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Research article

The dynamics of linked social–ecological action situations reveal governance changes in the Austrian Danube

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A R T I C L E I N F O

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A B S T R A C T

The situation-centered network approach was developed to examine the interdependencies among multiple decision-making situations and their functions in shaping environmental governance outcomes. The approach has been extended to conceptualize ecological situations and incorporate a temporal dimension to uncover the development of (un)successful institutional settings over time. However, little is known about the dynamics of social–ecological interactions in transforming governance processes, outcomes, and network configurations within situation-centered networks over time. This paper operationalizes a more dynamic perspective that builds on the Social–Ecological Action Situations (SE-AS) framework to uncover which social–ecological–institutional dynamics explain governance changes in a river-floodplain landscape located along the Danube east of Vienna, over the past four decades. Our approach emphasizes how outcomes of key social and ecological interactions serve as drivers that trigger responses, which in turn generate new pressures and reactions in subsequent governance periods. We introduce a novel conceptualization of the ecological Action Situation (AS) as river-floodplain landscape interactions, capturing how riverine dynamics interact with the governance system to produce policy-relevant outcomes in nature conservation and economic benefits. Our findings reveal the complex social-biophysical dynamics involved in resolving conflicts within the social and social–ecological ASs, ultimately contributing to the emergence of a polycentric, participatory, and adaptive governance system. Specifically, we find that riverine connectivity responds quickly to restoration measures, whereas navigability in the main channel, determined by water levels, exhibits more fluctuations despite bedload-related management. Furthermore, changes in ecological dynamics triggered responses within social ASs, which produced institutions that, in turn, shifted operational activities and ecological dynamics. While this approach is useful in tracing dynamic processes underlying longer-term governance changes, a deeper understanding of how such network dynamics unfold may require methodological extensions through analytic history and narrative approaches for counterfactual analysis, and comparative studies across other riverine governance contexts.

1. Introduction

The underlying connectivity of resource-use systems and functional interdependence between coupled social and ecological systems (SES) (Hein et al., 2021; Poeppl et al., 2017) pose significant challenges to environmental governance (Brondizio et al., 2009; Turnbull et al., 2018; Bodin et al., 2019). Scholars increasingly apply situation-centered approaches to unpack the social, institutional, and ecological complexity of SES governance (Baldwin et al., 2023b; Kimmich et al., 2022; Lubell and Morrison, 2021). Polycentric governance (PG), which emphasizes the interdependence of multiple semi-autonomous decision-making centers (Ostrom et al., 1961; Carlisle and Gruby, 2019), has been widely used to characterize governance systems of diverse natural resources (Ostrom, 2010; Thiel, 2016; McGinnis and Ostrom, 2012;

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Andersson and Ostrom, 2008). In parallel, analytical frameworks such as the Ecology of Games (EoG) (Lubell, 2013) and the Network of Action Situations (NAS) (McGinnis, 2011), rooted in the conceptual unit that Ostrom refers to as the Action Situation (AS) in the Institutional Analysis and Development (IAD) framework (Ostrom, 1990; Ostrom et al., 1994), have been developed to examine multiple linked decision-making situations. These frameworks have been applied to various SESs, such as the water-energy-food nexus (Kellner, 2023; Srigiri and Dombrowsky, 2022; Villamayor-Tomas et al., 2015; Kimmich, 2013, 2016; Kimmich and Sagebiel, 2016), the energy infrastructures (Baldwin and Tang, 2021; Gritsenko, 2018), fisheries (Schlüter et al., 2019), river basins (Sendzimir et al., 2010), and water supply systems (Angst et al., 2022; Lubell et al., 2014).

Despite growing interest in PG, relatively limited attention has been paid to feedback pathways and adjustment mechanisms that drive governance changes over time (Baldwin et al., 2023b; Morrison, 2017; Carlisle and Gruby, 2018). Feedback pathways capture how governance outcomes give rise to changes in contextual and operational arrangements, which then generate new outcomes (Baldwin et al., 2023b). Meanwhile, the NAS approach – though not always explicitly situated within the PG research – has been applied to examine temporal relations of linked ASs, providing analytical tools to investigate longer-term governance evolution (Möck et al., 2019; Kellner and Martin, 2023; Baldwin et al., 2023a; Delaroche et al., 2022; Méndez et al., 2022). Furthermore, most PG studies focus on the decision-making processes of social actors across governance levels, often treating biophysical systems as contextual factors (Cole et al., 2019). In doing so, they may overlook the critical effects of ecological processes in shaping governance outcomes, given their bidirectional relationships with social–ecological dynamics (e.g., food-web relations among fish species and their implications for fishing practices) (Schlüter et al., 2019). This perspective also limits the integration of natural science knowledge, which could provide more nuanced explanations of social–ecological phenomena beyond institutional dynamics (Epstein et al., 2013; Gunderson et al., 2017). The nascent Social–Ecological Action Situations (SE-AS) framework extends the IAD and NAS approaches by explicitly incorporating ecological dynamics (as ecological ASs) and their interplay with social–institutional processes to explain SES phenomena (Schlüter et al., 2019). This framework has been applied to fisheries (Orach and Schlüter, 2021), lake-catchment areas (Herzog et al., 2022), and the water-energy-food nexus (Kellner and Martin, 2023).

Yet little is known about how governance changes emerge from the evolving, bidirectional interactions between social–institutional and ecological processes over longer time. Addressing this gap requires explicitly integrating institutional analysis with ecological dynamics and incorporating a temporal dimension. In this study, we operationalize a dynamic perspective of the SE-AS framework (Schlüter et al., 2019) to examine governance change in a small-scale river–floodplain system along the Danube east of Vienna, Austria, over a period of approximately four decades. We ask: which social, ecological, and institutional dynamics and their interplay explain the governance changes in this riverine area? To answer this research question, we map and analyze the evolution of networks of linked SE-ASs across three distinct governance periods. Building on Baldwin et al. (2023b), we focus on feedback between AS dynamics and SE-AS networks. Specifically, we identify outcomes in one phase that become drivers in the next, triggering responses and actions. These dynamics reshape the SE-AS network, marking the transition to a new governance period and initiating the next cycle of AS dynamics.

The empirical setting of riverine governance is particularly suitable for our theoretical inquiry. There has been a substantial reduction in floodplain areas in most large river systems worldwide in the past 100 years, including the Danube Basin (Hein et al., 2021, 2016). This ecological degradation was largely driven by river regulation measures implemented to enhance economic benefits and human welfare. Once deemed great achievements, these control measures later led to conflicts among different resource use groups (García et al., 2019), particularly between efforts to conserve riverine ecosystems and manage rivers for human uses (Pahl-Wostl, 2006). Pahl-Wostl (2006) has noted increasing calls for a paradigm shift, from "fight against water and control the flood" to "give room to water". The latter approach stresses restoring the multifunctionality of river-floodplain ecosystems (Funk et al., 2021; Tschikof et al., 2024) and promoting integrated, adaptive, and collaborative governance (Baudoin and Gittins, 2021; Pahl-Wostl, 2009, 2006; Pahl-Wostl et al., 2007).

Our study area, a 48 km stretch of the Danube River, has undergone such a governance transformation. Although currently located within a national park, the river-floodplain area was exposed to pressures driven by river regulations and hydropower construction in the past (Reckendorfer et al., 2006). To address the resulting issues of floodplain disconnection and riverbed incision, a set of integrated river engineering measures has been recently implemented (Tögel and Baumgartner, 2016). The hydrological and ecological outcomes of these measures have been monitored, evaluated, and documented in studies (e.g., Funk et al. (2023, 2021, 2013), Reckendorfer et al. (2006)).

The accumulated hydrological and ecological knowledge provides a basis for operationalizing the SE-AS framework in this riverine setting, enabling identification and analysis of operational and institutional changes in relation to biophysical dynamics. We develop an ecological AS of *river-floodplain landscape interactions*, capturing the frequency of water flow between the main river channel and adjacent floodplain areas. We select two outcome measures that reflect central policy goals in nature conservation and navigation, and are directly shaped by the river-floodplain interactions. They include: (1) habitat connectivity (to what extent organisms can move and interact within the riverine landscape) and (2) navigability (to what extent navigation is constrained by low-water conditions in the main channel).

The contribution of this study is twofold. First, we advance situation-centered institutional analysis by explicitly integrating biophysical dynamics, an aspect often underexplored in governance research. We also extend the use of the SE-AS framework with a temporal dimension to capture feedback between AS dynamics and the reconfiguration of linked SE-ASs that drive governance changes. Second, we conceptualize and operationalize an empirically grounded ecological AS of riverine connectivity. This ecological AS provides an analytical space for integrating governance, ecological, and hydrological perspectives, supporting the identification and analysis of operational and institutional changes that both shape and are shaped by river-floodplain interactions within the broader governance network.

