our aim is not to replace political ecology but to complement it with an analytical language that is capable of reconstructing gradual sociomaterial transformations beyond moments of controversy or crisis.

Central to Bennett's materialism is the concept of assemblage as heterogeneous configurations of human and non-human entities that are provisionally connected through continuously changing relations. Assemblages are neither stable structures nor fixed networks; rather, they are the dynamic relational configurations that constantly undergo (de)stabilisation and reconfiguration. Bennett uses the term "thing-power" to describe the material capacities that individual entities bring to these assemblages (Bennett, 2004). Rather than restricting efficacy to human actors, thing-power denotes the capacity of material entities to affect, and to be affected within, sociomaterial constellations. Agency does not reside at the level of individual entities; rather, it emerges at the level of the assemblage itself. Assemblages act because heterogeneous entities continuously affect one another and thereby produce emergent capacities that cannot be reduced to the intentions or properties of individual components. This generativity is not confined to human arrangements; nature continuously generates new material constellations and, in Bennett's terms, the "pluriverse" exhibits a "generative mobility" (Bennett, 2005: 448). Instead of constituting passive backgrounds for human action, material entities participate in the continuous becoming of assemblages.

At this point, however, we slightly shift the analytical emphasis of Bennett's argument. For our purposes, thing-power is not understood as a fixed property of individual entities, which would contradict

the relational ontology of assemblages themselves. Instead, we understand thing-power as a *relational capacity* whose empirical significance depends on the concrete assemblage in which an entity participates. The relational capacity of an entity is shaped by the number and quality of its relations within an assemblage, by how far it reaches and how far it can be reached, by the moments in which it affects and is affected by others. Material entities therefore do not possess a stable or measurable amount of thing-power; rather, their contribution changes as assemblages are continuously reconfigured. This relational understanding has important methodological consequences. The analytical task is not to compare fixed amounts of thing-power, for example whether a stone possesses more of it than a fish, or water more than a riverbed. Such comparisons would presuppose fixed and comparable properties that are incompatible with the relational and dynamic character of assemblages. The task is instead to reconstruct how the relative significance of heterogeneous material contributions changes during processes of infrastructuring. As assemblages are transformed, some entities gain relevance and others lose it, while new entities emerge or disappear. The empirical question therefore concerns shifting configurations of thing-power rather than fixed material capacities.

This processual understanding also distinguishes our approach from interpretations that attribute an undifferentiated agency to all actants alike.³ Bennett explicitly emphasises that material capacities are differently embodied (Bennett, 2005; Coole, 2005). Material entities differ in the ways they affect and are affected; this is not because they possess essentially different ontological statuses, but because they participate differently in particular assemblages. Bodies, machines, rivers, sediments or technical artefacts therefore contribute to infrastructural processes in qualitatively different ways, depending on the sociomaterial relations through which they become connected.

As rivers are physically and geographically situated, corresponding analyses are methodologically linked to specific rivers or basins, as in local case studies. Hydrosocial research emphasises either the processual nature of hydrosocial interactions (the "hydrosocial cycle") or the historical becoming of multilayered, spatially bounded and complex "hydrosocial territories" (Boelens et al., 2016, 2025). We share this attention to singularity: (riverine) infrastructures are unique configurations, and no analysis should dissolve that. What remains largely absent, however, is a heuristic that is capable of capturing the multiplicity of entities involved and the processuality of emerging becomings, *and* is also able to reconstruct recurrent patterns of (hydrosocial) infrastructuring across cases. Existing research tends either to leave individual settings unconnected or, conversely, to generalise from a single case. Building on Bennett's relational understanding of thing-power, our framework therefore seeks neither to classify infrastructures nor to measure material agency. What it reconstructs instead are the *forces at play*: the relational capacities through which heterogeneous entities – human bodies, water, sediments, technical artefacts – shape infrastructuring processes, and whose relative significance shifts as assemblages⁴ are continuously reconfigured.

Analytical dimensions of infrastructuring

Building on the relational understanding of assemblages and thing-power, the following heuristic seeks to operationalise infrastructuring as a process of continuously changing sociomaterial configurations. Rather than deriving a new typology of infrastructures from Bennett's materialism, we build upon the existing body of infrastructure research. Drawing on an extensive review of the interdisciplinary literature, we identified six recurrent, but (analytically) disconnected strands along which infrastructures

³ A similar tendency appears in historical analyses that are increasingly informed by new materialism. Concepts such as thing-power are invoked, yet they have so far been used in a relatively undifferentiated manner and remain insufficiently integrated with the 'thick (historical) descriptions' within individual case studies; see, for example, a recent issue of *Technology and Culture* edited by Hansen and Schulze (2025).

⁴ Note that assemblages also increasingly receive attention in postcolonial hydrosocial research, as they locate multiplicity in water itself rather than in the perspectives taken on it (Reyes Escate et al., 2022; see also Tozzi, 2021).

have been examined and which were originally established in their fields of research. Rather than being categories introduced by our framework, they have largely evolved within different disciplinary traditions including history, political ecology, science and technology studies, anthropology and sociology, among others. Our contribution lies in bringing them into dialogue with each other through a relational-processual understanding of assemblages and thing-power. Instead of treating them as static characteristics, we reinterpret them as six *dimensions of infrastructuring*, each of which offers a complementary analytical perspective on the same empirical processes. Together, they allow us to reconstruct how heterogeneous material contributions change as infrastructural assemblages continuously emerge, stabilise and transform over time.⁵