2. Theory, methods, and data

2.1. The network extension of situation-centered institutional analysis

The IAD framework was originally developed by Elinor Ostrom and her colleagues to study the sustainable governance of common-pool resources (Ostrom et al., 1994; Ostrom, 1990). Instead of advocating for top-down regulations, IAD scholars have provided evidence that local users can establish self-governance arrangements to sustainably manage natural resources (Ostrom et al., 1994). Embedded within the biophysical and socioeconomic contexts, the action situation (AS) is the core analytical unit of the IAD framework, defined as the social space where actors interact and make strategic decisions (Ostrom, 2011, 2005). ASs can be understood as events, activities, venues, or instances of decision making (Kimmich et al., 2022); as cooperation or coordination games (Kimmich and Villamayor-Tomas, 2019); delineated based on governance tasks such as resource extraction, monitoring, rulemaking, and conflict resolution (McGinnis, 2011); and identified as situations at operational, collective-choice, and constitutional governance levels (Ostrom et al., 1994).

A network extension of the IAD framework was developed by addressing the interdependencies of multiple ASs in jointly affecting the governance outcomes, also referred to as a network of adjacent action situations (McGinnis, 2011; Ostrom et al., 2002; Kimmich, 2013; Pahl-Wostl et al., 2013; Sendzimir et al., 2010). Situations can be connected hierarchically across governance levels, or functionally when the outcomes of one affect the working components of the other (McGinnis, 2011). These AS connections have been formalized as directed linkages through flows of information, institutions, or biophysical transactions; or undirected linkages when situations share common actors (Kimmich, 2013; Kimmich and Villamayor-Tomas, 2019; Tan et al., 2023).

Later, the SE-AS framework was developed to explicitly account for ecological interactions in governance analysis (Schlüter et al., 2019). By extending the notion of AS beyond strategic actions taken by actors (with or without tangible connections to the biophysical world) in the IAD framework (Ostrom, 2005; Ostrom et al., 1994), Schlüter et al. (2019) conceptualized three types of ASs, including (1) ecological ASs (E-ASs), spaces where ecological entities interact, structured by biophysical rules; (2) social–ecological ASs (SE-ASs), spaces where social actors and ecological entities interact, constrained by both social and biophysical rules; (3) social ASs (S-ASs), spaces where social actors interact, bounded by social rules. The three types of ASs and their ties form the SE-AS network. Notably, S-ASs and E-ASs are connected only indirectly, through SE-ASs, which maintain direct linkages with both.

2.2. Study area and its historical development

We study governance changes along the Danube east of Vienna, including the main river channel and the adjacent floodplain areas (Fig. 1). It is an approximately 48 km stretch of the Danube River between the two capital cities of Vienna (Austria) and Bratislava (Slovakia). Located within one of the last free-flowing sections of the Upper Danube River, the river-floodplain landscape provides vital ecosystem functions and services (Funk et al., 2021; Schiemer et al., 2007). This stretch of the river is also an important international waterway as part of the Rhine-Danube Transport Corridor.

The governance processes of the riverine system along this stretch were divided into three governance periods (Fig. 2). We examined how the outcomes of key activities acted as drivers, triggering reactions and new problems at a later time. Period 1 began with the governmental planning of a hydropower plant (HPP) in the Hainburg area in 1983. Large-scale river engineering measures date back to the late 19th century. These interventions resulted in issues of riverbed incision, floodplain disconnection (Hein et al., 2006; Schiemer et al., 1999), and loss of floodplain habitats and biodiversity (Hein et al., 2016). The HPP plan sparked a nationwide environmental movement in Austria ("Occupation of the Hainburger Au") and legal actions taken by civil society (Gutschik et al., 2007).

As a result, the Donau-Auen National Park (NP) was established in the river-floodplain area in 1996, marking the beginning of Period 2. The integrated river engineering concept (in German: *Flussbauliches Gesamtkonzept*) was proposed while planning for the NP in 1995, which further led to the development of the Integrated River Engineering Project (in German: *Flussbauliches Gesamt Projekt*; FGP) since 1998 (Reckendorfer et al., 2005). The FGP aimed first to stabilize the riverbed and optimize low water regulation to secure navigation through bedload-related management (e.g., dredging gravels from downstream to upstream), and second, to restore nature conservation by restoration measures (e.g., reconnecting side channels and removing riverside embankments) (Reckendorfer et al., 2005). In the late 2000s, a pilot project was planned for a 3 km stretch in the Bad Deutsch-Altenburg area. This project, led by the federal ministry and the waterway company (Waterway Act, 2004), faced opposition from civil society and the private sector, leading to revisions in planning.

Period 3 began in 2012 with the implementation of the revised pilot project. A policy forum (2012–2015) was established to accompany the project. Later, the Catalog of Measures, a set of river engineering measures adapted from the pilot project, began being implemented in 2017 throughout the whole river-floodplain area (viadonau, 2018, 2024).

2.3. Data collection and analysis

Our approach builds on recent efforts to formalize analytical procedures for delineating and analyzing linked ASs (Baldwin et al., 2023a; Kimmich et al., 2022). Schlüter et al. (2019) further proposed a set of guiding questions to support the identification of E-ASs and social-biophysical dynamics. However, these studies offer limited methodological guidance for examining longer-term governance changes. Combining the insights, we developed four analytical steps to operationalize the SE-AS framework for qualitative analysis of governance changes, including: (1) identification of social–ecological dynamics; (2) demarcation of governance periods; (3) mapping of linked SE-ASs, and (4) analysis of governance dynamics (overview see Table A.1 in Appendix A). We define ASs broadly as events, activities, or social and/or ecological spaces where social actors and/or ecological entities interact and make strategic decisions. Following the SE-AS typology, we further distinguish among ecological, social–ecological, and social ASs (Section 2.1).

2.3.1. Analytical steps

Step 1: Identifying key social–ecological dynamics

This step focused on identifying key social–ecological aspects, guided by the following questions: What are the emergent social–ecological problems of concern? What biophysical processes drive these problems? Which key operational activities directly influence or are affected by the biophysical process? Which indicators and data are suitable for assessing the biophysical dynamics over time?

This step drew primarily on the hydrological and ecological knowledge from co-authors with decades of research in the riverine area, combined with institutional perspectives. This process led to the conceptualization of the E-AS and its linkages with (some initially identified) SE-ASs, e.g., river engineering measures and navigation. We selected E-AS indicators based on three criteria: (1) direct relevance to the issues of interest; (2) capacity to provide a meaningful basis for examining the dynamic interplay between biophysical processes and operational activities in the SE-AS governance system; and (3) availability of longitudinal datasets.

Step 2: Demarcating governance periods through key activities and events

While Steps 2 and 3 are presented sequentially, in practice, we conducted them in parallel through an iterative process: the demarcation of governance periods (Step 2) informed the identification of linked ASs (Step 3), while insights from network mapping further refined the delineation of periods.

This step was guided by the core question: What are the major turning points that signal structural or paradigm changes in the governance system? To address this, we constructed a timeline with chronologically ordered key events, activities, and decisions over approximately the past four decades (Fig. 2). The focus was on the emergence and changes of relevant rule-making and operational activities, the latter of which complement the operational aspects identified in Step 1. From this timeline, particular events were identified as turning points and served to demarcate governance transitions. The timeline was based on document analysis of secondary sources, including scientific literature, policy and organization reports, media coverage, and legal rulings.