(1) Routinised (in)visibilities

Infrastructures oscillate between *invisibility* and *visibility*, depending on whether they operate smoothly or experience disruption. They mostly maintain the claim of ubiquitous availability, which, once realised, is taken for granted and fades from everyday attention (van Laak, 2001: 185). As a "collective subconscious" (van Laak, 2020), they tend to emerge into visibility in moments of crisis or dysfunction (Star, 1999: 382; Bowker and Star, 2000: 33). At this point, the *Zuhandenheit* (readiness-to-hand) of infrastructure becomes intelligible as *Vorhandenheit* (presence-at-hand) (Heidegger, 1962; see also Tzavaras, 1989). In such moments, when dynamically stabilised assemblages are irritated or interrupted, the thing-power of the involved material entities becomes visible. Together with social actors, they form a highly demanding assemblage in which heterogeneous forces interlock to enable infrastructural performance. The smoothness and invisibility of functioning infrastructure thus rest on a dense web of thing-power whose effective functioning actively conceals it. The urban water supply, for example, is typically black boxed within daily hygiene routines, its sociotechnical features receding from view through reliable performance. Only when disruptions occur do they become visible, prompting the unravelling of the infrastructural components and sociomaterial dependencies. Apart from disruptions, infrastructure-related questions and decisions are reserved for experts (Kropp, 2018: 190). The characteristic smoothness and invisibility that (working) infrastructures produce (Sellami, 2020) is also a (modern) normative claim, which, in this ideal-typical form, is rarely achieved in the reality of malfunctions, deficiencies and repair needs (Hansen and Schulze, 2021).

(2) Conquest and construction of modern worlds

Even though the term infrastructure often appears neutral (van Laak, 1999: 290), it is deeply intertwined with *narratives of growth, progress and modernity*. Especially in the 20th century, infrastructures as "conquest technology" (van Laak, 2001: 374) were central to supranational visions of expansion and integration. They were a premise of progress and growth as, for example, in the opening up of territories by connecting them to railway networks; they were also a consequence, as seen in the establishment of water supply and sewage systems in response to inadequate urban sanitation (van Laak, 2017: 5). Infrastructures also maintain a co-constructive relationship with concepts and foundations of modernity (Edwards, 2003: 186). They materialise socio-ecological relationships with nature that are often shaped by the modern understandings of nature held by their builders; in that understanding, nature, in opposition to society and (control) technologies, tends to be positioned as a dangerous and unpredictable force in need of being tamed (ibid: 195). The worldviews of the contemporaneous authorities (e.g. political- or design-related) are "inscribed" (Akrich, 1992) in the very construction of (socio)technical assemblages. Once established, infrastructures not only stabilise these inscriptions but actively reinforce them. Through their concentrated materiality and *Zuhandenheit*, infrastructures feed these material dynamics back into societal routines, confirmatorily reinforcing the rhythms of (capitalist) modernity. As

⁵ The six dimensions are analytically distinguishable but empirically inseparable. Since infrastructures are understood as heterogeneous assemblages, changes observed within one analytical dimension inevitably affect the others.

soon as infrastructures are taken for granted, they become extremely difficult to displace or contest. This persistence is not only a result of social or political inertia; it is actively co-produced by the non-human entities involved whose material contributions stabilise existing orders. In addition to natural-societal boundaries, they also draw internal intra-societal boundaries: areas "connected" by infrastructure are perceived as "developed", as opposed to "disconnected" regions (van Laak, 2018: 1021).

(3) Public interest and urbanisation: Infrastructuring as the foundation of state control

Historically, the growing importance of infrastructures was closely related to, and a prerequisite for, the emerging (*nation*)*statehood* and increasing *urbanisation* in 19th century Europe. While the state had long been tasked with reactive relief and protection, its role began to shift towards a preventive and service-oriented approach (van Laak, 2018: 1021), which was publicly articulated as "existential provisions"⁶ (van Laak, 1999: 291). The focus shifted from coercion to targeted management of the population's needs (van Laak, 2017: 7). This was accomplished through centralised planning and control, which extended beyond political matters to increasingly encompass economic and other societal issues (van Laak, 2018: 1021). Due to the growing security of supply, social issues were reframed as technical issues in terms of a "technological fix" (cf. Rosner, 2004). This shift was underpinned by new "state knowledge" (van Laak, 2020) and new methods (for example, cadastre and statistical calculations) that were produced by infrastructures and facilitated extensive expansion. Infrastructures also played a crucial role in processes of urbanisation. There was a close intertwining of the development of landscapes and habitats, the expansion of various types of infrastructure, the formation of urban centres, and the proliferation of urban lifestyles (van Laak, 2001: 375). The forces of infrastructure assemblages and assembled state practices are mutually constitutive; through their thing-power, infrastructures not only shape the possibilities and trajectories of state action but also give rise to new assemblages and their forces at play.

(4) Entangled temporalities and progressive future narratives

Infrastructuring is also marked by a distinctive relation to *time*. As a materialised link, it weaves together past and future in a complex interplay, constituting scenarios that unfold in the present as promises in the future perfect tense (Hetherington, 2017: 42). The implementation of infrastructure projects is intended to ensure societal goals such as safety, security of supply, prosperity, and participation. Within infrastructure development, the present is imagined as the necessary past of a better future. This culminates in progressive narratives that produce subjects who aspire to, and align their visions with, prophesied futures, while categorising landscapes within a linear temporality of a "natural past" and an imagined "civilised future" (ibid: 40). Socio-ecological risks are externalised through a "colonisation of the future" (Kropp, 2018: 190). Infrastructures are therefore characterised not only by a large spatial, but also a vast temporal, reach (Bowker and Star, 2000: 35).

The invisibility of infrastructuring is linked to its operation across multiple temporal scales. Edwards (2003: 194-195) distinguishes "human", "historical", and "geophysical" time. While human time aligns with natural metabolic cycles (for example days, months, years or seasons), historical time is conceptualised on a linear scale of decades and centuries. Geophysical time spans millennia or even longer durations. The slow pace of infrastructural change relative to human time renders it largely invisible, except during periods of major transition. This perception shifts when set against geophysical time. Infrastructuring depends on the alignment of material elements that exist across these multiple temporal registers, each of which is attuned to a specific *infrastructural time*. Rivers, infrastructures, even climate are composed of matter which matters in different timescales and can be temporarily synchronised. Once synchronisation is achieved within complex assemblages (for example, rivers cooling

⁶ For a critical genealogy of the concept, see Folkers (2017).

power plants that supply energy for water purification), relatively stable equilibria can emerge that integrate substantial material forces and persist over time (Urry, 2011: 42).