Step 3: Mapping linked SE-ASs of three governance periods

Building on the governance overview (Step 2), this step mapped the linked SE-ASs within each period. We focused on examining the detailed working components of activities and uncovering additional situations that may have been overlooked in the timeline. Guiding

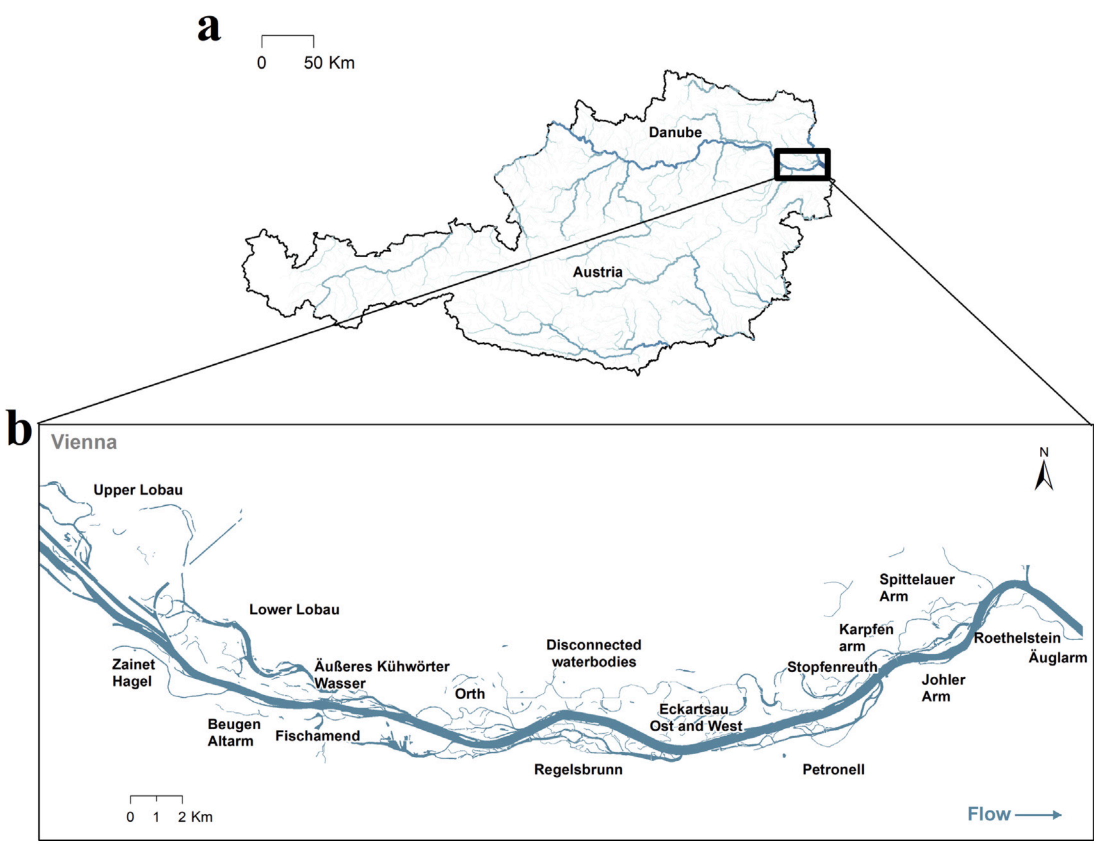


Fig. 1. (a) Geographic location of the Danube east of Vienna; (b) Floodplain sections in the Donau-Auen National Park.

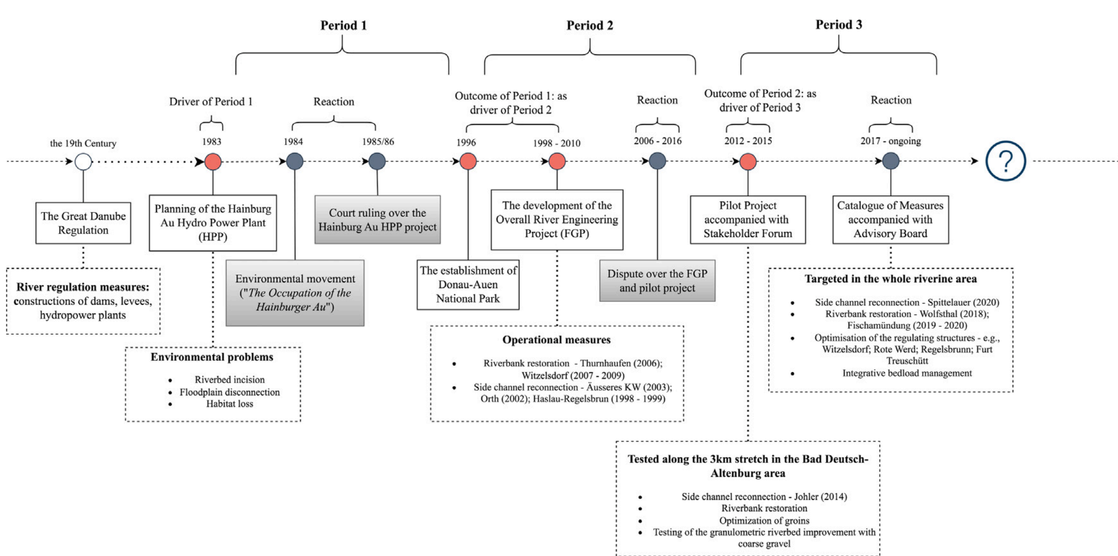


Fig. 2. A list of key events and activities in the river-floodplain area across three governance periods. Gray circles represent actions taken in response to pressures within each period, while red circles indicate outcomes of the responses that subsequently act as drivers in the following period.

questions include: Which concepts or theories can be used to delineate ASs? What are the key working components of each AS (involved social and ecological entities, institutions, interactions, and outcomes)? If a situation exerts influence over the other, or if any pair of situations shares common social or ecological entities?

Multiple sources of data were used to delineate and analyze situations over time, including the document analysis (Step 2), semi-structured interviews (40 to 90 min each), and an online survey with 12 policy actors between August 2022 and February 2023. These actors included representatives from the federal ministry (responsible for navigation regulation and waterway maintenance), the public sector (the national park and an international water management body), civil society (environmental NGOs), and the private sector (navigation association and the waterway company established by the government).

The delineation of ASs focused on the operational level SE-ASs and collective-choice level S-ASs, given that the E-AS has already been conceptualized in Step 1. This process was guided by the notion of governance function (McGinnis, 2011). Aggregation (of many individual settings) or disaggregation of ASs was used to best reflect governance dynamics. Some (e.g., policy forum) are disaggregated to capture distinct influences, while others (e.g., discourse) are aggregated to reflect broad influences that cannot be pinpointed to a single setting. These situations were classified as SE-ASs or S-ASs, depending on whether ecological entities or social–ecological interactions were present. Details of the E-AS are outlined in Section 2.3.2.

Lastly, AS linkages were identified using formalized typologies (Kimmich, 2013; Kimmich and Villamayor-Tomas, 2019; Tan et al., 2023). The resulting SE-AS networks – visualized as box-and-arrow diagrams (Fig. 6a–c) – depict linked SE-ASs across three governance periods. While similar to a NAS graph (McGinnis, 2011), the SE-AS network explicitly integrates ecological dynamics (as the E-AS) and its connections to social–institutional processes.

Step 4: Analyzing dynamics of linked SE-ASs that drive governance change

Finally, we adopted a dynamic perspective to analyze governance change of the constructed SE-AS networks. The guiding question was: What are the key social–ecological–institutional drivers, responses, and outcomes shaping governance transition over time?

We examined specific SE-AS configurations, represented as structural connections of ASs in the network, to understand how they shaped governance changes. These configurations highlight how outcomes from one phase (e.g., new policymaking in an S-AS, increased floodplain disconnection in the E-AS, or alterations in river engineering measures in a SE-AS) may act as drivers that trigger responses. These responses, in turn, generate outcomes that emerge as new pressures within the governance system. As a result, these changes lead to a reconfigured SE-AS network for the subsequent period.

2.3.2. Analyzing the ecological AS

Informed by analytical Step 1, we identified Lateral Hydrological Connectivity (LHC) - the exchange of water between the main channel and its adjacent floodplains, measured as inundation frequency of floodplain waterbodies in days per year (Reckendorfer et al., 2006) - as the core physical process underlying floodplain disconnection and riverbed incision. Based on this, we selected two outcome measures: (1) habitat connectivity (HC) within the river-floodplain area, and (2) navigability in the main channel. They reflect policy interests of nature conservation and navigation that are most central to the riverine governance context; guide the identification of key operational activities that shape and are shaped by the riverine connectivity; and are supported by long-term datasets.

Ecological analysis on HC

HC, which measures the extent of animal movement between and within the main river channel and adjacent floodplain areas (Fig. 1), is a key ecological indicator for assessing biodiversity and how freshwater communities interact with their habitats (Funk et al., 2021; Reckendorfer et al., 2013; Funk et al., 2013; Schiemer et al., 2007). Derived from LHC, a key determinant of floodplain ecology and a surrogate for important habitat variables (e.g., water depth, flow velocity, and water quality) (Funk et al., 2013), HC directly reflects how the ecological conditions in the riverine landscape affect biodiversity. Importantly, restoration measures in the study area explicitly aimed to enhance LHC (Schiemer et al., 2007), making HC a logical and contextually relevant choice for assessing ecological outcomes. In this way, HC reflects the direct and indirect impacts of LHC changes, particularly those driven by restoration measures, on floodplain habitats.

We calculated HC at the floodplain level using the dPC metric (Fig. 3), which ranks floodplain locations according to their importance in maintaining the movement of organisms in the riverine landscape (Bodin and Saura, 2010). The analysis relied on published LHC datasets for 1996, 2003, and 2020 (Reckendorfer et al., 2006; Funk et al., 2023). Due to the unavailability of continuous temporal data, we used these three years as representative points for the three identified governance periods, respectively. The dPC calculation is provided in Appendix B.

Environmental analysis on navigability

Navigability was selected as an E-AS outcome because it represents the key policy objective for the navigation sector and is affected by riverbed incision and bedload-related management. To assess navigability, we used datasets on the daily water levels[1] in the main channel, recorded at the Hainburg monitoring station (Wasserstandsnachrichten und Hochwasserprognosen, 2024), alongside the *Low Navigable Water Level* (LWL) (in German: *RegulierungsNiederwasser*) thresholds from 1955 to 2020. The thresholds are published in official reports titled *Characteristic Water Levels of the Austrian Danube* (in German: *Die kennzeichnenden Wasserstände der österreichischen Donau* [KWD]), available for the periods 1949–1955 (Bundesstrombauamt, 1951), 1956–1962 (Bundesstrombauamt, 1959), 1963–1974 (Bundesstrombauamt, 1970), 1975–1983 (Bundesstrombauamt, 1978), 1984–1995 (Wasserstraßendirektion, 1986), 1996–2009 (Wasserstraßendirektion, 1998), 2010–2019 (viadonau, 2012), and from 2020 (viadonau, 2020).

The LWL threshold is a statistical reference point, defined as the water level that is reached or exceeded 94% of the time over a long-term reference period (Klasz et al., 2013). According to the Danube Commission (1988), the fairway must be maintained to ensure a minimum water depth[2] of 2.5 meters at LWL. For this purpose, riverbed elevations are regularly monitored, particularly along shallow sections, and maintenance measures such as dredging are carried out to maintain the required depth. This international standard informs navigation activities, such as shipment schedules and cargo loads, under the most limiting hydrological conditions. When daily water levels fall below LWL, the 2.5-meter minimum depth is not guaranteed, leading to operational restrictions for navigation.

In this study, we first analyzed long-term trends in LWL thresholds, as an indicator of riverbed incision in the main channel (Fig. 4). A decline indicates increased incision, which undermines navigation. We then calculated the number of days per year from 1955 to 2020, during which water levels in the main river channel were above (navigable) and below (unnavigable) the corresponding LWL threshold (Fig. 5). The count of days below this threshold serves as a proxy for the frequency of low-water events constraining inland navigation, relative to planning expectations.

Following the three governance periods identified in Section 2.2, we distinguish three intervals for analysis: Period 1 (1983–1996), Period 2 (1996–2012), and Period 3 (2012–2020). Data from 1955 to 1983 are included to provide historical context for water level conditions, particularly regarding the impacts of the Great Danube Regulation.

3. Results

Table 1 presents an overview of the identified ASs, including the involved human and non-human entities, interactions, and outcomes. The situations are grouped by the three AS typologies of the SE-AS framework. The red box marks the three situations that occurred later, while the rest were present across all periods. The working components within each AS may differ across periods.

First, we identified four SE-ASs, including river converting measures ($AS_{MEASURE}$), navigation (AS_{NAV}), monitoring ($AS_{MONITOR}$), and national park management (AS_{NP}). The latter emerged during Period 2.

[1] Water levels are recorded as relative values with reference to the gauge zero, which is usually set below the riverbed, and are then converted to absolute elevation in meters with reference to the Adriatic Sea (Wasserstandsnachrichten und Hochwasserprognosen, 2025).

[2] The minimum water depth is calculated as the difference between the water level and the riverbed elevation at the shallowest point in the fairway.

Table 1
A list of identified social–ecological, social, and ecological ASs in the riverine governance system over time; the red boxes highlight the three situations that occurred at later periods.

AS	Descriptions	Human/non-human entities	Interactions and outcomes	Attributes
Social–Ecological Action Situation (SE-AS)				
$AS_{MEASURE}$	River engineering measures, e.g., dams; dredging; and side-channel reconnections	Federal ministry; the waterway company; others (e.g., contracted companies for operation); the riverine entities	Affect the biophysical system in tangible ways; structured by human-constructed and ecological rules, as well as information on the riverine conditions	All three periods; Operational level
AS_{NAV}	Inland navigation activities	Navigation industry; the main river channel	Affect the biophysical system in tangible ways; constrained by the water level and riverbed incision	All three periods; Operational level
$AS_{MONITOR}$	Monitoring activities of riverine conditions	Federal ministry; scientific community; the waterway company; national park authority; the riverine entities	Monitored information used to inform navigation, discourse, and policy makings	All three periods; Operational level
AS_{NP}	Management activities by the national park authority	National park authority; The NGO, who owns part of the land in the national park; the riverine entities	Operational activities implemented by the national park authority to restore and improve ecological conditions of the riverine area	Period 2 and 3; operational level
Social Action Situation (S-AS)				
AS_{NAT}	Policy-making at the national level	National government; federal ministry	Relevant legislations in managing the river-floodplain area: e.g., the National Park Act; Federal Waterway Act	All three periods; Collective-choice level
AS_{COURT}	Court ruling	Court; NGOs; federal ministry; the waterway company	Lawsuits over the hydropower plant construction and the pilot project planning	All three periods; Collective-choice level
$AS_{DISCOURSE}$	Public discourse in terms of managing the river-floodplain area	A variety of actors involved in the discourse of the river-floodplain management	Discourse produced and disseminated by different interest groups, taking forms of information briefing, environmental movement, media coverage, etc.	All three periods; Collective-choice level
AS_{FORUM}	Policy forum	A selected list of actors from the public sector, private sector, and civil society	Actors with various policy interests participate in the policy forum, coordinated by the waterway company, discussing operational measures, receiving information, etc.	Period 3; Collective-choice level
AS_{SUPRA}	Legislations and funding by the supranational authorities	The EU and international organizations	Relevant legislations set by the supranational authorities in managing the river-floodplain area: e.g., the EU Water Framework Directive and the fairway parameter set by the Danube Commission	Period 2 and 3; Collective-choice level
Ecological Action Situation (E-AS)				
$E\text{-}AS_{LANDSCAPE}$	Key biophysical dynamics in the riverine system	18 floodplain areas and the main river channel	The interaction is captured as the frequency of lateral hydrological exchanges, producing outcomes on habitat connectivity and navigability. The outcomes shape and are shaped by its biophysical rules and operational activities	All three periods

In addition, five S-ASs were identified, including national policymaking (AS_{NAT}), court rulings (AS_{COURT}), public discourse ($AS_{DISCOURSE}$), policy forum (AS_{FORUM}), and supranational policymaking (AS_{SUPRA}). In particular, AS_{SUPRA} emerged in Period 2, while AS_{FORUM} emerged in Period 3. Lastly, the E-AS of river-floodplain landscape interactions ($E\text{-}AS_{LANDSCAPE}$), as described in Section 2.3.2, was present across all periods.

In the following, we first present the conceptualized E-AS and then analyze the three SE-AS governance networks over time.

3.1. The conceptualized E-AS: River-floodplain landscape interactions

Given the riverine governance context, we propose a novel conceptualization of the E-AS as river-floodplain landscape interactions, which goes beyond the examples of E-ASs identified by Schlüter et al. (2019). We consider the main river channel and 18 floodplain locations (Fig. 1) to be the ecological entities. Their interactions are captured as the exchange of water (inundation frequency of floodplain waterbodies in days per year), known as LHC (Reckendorfer et al., 2006). The hydrological interactions produce outcomes that impact nature conservation and inland navigation, measured via two indicators: (1) HC, the extent of animal movement within the riverine landscape (Saura and Pascual-Hortal, 2007; Saura et al., 2011), and (2) navigability, the extent to which navigation is constrained by low-water events (Section 2.3.2).

Specifically, a riverine landscape with higher LHC, which indicates greater connectivity between the main river channel and its floodplains, provides new pathways for animal movement (higher HC). This connectivity benefits fish species that rely on floodplain habitats to complete their life cycles, thereby supporting species richness, which is essential for enhancing ecosystem resilience. Conversely, when the

LHC is low, aquatic biodiversity in the floodplains becomes isolated, leading to habitat degradation and, over time, the transformation of these waterbodies into terrestrial areas (Funk et al., 2021; Reckendorfer et al., 2013; Funk et al., 2013; Schiemer et al., 2007). The impact of the LHC on navigation depends on the water level of the main river channel. During periods of low discharge, higher LHC reduces the water level in the main channel and, thus, a lower water depth for ships (negative for navigation). However, during high discharge and extreme flood events, increased LHC helps reduce erosive forces in the main channel as the discharge is distributed over a larger cross-section, thereby benefiting navigation. In the long term, improvements in LHC help mitigate the riverbed incision rate, preventing the rapid deepening of the riverbed, which is beneficial for both nature conservation and inland navigation (Reckendorfer et al., 2005; Schiemer et al., 2007).