(5) Sociotechnical hybridity and resistance

Infrastructures are characterised by *hybrid stabilisation*. As assemblages, they are sociotechnical hybrids (Edwards, 2003: 188; Kropp and Sonnberger, 2021: 192), forming a "seamless web" (Hughes, 1986) of social and technological units. They do not emerge in a vacuum but are connected to, and embedded in, existing practices, technologies and infrastructure configurations (Star, 1999: 381-382). This coupling with "cross-sectoral infra- and practice structures" (Kropp, 2023: 323) results in a twofold stabilisation, in that connections among infrastructure components via "heterogeneous engineering" (Law, 1987) are reinforced by their embedding in broader structures and practices that enhance robustness (Callon, 1986: 32). Moreover, institutional anchoring and path dependencies due to economic investments lead to a resistiveness (Kropp and Sonnberger, 2021: 194) or "obduracy" (Hommels, 2005) against transformation. The dynamic stabilisation arises from the interplay of material contributions and functional couplings, which direct (material) forces at play and delineate the spectrum of potential interventions within the infrastructure. Simultaneously, their vast scope turns them into "central political levers" (Neckel, 2022: 165) for societal transformations, although such efforts are impeded by the absence of clearly identifiable responsible actors (Kropp and Sonnberger, 2021: 205). For it remains true that "nobody is really in charge of infrastructure" (Star, 1999: 382).

(6) Mental-material feedbacks in infrastructural ordering

Infrastructures structure societal order, as they direct society along specific trajectories that are reinforced by norms and standardisations, while alternative futures are contested, marginalised or excluded (Barlösius, 2019; Franke, 2024). Existing road networks, for example, heavily influence transformations of automotive transport; electric, hybrid and combustion-based vehicles are designed to use the same lanes, and electrical-charging infrastructure builds upon the "old" system. Alternative visions such as avoiding individual transport appear not only difficult to realise but barely imaginable. Beyond the spatial dimension, this also applies to temporal regimes. Lighting technologies such as the incandescent bulb contribute to a partial decoupling of social life from natural daylight, reshaping every day and work rhythms and, in turn, driving the ongoing search for further and increasingly sophisticated forms of artificial illumination. Here, material conditions and historically sedimented expectations intersect. The latter can manifest as "mental infrastructures" (Welzer, 2011) that shape the cognitive and practical horizons for future infrastructural projects. Only their interplay renders the full structuring effects visible.

As noted earlier, each of these six dimensions is shaped by processes of infrastructuring, which are understood as dynamic and continuous formations of (re)arranging. From planning and construction to final operation, infrastructures rely on "infrastructural work" (Bowker, 1994) involving continuous construction, dismantling and maintenance, and the mutual (de)stabilisation and interaction of components within the sociotechnical assemblage. With regard to rivers and hydrosocial relations, reconstructing infrastructuring along these dimensions does not yield general laws, nor does it dissolve the singularity of each case. What it offers instead is a way to render singular configurations analytically comparable, a way of moving "from generalization to potentiality" (Tavory and Timmermans, 2014: 118). We now turn to the rectification of the Upper Rhine, where this heuristic is put to work.

"TAMING THE WILD RHINE": FORCES AT PLAY IN THE RECTIFICATION OF THE UPPER RHINE

The history of the Rhine is one of profound transformations. It is also a history that renders visible the heterogeneous forces at play in hydrosocial infrastructuring. Since its formation during the middle Miocene, the river has undergone major morphological changes (Gibbard, 1988). The first large-scale

anthropogenic interventions occurred during the Roman settlement when bridges, small canals and flood defences were built to make the river navigable (Buck et al., 1993: 37). At that time, the idea of a continuous river was still a distant prospect. Manoeuvrable, but disconnected, stretches of the river were connected by land roads (Febvre, 1994b: 213). Until the 19th century, this "wild river" (Buck et al., 1993: 40) in the Upper Rhine region was characterised by a dynamically shifting braided zone where the river branched and forked, making it difficult to delineate a stable river course (Figure 1). The Upper Rhine, in particular, experienced constant changes due to erosion and frequent flooding (Blackbourn, 2006: 81-82).

These unpredictable dynamics posed considerable risks to riparian communities. Marshy landscapes and the humid climate provided ideal breeding grounds for mosquitoes, fostering widespread outbreaks of malaria, cholera and typhus (Buck et al., 1993: 41; Cioc, 2002: 51). The shifting riverbed hindered navigation⁷ and sparked continuous disputes over territorial claims to the constantly changing landscape. The case of Breisach illustrates how closely settlement patterns and territorial claims were entangled with the river's shifting materiality. The city was situated on the left bank of the Rhine in Roman times, flanked by the river on both sides in the 10th century, became left-bank again in the 13th century, and finally shifted to the right bank in the 14th century (Buck et al., 1993: 41).

Figure 1. View from the Isteiner Klotz up the Rhine towards Basel, by Peter Birmann, c. 1819



Source: Wikimedia Commons.

⁷ This also affected trade; the varying conditions and demands produced types of boats that were specific to particular stretches of the Rhine, each operated by distinct shipping companies (Looz-Corswarem, 2008).

To address the river's hazards, various structural measures were implemented over time, including the first documented meander cut in 1391 (Blackbourn, 2006: 5). These local interventions, however, mostly only shifted the problems to other river sections or to the opposite bank (Zier, 1970: 394). By the 18th century, a power struggle had emerged between the Palatinate communities on the left bank and the Baden communities on the right. The factions became entangled in a "hydrological leapfrog" (Blackbourn, 2006: 84), with each forced to react to the other's actions. The reign of Frederick the Great marked a shift in the (German) approach to water, exemplified by the mid-18th century drainage of the lower Oderbruch (ibid: 38-41). Supported by emerging techniques such as topographical mapping and the rise of geography as a scientific discipline, these efforts reflected an instrumental contemporary approach to nature. The "untamed water" resisted this imposed order, however, and was regarded as the greatest natural "enemy" (ibid: 44-48).

The river's fluid and dynamic material form also manifested in cultural references. For much of its history, the Rhine lacked a consistent identity and was imbued with diverse (symbolic and functional) meanings by different societies (Kaufmann, 2005: 123). While efforts towards peaceful cooperation emphasised the river's unifying effect, antagonistic processes highlighted its role as a border. The large-scale straightening project of the 19th century marked a turning point, solidifying the river's distinct identity. According to Febvre (1994b: 214),

The unified great Rhine is a modern invention of humanity: created by politicians, economists, industrialists, and traders – with the active assistance of engineers. Until the 19th century, there were "multiple Rhines" that were more or less successful at different times. These "Rhines" emerged from a multitude of independent efforts, influenced by ever-changing patterns of transportation and trade – much like the people living along its banks, who were constantly in motion in their pursuit of happiness.

A central figure in the emergence of this "modern" Rhine was the Baden engineer Johann Gottfried Tulla (1770-1828). To counteract the river's dynamics, his approach involved straightening extensive stretches of the Upper Rhine by cutting through 18 meanders; this increased flow velocity and lowered water levels, thus mitigating the risk of flooding. The project provides a productive case for examining hydrosocial infrastructuring. The rectification profoundly reshaped the river's sociomaterial configuration and, with it, societal relations with nature across large spatial and temporal scales. Construction began in 1817 and continued until 1876 (Bernhardt, 2016: 125). By the late 1870s, the river had lost about a quarter of its original length. Over 2200 islands and large sections of floodplain had been eliminated and 240 km of primary dykes had been built (Cioc, 2002: 151; Blackbourn, 2006: 97-98). While interventions into the Rhine were not new, we argue that this project changed their scale and coordination, setting in motion a multifaceted sociomaterial process that continuously transformed the river itself into a hydrosocial infrastructure whose effects, as river heritage, still resonate today.

Given our perspective of new materialism, it is worth asking why one should follow a (human) engineer? Does this not risk reproducing an anthropocentric bias? Historical sources present different pictures of Tulla. While some emphasise his achievements as "the man who tamed the wild Rhine" (Knäble, 1970; Zier, 1970; Blackbourn, 2006), more recent research highlights the project's transnational dimensions, the numerous actors involved, and the broader contextual frameworks in which both he and the project were embedded (Bernhardt, 2016). In line with the latter, we avoid any form of heroism; instead, the prominence of historical human actors can be deconstructed as the effect of alliances and heterogeneous materials, which emerge as agentic entities only through their relationality within an assemblage (Law, 1990).⁸ Accordingly, we approach Tulla's work as an entry point, guided by a "naive

⁸ Research on Large Technological Systems (LTS) has productively shown how such systems achieve stability through the alignment of heterogeneous components (Hughes, 1983, 1987), and how network building simultaneously reshapes technology, wet nature, landscapes, economies and political orders (van der Vleuten and Disco, 2004; van der Vleuten, 2004). We share this

realism [that] takes human fascination with objects as a clue to the secret life of nonhumans" (Bennett, 2004: 358). Our analysis unfolds as a "speculative onto-story" (ibid: 349) along the infrastructural dimensions previously identified, highlighting the shifting configurations of thing-power during the river-straightening project. Beyond this single case, it offers a heuristic for grasping non-human agency as heterogeneous *forces at play* within hydrosocial infrastructuring.

(1) Routinised (in)visibilities

Tulla's project aimed to render the Rhine controllable and predictable, integrating it into emerging sociotechnical networks while relegating the river's natural uncertainties to the background of everyday life. Yet the river's repeated floods, constantly shifting channels, and other non-human factors such as climate, sediment and wildlife had long imposed constraints on riverside populations, at times forcing entire settlements to relocate (Blackbourn, 2006: 79). It was precisely the thing-power at play that enabled the project, while also making it challenging: the river's material dynamics set the stage for intervention, shaping what could be envisaged, planned and achieved. Throughout all phases of the project, from planning to construction and eventual stabilisation, the (in)visibility of the river's thing-power was decisive. During planning, the river's forces had to be made legible through maps, surveys, hydraulic calculations and engineered interventions. Through these practices, flowing water, sediment and riverbed were no longer perceived as an undifferentiated natural force; rather, they were rendered comparable and (re)aligned as distinct material components with specific capacities that could be mobilised in relation to one another. By stabilising and reshaping the riverbed, engineers sought to redirect the river-related material forces at play, harnessing one force through another. Scientific-technical visibility thus enabled the Rhine's material energies to be turned into instruments of regulation. During construction, successive cuts, dykes and straightened channels sought to channel and constrain the river's energy, rendering its material capacities simultaneously productive and backgrounded. At the same time, the project remained marked by a continuous interplay between attempted invisibilisation and moments in which the river asserted itself through floods, sediment shifts, or unexpected flow dynamics, thereby making its material force unavoidable and tangible. The river's apparent predictability and the smooth functioning of the straightened course thus rested on a dense and highly demanding network of interlocking material and social forces, whose visibility fluctuated throughout the project.