These biophysical dynamics are further affected by the riverine landscape itself and human interventions. First, LHC is constrained by the riverine landscape, that is, the locations and structure of different floodplain areas. Second, a set of operational activities ($AS_{MEASURE}$; AS_{NP}) directly modifies the riverine landscape, shaping the E-AS dynamics. Restoration measures such as side-channel reconnections enhance connectivity between the main river channel and floodplain areas, improving LHC and HC (Hein et al., 2006). Yet, they may lower water levels in the main channel as more water is diverted into floodplains. Conversely, engineering measures such as river channelization and groin construction could stabilize water flow in the main channel, providing benefits for flood control, hydropower generation, and navigation. However, these measures cause riverbed incision (by concentrating flow and eroding the bed) and disconnect floodplain areas from the main river channel. Bedload management measures, including dredging and gravel additions, are implemented to stabilize the riverbed and maintain the required minimum water depth for navigation (Danube Commission, 1988). Finally, navigation activities (AS_{NAV}) can affect animal movement and biodiversity in the floodplain ecosystems, due to ship-produced waves (Bondar-Kunze et al., 2024).

3.2. The SE-AS network changes over three periods

3.2.1. Period 1: Collective actions by civil society against top-down river governance prioritizing economic benefits

Earlier governance systems may have existed prior to Period 1 (Fig. 6a) identified in this study. Here, we consider the Great Danube Regulation, dating back to the late 19th century (Reckendorfer et al., 2005), as the key governance context that set the stage for plans to construct the Hainburg HPP in 1983 (AS_{NAT}). The governance system was characterized by top-down decision-making, with limited participation of non-governmental actors in planning, implementation, and monitoring activities. Policy was primarily aimed at promoting economic benefits and human welfare, as reflected in a set of river regulation measures, such as the construction of dams, levees, and HPPs.

The E-AS analysis reveals ecological and environmental degradation in Period 1 ($E\text{-}AS_{LANDSCAPE}$). At the floodplain level, both LHC and dPC were at their lowest in 1996 compared to 2003 and 2020 (Fig. 3). Also, Fig. 4 shows significant riverbed incision in the main river channel, with an average deepening rate of 2 to 3 cm annually during the 1980s and 1990s (Klasz et al., 2013). The deepened riverbed reduced navigation capacity, aligning with the increased frequency of days when water levels fell below LWL during Period 1 (Fig. 5).

In response to these degradations (E-AS) and the growing environmental awareness in the West in the 1960s ($AS_{DISCOURSE}$), the Hainburg HPP construction plan was met with tremendous resistance by civil society. Lacking access to the formal decision-making process, non-governmental actors leveraged the available social situations as strategic responses to oppose the plan. We identified two key actions:

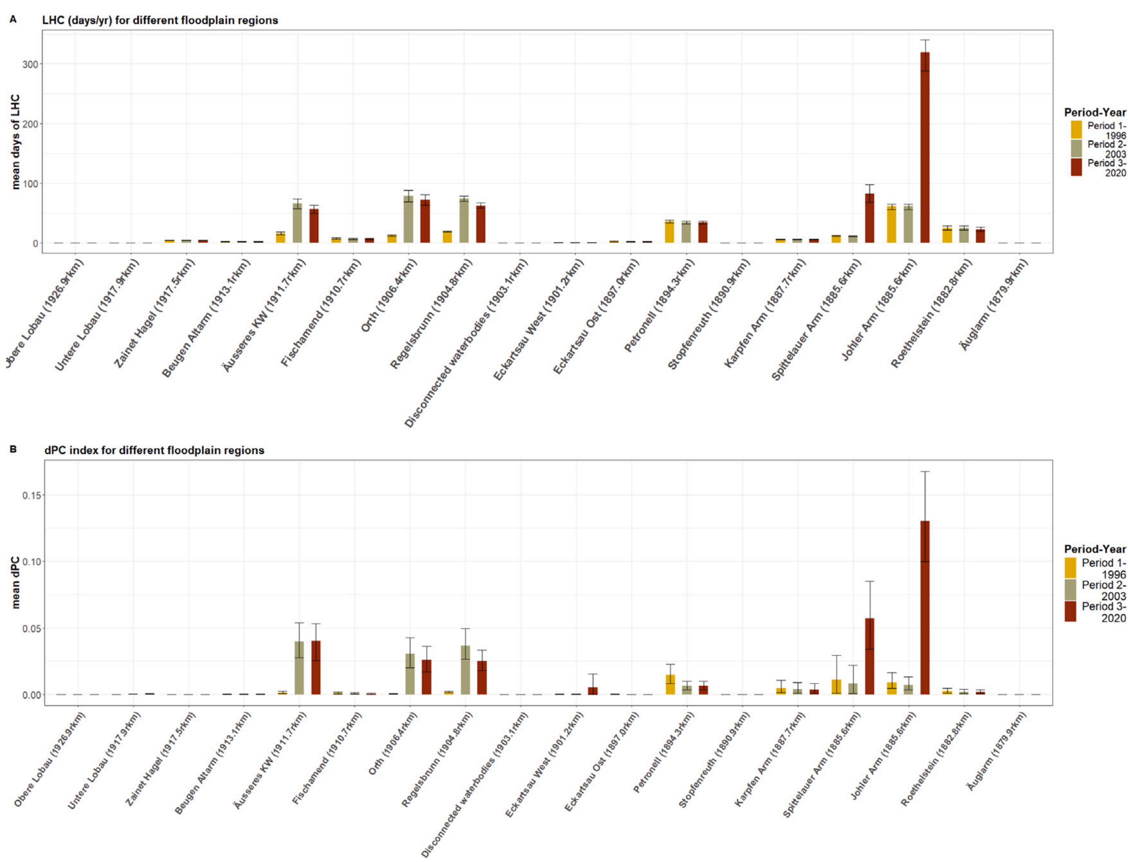


Fig. 3. Comparison between the average days per year of lateral hydrological connectivity-LHC (A) and the average habitat connectivity-dPC (B) for the different floodplain regions (indicated with names and river kilometers/locations) in the Donau-Auen National Park.

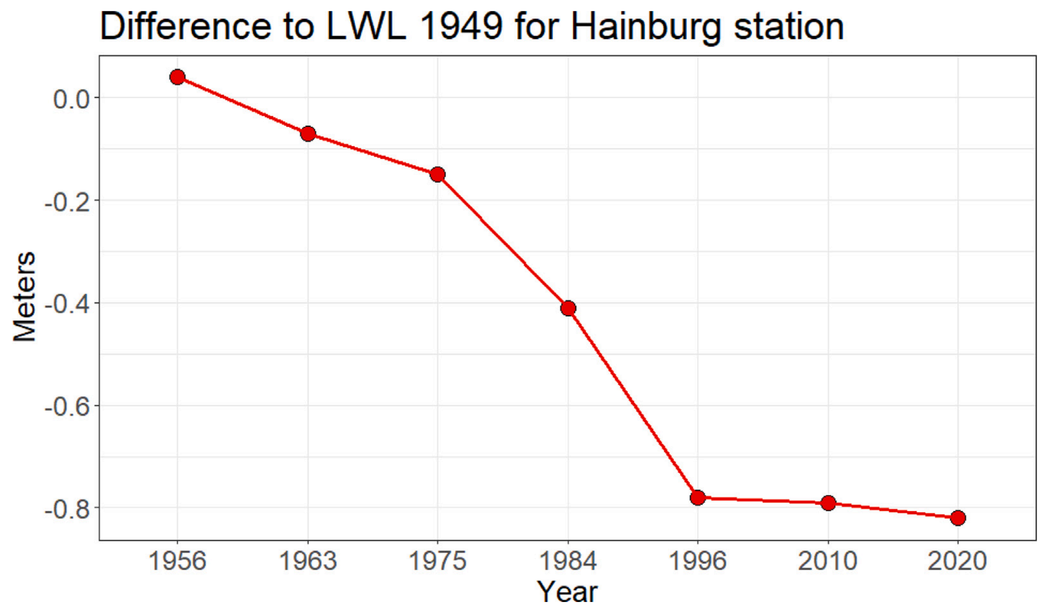


Fig. 4. The difference, in meters, of the Low Navigable Water Level (LWL) recorded between 1956 and 2020 compared to the LWL of 1949 as a reference point.