(2) Conquest and construction of modern worlds

The straightening project was a 'modern' undertaking in many respects. Beyond the immediate dangers to human life resulting from the river's unpredictable dynamics, economic activities had been repeatedly disrupted. Recurring floods and storm surges inundated cellars, stables and fields for extended periods, systematically undermining agricultural operations (Zier, 1970: 432-433). Channelling the river promised not only the preservation of existing agricultural land; in the Upper Rhine region alone, it also unlocked vast areas for settlement and agricultural expansion, converting 10000 hectares of natural floodplains into agriculturally and industrially usable land (Cioc, 2002: 153-154). At the same time, the project laid the groundwork for the emergence of "modern water" (Linton, 2014). By stabilising flows and straightening the river's course, the Rhine was rendered legible and governable, enabling the usage of its water as an abstract, quantifiable resource. The increasing predictability of the river, its continuous navigability, and the "availability" (Rosa, 2020) of its waters provided the foundation for emerging forms of capitalist utilisation in the following decades, that is, for irrigation, industrial cooling, drinking water and energy generation. The river and its materially transformed environment were thus actively incorporated into new forms of capitalist value creation. The persistence of non-human elements was deliberately integrated into the emerging sociotechnical assemblages, their material endurance actively

attention to heterogeneity but shift the focus towards 'assemblage building', where agency is distributed rather than primarily located in a system builder and where sociomaterial configurations emerge in continuous and open-ended processes.

contributing to the consolidation of the infrastructure and the entrenchment of modernist modes of ordering nature. This selective incorporation also entailed processes of displacement: while certain non-human entities were enrolled as productive resources, others – and with them established human practices – were rendered obsolete. Construction led to the disappearance of livelihoods tied to ferries, floating mills, reed cutting and fowling, while the depletion of floodplains caused severe biodiversity loss, particularly among birds, insects, amphibians and fish, undermining practices such as fishing and Rhine gold extraction (Blackbourn, 2006: 104-113).

The project was underpinned by scientific methods and techniques and heavily shaped by contemporary ideals of Enlightenment and corresponding instrumental approaches to nature. This is exemplified in a letter Tulla wrote to a Hessian engineer in which he laments the competing interests that repeatedly arose during the rectification:

The difficulties and obstacles that stand in the way of rectification of the Rhine do not lie in the task itself (...) but make themselves felt for the most part according to the degree to which individual interests or the interest of whole communities come into play, and *whether the active agents are more or less enlightened and moral* (Tulla, 1825, cited in Blackbourn, 2006: 99; emphasis added).

(3) Public interest and urbanisation: Infrastructure as the foundation of state control

In the late 18th and early 19th centuries, Europe experienced profound political change and the emergence of modern statehood. Tulla's lifetime in Baden spanned three successive forms of government: the Margraviate (until 1803), the Electorate (1803-1806), and the Grand Duchy (from 1806). His plans to straighten the Upper Rhine aligned with both internal and external political interests. Domestically, the project promised enhanced territorial control, security and economic development, while also serving foreign policy concerns as the Rhine formed a strategic border with France (Zier, 1970: 416). Since the 18th century, rivers had been conceived as "natural" national boundaries in France, a narrative that can be traced back to Caesar, who declared the Rhine to be the demarcation line between the Belgae and the Germanic peoples (Febvre, 1994a: 26; Blackbourn, 2006: 95). As a territorial boundary, however, the Rhine was profoundly unstable. Cases such as Breisach illustrate how its shifting course undermined fixed claims to land and jurisdiction, turning the river itself into a persistent source of political uncertainty. Resulting dynamics like the previously described "hydrological leapfrog" can be seen as the outcome of local (political) assemblages that remained too fragmented to counter the river's dynamics. As long as authority stayed dispersed across competing riparian communities, the river remained politically "unavailable" in Rosa's (2020) sense: authorities could only react to its effects rather than assert direct control over its trajectory. The rectification offered greater control over this unstable border and attracted considerable interest from France (Blackbourn, 2006: 96).

Initially, both internal and external administrative organisation impeded Tulla's initiative. The Margraviate's fragmented authority and the need for bilateral agreements across the targeted river stretch hindered a project of this scale and hydraulic engineering was not officially integrated into the administration until 1789 (Zier, 1970: 413-415). These constraints were gradually eased after Baden was elevated to a Grand Duchy in 1806, accompanied by substantial territorial expansion, population growth (Bernhardt, 2016: 59), and far-reaching administrative centralisation and reforms. The establishment of the Supreme Directorate of Water and Road Construction, influenced by Tulla, marked the institutional embedding of hydraulic engineering within the state apparatus as Baden's "modernisation agency" (Bernhardt, 2016: 138). At the international level, Napoleon's control of the Rhine's left bank led to centralised river management under the *Magistrat du Rhin*. After 1815, this was succeeded by the Central Commission for Navigation on the Rhine (CCNR), which is recognised as the oldest modern institution for international cooperation (Rittmüller, 1996). This new political and institutional configuration facilitated the project by simplifying coordination and reinforcing the Rhine as a unifying territorial symbol (Blackbourn, 2006: 94-96).

A further key development concerned the centralisation of administrative responsibility and funding for river engineering projects. Prior to these reforms, flood protection along the Rhine was organised through the Rhine Dyke Regulation, which required individual municipalities to finance and provide labour for protective measures (Zier, 1970: 433). Until the early 19th century, such works relied largely on unpaid, compulsory *corvée* labour. This source of labour was unevenly distributed along the river and difficult to coordinate, and conscripted workers frequently resisted, necessitating extensive military supervision (Buck et al., 1993: 75); from the project's perspective, it was therefore highly inefficient (Zier, 1970: 433). Under Tulla's influence, responsibility for Rhine protection shifted from local municipalities to the state. This was formalised by a decree in 1816, prior to construction (Knäble, 1970: 451-452).

Within this evolving political landscape, the project was both a product of emerging statehood and a key driver in shaping state formation and differentiation. Closely aligned with the political and territorial goals of the Baden rulers, it generated numerous synergies. Tulla drew on a vast body of state knowledge, which he expanded considerably, laying the foundation not only for river regulation but also for broader practices of surveying, territorial ordering and administrative control. The land "(re)claimed" from the river was converted into productive agricultural space, while the newly defined river course provided a (presumably) stable and reliable national border. This centralisation further consolidated the state's role as guarantor of security while extending the reach of political authority along the Rhine. By coupling labour, materials and river dynamics within a coordinated state apparatus, previously dispersed capacities could be mobilised more effectively. The resulting infrastructural works functioned as material participants; they concentrated agency and precluded alternative arrangements, and through their material endurance they actively sedimented state control along the river.