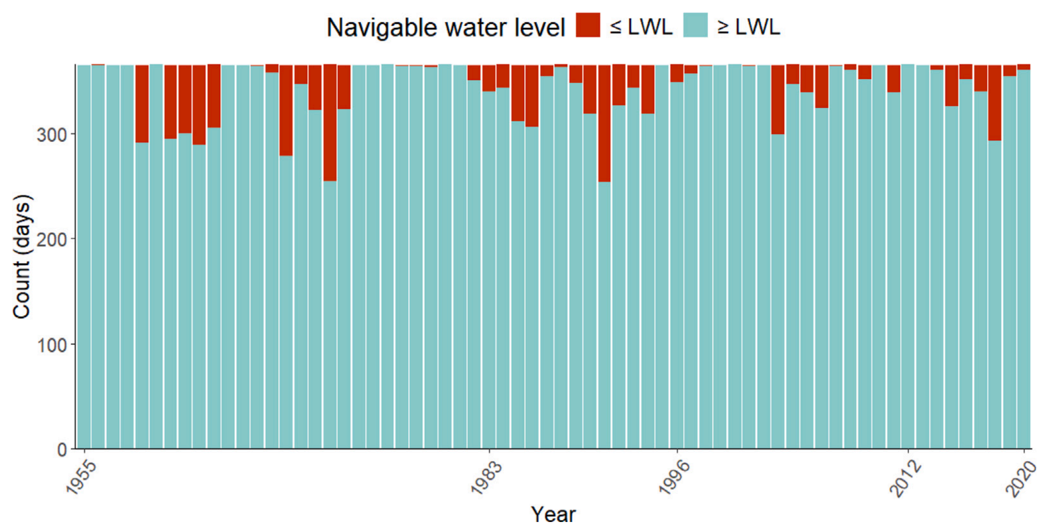


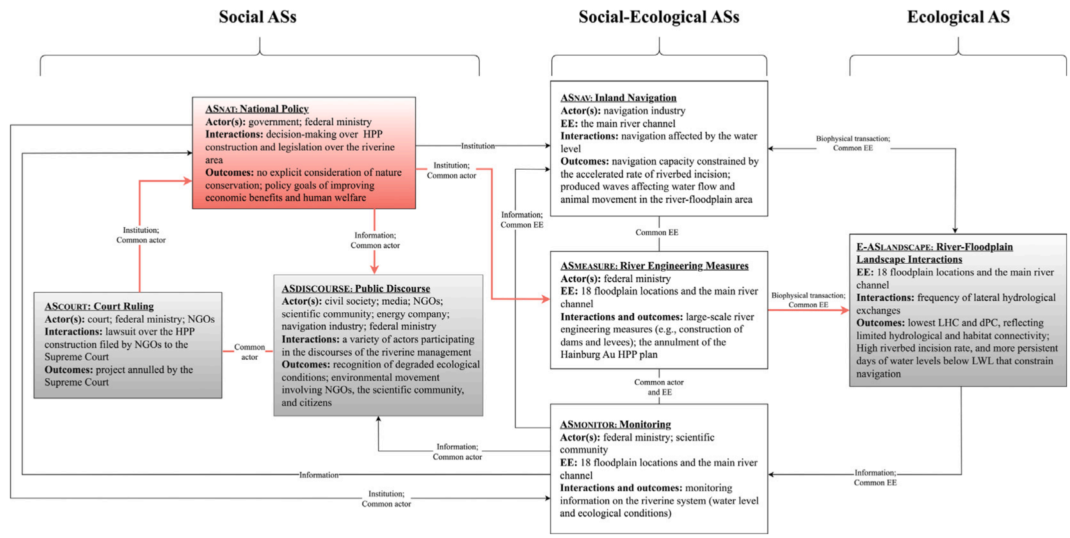
Fig. 5. Frequencies of days above and below the Low Navigable Water Level (LWL) in meters above the Adriatic Sea level (m.a.s.l.) for 1955 to 2020 recorded at Hainburg gauge station. The LWL thresholds throughout this period were the following: (i) for 1955: 137.24 m.a.s.l. (Bundesstrombauamt, 1951); (ii) for 1956–1962: 137.28 m.a.s.l. (Bundesstrombauamt, 1959); (iii) for 1963–1974: 137.17 m.a.s.l. (Bundesstrombauamt, 1970); (iv) for 1975–1983: 137.09 m.a.s.l. (Bundesstrombauamt, 1978); (v) for 1984–1995: 136.83 m.a.s.l. (Wasserstraßendirektion, 1986); (vi) for 1996–2009: 136.46 m.a.s.l. (Wasserstraßendirektion, 1998); (vii) for 2010–2019:136.45 m.a.s.l. (viadonau, 2012); and (iii) for 2020:136.42 m.a.s.l. (viadonau, 2020). We show years included in our study: 1983–1996 (Period 1),1996–2012 (Period 2) and 2012–2020 (Period 3).

first, the creation of a nationwide environmental movement organized by civil society, consisting of environmental NGOs, citizens, and the scientific community ($AS_{DISCOURSE}$); and second, legal action taken by a coalition of environmental NGOs (overlapping with the environmental movement) against the project. In the end, the Austrian Supreme Court of Justice ruled to annul the decision allowing the construction of the HPP (AS_{COURT}). The institutional outcome at the judicial level constrained policymaking (AS_{NAT}), which subsequently affected operational activities ($AS_{MEASURE}$) and biophysical outcomes ($E\text{-}AS_{LANDSCAPE}$).

To summarize, key network dynamics in Period 1 were captured via two sets of SE-AS configurations. The first involved ecological and environmental degradation (E-AS), driven by large-scale river engineering measures (SE-AS). It triggered responses from multiple linked S-ASs (policymaking, court ruling, and discourse), where discursive and legal actions were taken by civil society in response to policymaking concerning the HPP project. As a result, the management paradigm of "fighting against water and controlling the flood" was challenged, paving the way for policy goals that incorporated nature conservation alongside economic benefits and human welfare, in the following governance period. However, in Period 1, the non-governmental participation in formal decision-making processes remained limited.

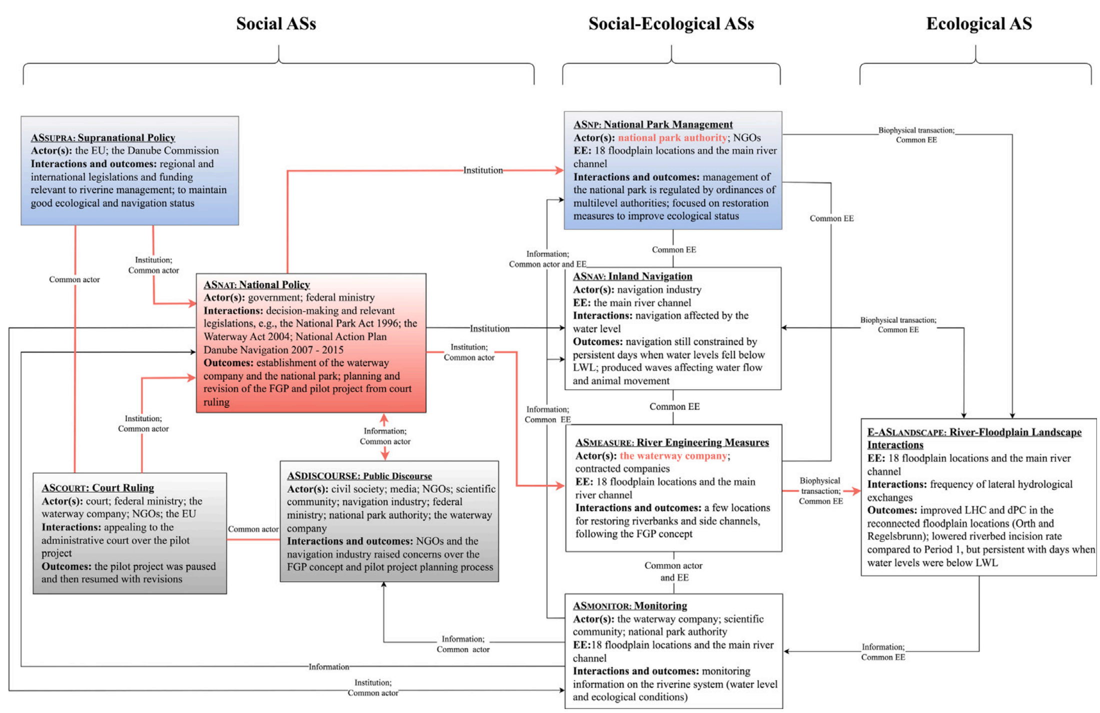
3.2.2. Period 2: A new phase with aligned policy goals but disputes over project planning

The SE-AS network in Period 2 (Fig. 6b) emerged as an outcome of the key dynamics described for Period 1. Specifically, the Donau-Auen National Park in the river-floodplain area was established (National Park Act, 1996) about a decade after the environmental movement. This introduced an additional SE-AS (AS_{NP}), including measures of



(a) Period 1

Fig. 6. The networks of linked SE-ASs for Period 1 (a), Period 2 (b), Period 3 (c). Each box represents an AS, including the involved social actors and/or ecological entities, their interactions, and outcomes. Situations are linked directly via information, institutions, biophysical transactions, or indirectly when sharing a common actor or ecological entity (Kimmich, 2013). S-ASs, SE-ASs, and the E-AS are positioned on the left, middle, and right, respectively. Color highlights: red-shadowed boxes indicate drivers; gray-shadowed boxes indicate reactions to the drivers; and blue-shadowed boxes indicate newly created situations. Key AS dynamics for each period are highlighted with red-colored AS linkages.

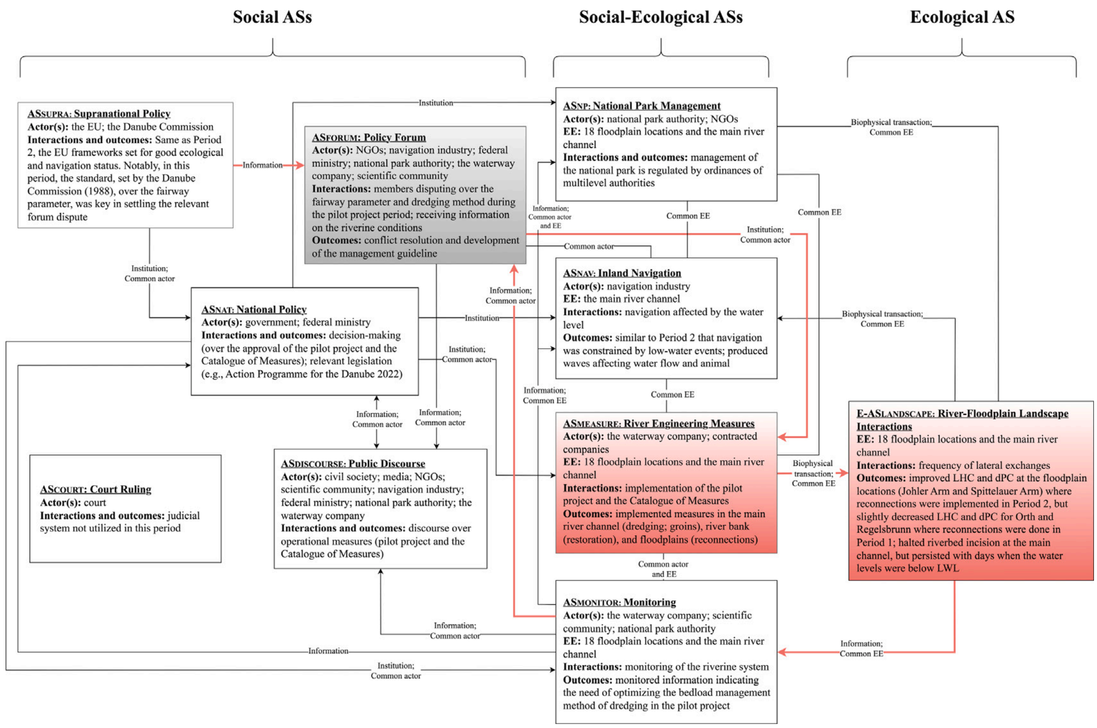


(b) Period 2

Fig. 6. (*continued*).

riverbank restoration and side channel reconnection, aiming to promote nature conservation (E-AS). The ecological analysis shows that floodplain locations where restorations were implemented (Orth in 2002 and Regelsbrunn in 1998) had increased LHC and dPC compared to the previous period (Fig. 3). The water level analysis indicated a reduction in the riverbed incision rate since 1996 (Fig. 4), although days of water levels below LWL persisted (Fig. 5). Extreme climate events, such as the drought of 2003, may explain the fluctuations in water levels (Habersack et al., 2013; Scholten and Rothstein, 2017).

Furthermore, to comply with national park regulations, a new FGP concept (Section 2.2) was developed and reflected in the planning of the pilot project in the early 2000s. Operational tasks fell under the jurisdiction of the waterway company, a limited liability company established and owned by the federal government. The company is responsible for waterway management, regulated under the Aus-



(c) Period 3

Fig. 6. (*continued*).

trian Waterway Act (2004). Consequently, both the national park and the waterway company become key actors, playing leading roles in multiple SE-ASs ($AS_{MEASURE}$, AS_{NP}, and $AS_{MONITOR}$).

Austria's EU membership formed another key institutional context for Period 2, which introduced EU-level legislation influencing riverine management. This is represented in the network by the addition of one other S-AS, supranational policy-making (AS_{SUPRA}). This situation produced institutional outcomes, such as the Water Framework Directive (Council of the European Communities, 2000), the Habitat Directive (Council of the European Communities, 1992), and the Trans-European Network for Transportation (TEN-T) (Council of the European Communities, 2013). These pieces of EU legislation aimed to maintain "good ecological status" and "good navigation status", directly influencing rules and operations in Austria. The FGP concept was consistent with EU policy goals in promoting multifaceted interests. Overall, decision-making capacities among the set of S-ASs and SE-ASs remained with state-owned public organizations, though they shifted from the federal ministry to the waterway company and the national park.

The emergent SE-AS network in Period 2 triggered a set of reactions. Both the FGP and pilot project planning were criticized and opposed by environmental NGOs and navigation industry, as found in policy briefings and media coverage ($AS_{DISCOURSE}$). Concerns were raised about the lack of involvement of nongovernmental actors in project-planning processes. Environmental NGOs further highlighted issues such as insufficient transparency, inaccessible information, and deficiencies in large-scale project planning. These actors then appealed to the administrative court and the European Commission, alleging violations of legislation due to the absence of an environmental impact assessment (AS_{COURT}). In 2011, the state of Lower Austria ruled the pilot project incompatible with the National Park Act (1996). In response, the ministry and the waterway company revised the pilot project and later regained the permit from the state.

In summary, a more complex governance network emerged in Period 2 as a result of the dynamic changes identified in Period 1. It introduced nature conservation into riverine management in the formal decision-making space. New actors – the waterway company and national park authorities – took charge of operational activities, implementing a new set of river restoration measures. Two key sets of governance dynamics were identified in the reconfigured SE-AS network in Period 2. First, the direct impact of the implemented river measures on E-AS led to improvements in nature conservation (higher LHC and dPC for floodplain areas with reconnection measures). Despite a reduced riverbed incision rate, there were still limits on navigation during low-water events. Second, we observed similar S-ASs dynamics as in Period 1, with judicial and discursive actions taken in response to policymaking and limited access to formal decision-making processes. Notably, the involvement of both the private sector (navigation industry) and civil society (environmental NGOs) signaled the emergence of a broader coalition between the two policy groups.

3.2.3. Period 3: Conflict resolution in a policy forum, where scientific knowledge and monitoring information matter

The SE-AS network in Period 3 (Fig. 6c) evolved from the dynamics described in Period 2. A policy forum (AS_{FORUM}) was created to support the implementation of the revised pilot project, initiated by the environmental NGOs and established with support from the waterway company. The forum consisted of actors from the private sector (the navigation company, a fishing organization), the public sector (federal ministry, the national park), and civil society (environmental NGOs). The waterway company was in charge of the implementation of the pilot project and the coordination of the policy forum. Operationally, $AS_{MEASURE}$ marked the implementation of the revised pilot project within the Bad Deutsch-Altenburg riverine area. In line with the FGP concept (Section 2.2), the pilot project included ecological restoration measures (e.g., reconnection of the Johler Arm; riverbank restoration) and riverbed stabilization methods (e.g., gravel additions with coarser material, dredging activity, groin constructions).