(4) Entangled temporalities and progressive future narratives

The Rhine rectification project confronted a multiplicity of heterogeneous (material) time regimes that shaped social and political life long before large-scale intervention became conceivable. Rather than following a single "natural" rhythm, the river brought together different temporalities. On the one hand, hydromorphological processes such as seasonal flooding, sediment transport and the gradual shifting of the riverbed followed comparatively amorphous, cyclical patterns that resisted stable (human) coordination. On the other hand, these dynamics were entangled with biological temporalities such as breeding cycles of mosquitoes and incubation periods of waterborne diseases, which translated environmental conditions into recurring health risks for riparian communities (Buck et al., 1993: 41). The newly arranged assemblage of the Rhine and its materially driven rhythms affected other assemblages nearby, such as related everyday practices and river use; it thus structured time as much as space.

It was against this background that Tulla sought to reframe the river temporally as well as spatially. Central to his project was the narrative contrast between a "wild Rhine" and a "tamed" or "corrected" river, which wove together a problematic past, a decisive moment of intervention in the present, and the anticipation of a stable and improved future. The straightening project was framed as a one-time and present-day (economic) investment, promising long-term stability and enduring future returns. This is illustrated from one of Tulla's own memorandums at the time:

Would it not be more beneficial and practical for the riparian states and residents to spend even greater sums than before for a common purpose, gradually forcing the Rhine into a continuous straight course (...) and *preserving it in this course forever?* (Tulla, 1822: 47-48; emphasis added).

This passage highlights not only the projected social and economic benefits, but also the establishment of a specific *infrastructural time*, that is, a temporally stabilised river course that would endure across generations. Within this narrative, the present expenditure of time, money and effort was framed as the necessary precondition for a better future; the present is viewed as the necessary past of what was yet

to come. As Tulla put it: "Everything along this stream will improve once we undertake the rectification work" (Tulla, 1822, cited in Cioc, 2002: 38).

During the implementation of the project, however, this linear and future-oriented temporal regime remained in constant tension with the river's own responses. Construction work could only proceed during periods of low water, forcing workers and engineers to adapt their schedules to seasonal fluctuations (Bernhardt, 2016: 46). Flood events repeatedly disrupted ongoing works and compelled Tulla to revise plans mid construction (Zier, 1970: 439). Rather than following a smooth trajectory towards a predefined future, the project was marked by continuous temporal adjustments, revealing how persistently the river's dynamics reasserted themselves within the very process meant to contain them.

In the longer term, the rectification project also reconfigured temporal relations beyond the immediate construction site. Potential side effects such as ecological transformations, the erosion of traditional river-based livelihoods, or the displacement of flooding problems downstream were largely externalised into the future and subordinated to the overarching promise of progress (Blackbourn, 2006: 104-116). The new economic activities that emerged along the straightened river in the following years were grounded in temporal regimes demanding increased coordination, speed and reliability. Together with technological innovations such as steamships, these developments gradually overlaid capitalist temporalities onto natural rhythms, reflecting the broader emergence of time as a "modern", abstract factor (cf. Bauman, 2000: 110-113; Rosa, 2012: 161-175). The Rhine's material processes were increasingly incorporated into a modern infrastructural time, reflecting an ongoing effort to synchronise the river's material rhythms while progressively disentangling it from local and ecological temporalities. Even after the rectification was completed, however, the river continued to assert itself. The deepening of the riverbed caused groundwater levels to drop in parts of the Upper Rhine, leading to droughts during prolonged dry spells, while altered hydrological conditions affected local flora and fauna and increased flood risks in downstream regions of the Middle and Lower Rhine (Blackbourn, 2006: 114-116).

(5) Sociotechnical hybridity and resistance

The sociomaterial character of the Rhine rectification becomes particularly visible through the assemblage-building work that Tulla pursued across multiple roles. Rather than acting solely as an engineer, he sought to weave his "seamless web" (Hughes, 1986) by aligning technical knowledge, scientific practices, administrative authority and political coordination.

In his technical role, supported by a growing network of hydraulic engineers (Bernhardt, 2016: 91), Tulla adapted emerging hydraulic knowledge to the requirements of large-scale river regulation. In the early 19th century, German hydraulic engineers were applying principles from 18th century scientists such as Bernoulli and Euler to river management; they were also building on the new concept of "technology" (Blackbourn, 2006: 89-90). This approach drew on a longer lineage of river engineering practices dating back to the Italian Renaissance that sought to harness the forces of rivers by channelling them into a single regulated bed (Cioc, 2002: 37). Tulla explicitly built on these developments, combining scientific theory, systematic testing and practical expertise (Blackbourn, 2006: 99-100). Alongside his hydraulic engineering work, he conducted research and published studies on hydraulics and hydrology, road and bridge construction, land surveying, cartography, mechanical engineering in mining, and metallurgy (Knäble, 1970: 450).

Standardising measurement along the Upper Rhine was not merely a technical task, and here Tulla's multiple roles intertwined. Beyond his scientific and technical expertise, he also acted as a (reluctant) diplomat, engaging in constant persuasion and standardisation efforts, particularly during negotiations with France, Bavaria and Hesse (Zier, 1970: 435; Cioc, 2002: 52). In the early 19th century, 20 different units of measurement were in use along the targeted section of the Rhine (Buck et al., 1993: 79). The challenge was to unify these units, particularly by adapting to the French metric system. While Tulla did not fully succeed, he laid the groundwork for later transitions (Knäble, 1970: 460) which paved the way

for further standardisation such as unified gauge scales and measurements of flow velocities (Cioc, 2002: 51). Notably, the effectiveness of these diplomatic and institutional efforts remained closely entangled with the Rhine's material dynamics. Severe floods repeatedly altered political constellations and decision-making horizons. The establishment of the *Magistrat du Rhin*, for instance, was a reaction to the devastating floods of 1801/1802 (Bernhardt, 2016: 115), while the protracted negotiations between Baden and Bavaria only culminated in agreement after the floods of 1816/1817 intensified the pressure to act (Blackbourn, 2006: 96).

The project also faced opposition within Baden. Tulla was therefore compelled to repeatedly defend both the feasibility and the principles of his project against political scepticism and public doubt (Zier, 1970: 417). As part of this public relations work, he published two memoranda, one of which articulated a maxim that became emblematic of the undertaking: "No stream or river, the Rhine included, needs more than one bed; as a rule, multiple branches are redundant" (Tulla, 1812, cited in Cioc, 2002: 3).

Beyond these immediate debates, Tulla also undertook notable educational work (Zier, 1970: 441). He ensured that the methods and techniques he developed were passed on to subsequent generations of engineers (Knäble, 1970: 455-456), and in 1807 he founded the application-oriented Technical University in Karlsruhe (Bernhardt, 2016: 97). Transferring his ideas and ideals across generations was crucial to the project's continuation. This was further reinforced by the gradual mythologisation of his person and achievements, which left a lasting impact on subsequent generations of engineers (Cioc, 2002: 72; Bernhardt, 2016).

Tulla's heterogeneous engineering approach, while challenging at the outset of his project, ultimately contributed to a hybrid stabilisation of the Rhine infrastructure assemblage during and after construction. As laws were enacted, new institutions formed alongside the emerging centralised state; scientific and technical standardisation also advanced, and an assemblage of interconnected, diverse infrastructures gradually took shape. Despite these efforts at coordination and stabilisation, the rectification project remained deeply shaped by material, technological and organisational constraints. Construction technology was limited and much of the work relied on manual labour, with each cut requiring approximately 4000 workers (Cioc, 2002: 52). The process was also accompanied by setbacks, financial miscalculations, protracted political negotiations, and uncertainties linked to both human and hydrological factors (Bernhardt, 2016).

(6) Mental-material feedbacks in infrastructural ordering

A central outcome of Tulla's project was what Blackbourn (2006: 117) has described as "changing mental horizons". It established a promise of security for future generations and contributed to a transformation of contemporary "mental infrastructures" (Welzer, 2011). The Rhine, once experienced as an uncontrollable force, increasingly came to be perceived as an alterable and controllable entity (Blackbourn, 2006: 118). The material reconfiguration of the river fed back into the emergence of a new "water culture" (Geels, 2005), which was manifested in shifting perceptions of risk, responsibility and possibility. Those who (re)settled along the Rhine relied on a state-backed promise of security that was grounded in scientific control technologies that both sought to tame the river and facilitated an instrumental, commodifying approach to nature.

The project's multiple objectives of flood protection, improved navigation, agricultural expansion, local development, and the stabilisation of a national border (Buck et al., 1993: 76), were thus accompanied by a reorientation of collective expectations. Tulla explicitly sought not only to regulate the river materially but also to instil trust in the durability of this new order, encouraging settlement and the productive use of reclaimed land (Blackbourn, 2006: 102). In the post-correction period, this translated into normative expectations of progress, which were increasingly seen as the achievement of maximum security against the formerly "wild" river (ibid: 112-113).

These changing mental horizons, in turn, favoured further interventions. Subsequent engineering projects did not merely build upon Tulla's corrections; they actively (re)corrected them, gradually transforming the Rhine into an increasingly canal-like infrastructure (ibid: 118). The Rhine rectification exemplifies a recursive material-mental feedback loop in the sense that material interventions reshaped perceptions of what was feasible and desirable, and these altered perceptions in turn legitimised and propelled further infrastructural ordering, thus setting in motion a logic of "technological fixes". Over time, this dynamic sedimented into a durable material arrangement in which earlier interventions persist as materially present reference points. The Rhine's course still largely follows Tulla's plans, and even the valley route he mapped in 1801 – still forming the basis of the German-French border today (Buck et al., 1993: 79) – persists as a materially (presumably) stabilised outcome of earlier infrastructural interventions. These enduring material arrangements exert a quiet formative force, stabilising infrastructural ordering through their continued material presence and mental sedimentation. As the historian Febvre already stated in the early 20th century:

The Rhine is a river of maps. In the past, it was sometimes a moat, sometimes a connecting line, sometimes a road. Today, it is all of these at once – tenfold amplified. And more than that: a *system of thoughts*, almost self-perpetuating. A system built on predominantly false and even harmful thoughts. Thoughts, initially devised by humans but now ruling over them (Febvre 1994a [1935]: 206; emphasis added).

Table 1 summarises the application of the heuristic to the case study, highlighting the heterogeneous forces at play across the six analytical dimensions.

What later generations inherited from the rectification project was not simply a straightened river but a process already under way. Its (im)material sediments kept working long after construction ended, prompting further corrections and foreclosing alternative paths. These "sediments" included the lowered groundwater table, the institutional arrangements and legal regulations and the expectation that the Rhine could be managed. Hydrosocial infrastructuring of rivers, in this sense, never starts from scratch; it unfolds as an ongoing interplay in which the *forces at play* sediment into a river heritage that shapes each subsequent reconfiguration.

TOWARDS A RELATIONAL APPROACH TO HYDROSOCIAL FORCES AT PLAY

In this article, we developed a sociological approach to rivers, understanding them as hydrosocial infrastructures. Merging Bennett's concept of thing-power with analytical dimensions of infrastructuring, we proposed a theoretically grounded heuristic enabling process-sociological analyses of the sociomateriality of rivers across six (infrastructural) dimensions. We applied this framework to the historical case of the Rhine rectification under Johann Gottfried Tulla. This enabled a deconstruction of his engineering work as the product of a heterogeneous assemblage and showed how material contributions shifted in the river's gradual transformation into a dynamically stabilised hydrosocial infrastructure. This perspective combines attentiveness to the specificity of the case study with a systematic grasp of the heterogeneous forces at play (Table 1). What travels from the Rhine to other cases are not primarily findings but questions; these include: which entities gained or lost significance, along which dimensions, and what were the consequences for the assemblage as a whole. This opens (hydrosocial) infrastructuring processes to comparative analysis beyond the single case.

The persistence of the hydrosocial entanglements traced here becomes evident when we turn to the present. The impact and consequences of the straightening and subsequent interventions endure as river heritage, continuing to shape present-day hydrosocial dynamics. For the Lower Rhine section, riverbed incision – caused by past human intervention – is expected to continue until 2100; in the future, the incision is likely to become increasingly entangled with additional climate-change-related drivers (Ylla Arbós et al., 2023). At the same time, since the mid-20th century, growing countervailing trends have

Table 1. Application of the processual heuristic to the Rhine rectification project

Dimension	Elements of the rectification project	Forces at play
(1) (In)visibility	Claim of a controllable, invisible river versus "natural" course and weather conditions (including extreme events like floodings) Visibility and alignment of heterogeneous materialities based on scientific and technical methods versus material resistance	Interplay of visibility and attempted invisibilisation; material forces at play are alternately backgrounded and asserting themselves
(2) Modernity	Development of areas for settlement and agricultural use versus risks of riverine land use Fostering of the "availability" of (modern) water versus its "unavailability" "Control project" based on a "modern" understanding of nature versus uncontrollable/unforeseen side effects Displacement of (non)human entities and practices along the river versus the destabilisation of ecological systems Application of scientific methods and techniques grounded in Enlightenment ideals versus epistemological blind spots and "mysteries"	River dynamics are enrolled as productive resource; confirmatory effect of material entities in "modern" assemblages
(3) Statehood and urbanity	Project as both an outcome of and a major catalyst for state formation and differentiation Shifting responsibility for the river from municipalities to the state (as the guarantor of safety) considering the river's range of influence Building on, and generation of, new forms of infrastructure-mediated "state knowledge" Promise of (more) stable territories and borders Institutional embedding of hydraulic engineering within the state apparatus	Material dynamics of the river as a constraint on political action; infrastructural works as material participants in state apparatus

(4) Entangled temporalities	Juxtaposition of the "wild nature" of the past/present and the "tamed nature" of the future Establishment of a specific infrastructural time Promise of security formulated in the future perfect tense Externalisation of side effects ("colonisation of the future") Emergence of "modern" time regimes along the straightened river Increasing disentanglement from "natural" rhythms	Competing material rhythms resisting and (re)shaping infrastructural time
(5) Hybrid stabilisation	Sociotechnical-assemblage character of the project Anchoring through standardisation and norm-setting processes Dissolution of old practices and creation/integration into new ones	Heterogeneous elements aligned into hybrid stabilisation; material contributions consolidating the assemblage
(6) Mental – material feedbacks	Change in "mental horizons" or "mental infrastructure": shift from the "wild, untameable river" to a canalised, controllable entity New "water culture" (transformed perception of risk, responsibility and possibility) Progress, defined as a promise of security against the river Continuity of the idea of a river with a single river course Material-mental "river heritage"	Material arrangements and "mental infrastructures" recursively (re)shaping and reinforcing one another

emerged. In response to the impacts on flood protection, navigation, hydropower, groundwater and ecology that have resulted from disrupted sediment balance and river morphology, since the 1980s over 140 river restoration measures have been initiated along the Upper Rhine, including the reconnection of side channels and the revitalisation of particular habitat areas (Krapesch et al., 2024).

The rectification unfolded within a hydrosocial configuration in which the ontological separation of nature and culture remained largely unchallenged. Deeply inscribed in European ways of perceiving reality, it was reinforced along the Rhine by the promises of growth and security that the project held out.⁹ Water ontologies, however, differ across societies and contexts (Yates et al., 2017) and so do the infrastructuring processes they inform.¹⁰ Precisely because the heuristic is derived descriptively from existing infrastructure research rather than prescribed on theoretical grounds, it remains open to what such cases bring to light and can be extended by them.

More generally, this article contributes to the sociological research on societal transformation. Societies' demands for change are increasingly being reflected across (social science) research; sociology too needs to transcend disciplinary boundaries and develop new approaches to empirical inquiry if it is to (re)position itself within science and society (Schmitt et al., 2024). As human agency acquires "planetary" scale (Chakrabarty, 2021), sociology also needs to embrace the new responsibilities arising through the interweaving of human-historical and Earth-systemic (time) regimes. The strength of sociological approaches lies in their capacity to recontextualise and decentre infrastructures against dominant technicist or solutionist "technological fix" conceptions. In doing so, they provide a footing for shared conceptual frameworks within inter- and transdisciplinary collaborations. Sociological perspectives add value to interdisciplinary analyses through their capacity to synthesise and their conceptual flexibility in addressing heterogeneous elements within (hydrosocial) transformations. In this way, sociology might not just mediate in (water-related) multidisciplinary research (Schulz and Gros, 2024); it may analytically uncover significant and heterogeneous forces at play.

Building on insights from the Rhine case, future research should assess the applicability of this enriched infrastructure concept to other (infrastructure) phenomena such as dam building, mining and renewable energies, in order to analyse ongoing infrastructuring and decode its elements across diverse socio-environmental contexts. Both theoretical understanding and practical engagement with infrastructure (trans)formation can thereby be advanced. Considering the changing sociometabolic circumstances of future societies, it might be especially fruitful to focus on hydrosocial infrastructuring, as water availability and quality are increasingly becoming cross-border political issues with powerful social and natural forces in motion.

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⁹ Even though they remain scarce along the Rhine, local conflicts and water movements in Germany indicate that in Western societies the 'modern' ontologies of water are increasingly contested (Hein and Thomsen, 2023; Franke, 2024).

¹⁰ This applies in particular to the 'modern' relation between nature and society that shaped the Rhine case. Where the two are not treated as separate (Law, 2015; McLean, 2017), infrastructuring would be traced along different orderings.

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