Key dynamics started from stakeholder conflicts within the AS_{FORUM}, particularly over the waterway parameter and the river stabilization methods. First, navigation actors advocated for maintaining a minimum water depth of 2.8 meters at LWL to promote navigability. This position was opposed by environmental NGOs, who argued that maintaining such depth would require more intensive river engineering, e.g., constructing longer groins, which could exacerbate riverbed incision and disconnect floodplains. They also pointed out that the international standard has set the minimum water depth of 2.5 meters at LWL, which should likewise apply to the Austrian Danube (Danube Commission, 1988) (AS_{SUPRA}). Secondly, both NGOs and navigation actors raised concerns over the riverbed stabilization method of the dredging introduced by the waterway company. It aimed to reduce erosion by transporting larger-than-usual gravel upstream. Criticisms were raised on the potential risks of large gravel to vessel safety and the lack of a detailed assessment prior to the method's implementation.

Interviews with forum members holding different positions shed light on the conflict resolution process. We found that this process was largely facilitated by learning within the forum (AS_{FORUM}), supported by active engagement, inter-sectoral communication, and the dissemination of monitoring information ($AS_{MONITOR}$) on riverine outcomes (E-$AS_{LANDSCAPE}$). First, the forum provided a platform that supported communication between the two otherwise disconnected policy groups, namely the navigation sector and environmental NGOs. They negotiated the fairway condition, particularly the minimum water depth to be maintained, a decision with potential trade-offs between navigation and nature conservation. Over time, this exchange fostered a consensus on the need to secure multifaceted policy goals. The legal status of the national park, guaranteed by the National Park Act (1996), ensured the prioritization of nature conservation. NGOs, for their part, pointed out the necessity of proactively bridging knowledge gaps despite their limited organizational capacity. Second, monitoring data, produced and distributed by the waterway company and the scientific community entrusted by the forum, revealed the need for an optimization of the dredging method. These findings also prompted critical reflections on the FGP approach, which had focused on large-scale measures without sufficiently considering more adaptive planning, implementation, and integrative monitoring.

Insights gained from this conflict resolution process were formalized in a management guideline co-developed by forum members. The guideline directly informed the development of the Catalog of Measures, a set of river engineering measures revised from the pilot project, which was implemented from 2017 throughout the whole river-floodplain area ($AS_{MEASURE}$). The paradigm of "learning from the river" and "let the river do the work", in contrast to "fighting against water and control the flood", was explicitly articulated in the guideline (AS_{FORUM}). Key institutional and operational adjustments included: (1) agreement on maintaining the minimum water depth of 2.5 meters (down from 2.8 m) at LWL; (2) shifting to smaller and step-by-step projects, supported by adaptive planning and scientific inputs; (3) optimizing dredging with a longer transport distance and using smaller and natural-size gravel for additions; (4) adjusting groin constructions to minimize its ecological impacts. Furthermore, restoration measures continued in other riverine areas.

The E-AS analysis revealed positive ecological outcomes in the newly connected floodplain areas (Johler Arm in 2014 and Spittelauer Arm in 2019), which were found with higher LHC and dPC in Period 3 compared to Period 2 (Fig. 3). However, a slight decrease in LHC and dPC was found at Orth and Regelsbrunn in Period 3 compared to Period 2. Connections were implemented in the two floodplain areas in the late 1990s and early 2000s. The results indicate that, despite a reduced incision rate compared to the pre-national park period (as shown in Fig. 4), historical river regulation measures may continue to exert long-term negative effects by driving ongoing riverbed incision. Similar to Period 2, days of water levels below LWL persisted, limiting inland navigation in Period 3 (Fig. 5).

Overall, the SE-AS network in Period 3 demonstrates a governance shift from judicial and discursive reactions towards participatory conflict resolution. Key network dynamics in this period were captured in the configuration linking the E-AS, SE-$AS_{MEASURE}$, SE-$AS_{MONITOR}$, and S-AS_{FORUM}. Specifically, monitoring information and scientific knowledge were mobilized by the forum to guide institutional and operational adjustments, which in turn shaped biophysical dynamics. Notably, while court rulings (AS_{COURT}) were instrumental in shaping governance trajectories in both Periods 1 and 2, they were not actively utilized in Period 3. Nevertheless, their presence demonstrated the potential institutional arrangements accessible to non-governmental actors.

4. Discussion

4.1. Network dynamics over time

This study adopts a dynamic perspective of the SE-AS framework (Schlüter et al., 2019) to examine governance changes in a riverine system along the Austrian Danube across three periods. The dynamic perspective – tracing the sequence of social-biophysical drivers, responses, and outcomes – is grounded in systems thinking, which emphasizes that new problems arise due to solutions to the old problems (Senge, 1990). It provides an operationalizable analytical lens to examine social–ecological feedback pathways that underpin longer-term governance changes (Baldwin et al., 2023b).

We highlight several key dynamics identified within and across the SE-AS networks. First, new actors (e.g., the national park authority; the waterway company) and ASs (e.g., national park management and the policy forum) may emerge as outcomes of SE-AS dynamics in previous periods. This provides insights into conceptualizing temporal linkages between ASs, supplementing the existing typology predominantly focused on a single governance period (Kimmich, 2013; McGinnis, 2011). Second, situations may exist but not be utilized in the network, for example, the inactive court rulings (S-AS) in Period 3. Third, while SE-AS configurations may appear structurally consistent over time, it is crucial to examine internal changes within an AS (e.g., entry or exit of actors, positions, and choices of actors) or the nature of AS linkages, which could contribute to explaining governance changes.

Important questions remain regarding why certain network dynamics emerged. For instance, in resolving conflicts over constructing the HPP (S-AS), why were the legal and discursive actions employed? Would the outcomes of these situations have always led to the observed institutional changes in the national legislation and the establishment of the national park? Analytic history and narrative approaches to counterfactual analysis (Levy, 2015; Mahoney and Barrenechea, 2019; Kimmich, 2016), as well as comparative studies across other riverine governance settings, could provide a valuable empirical basis for examining whether, and under what conditions, certain network structures are more or less likely to emerge within specific governance systems. Our analytical process could also be refined by conducting another round of stakeholder interviews after constructing the initial SE-AS networks in Step 3 (Section 2.3.1), explicitly inviting participants to reflect on the emergence of particular responses to pressures.

This paper employed a qualitative perspective to explore the temporal development of governance networks. Future research could benefit from a quantitative analysis of the temporal development of these networks, utilizing formalized tools and concepts from network and connectivity science, which has also been identified as a research gap in NAS research (Kimmich et al., 2022). We propose several directions for future investigation. For instance, different types of relationships between and among the two node sets – ASs and actors – could be organized into a multimode network. Applying multimode motif analysis would allow researchers to quantify the emergence and frequency of recurring structural patterns over time. Centrality measures could help identify influential actors or situations—those occupying key structural positions within the network. Moreover, the concepts of structural and functional connectivity could be applied to quantify the direct and indirect influences of one node on another; and to examine whether and how the network structure co-evolves with its dynamics over time (Turnbull et al., 2018; Voutsa et al., 2021). This approach could be fruitful as we discovered rather different network structures and dynamics in the three governance periods.

4.2. Rule-structured situations in the SE-AS framework

The SE-AS framework (Schlüter et al., 2019) distinguishes three types of ASs, depending on the involved social and/or ecological entities, their interactions, and human-made or ecological rules. Ostrom's conceptualization of ASs recognizes biophysical systems and units in shaping decisions and choices. The role of various biophysical variables has been well-documented in many appropriation and provision situations of the CPR governance (Ostrom, 1990; Ostrom et al., 1994; Ostrom, 2005; Kimmich, 2013). We propose that the SE-AS typology corresponds closely with Ostrom's operational-level ASs, whereas the S-AS typology aligns with collective-choice and constitutional-level ASs. For the latter, interactions and outcomes occur within social space and are structured by human-constructed rules, among other contextual factors.

A key novelty of the SE-AS framework is its explicit consideration of ecological dynamics (captured as the E-AS) and their interplay with human actions. Both E-ASs and SE-ASs account are shaped by biophysical rules, addressing the "missing ecology" in the IAD framework (Epstein et al., 2013). While rooted in resilience thinking (DeBoer et al., 2024; Biggs et al., 2015), the SE-AS framework also supports rule-based reasoning, facilitating the diagnosis of both human-constructed and ecological rules that structure multi-level social, ecological, and social–ecological interactions in SES governance.

The key biophysical rule in our case is the extent of hydrological connectivity between the main channel and adjacent floodplain areas, which generates trade-offs between maintaining water depth for navigation in the main channel and sustaining habitat connectivity within the riverine system. For instance, concentrating water in the main channel via measures like groin construction can secure navigation depth but disconnect floodplains and cause habitat degradation. Side-arm reconnections enhance hydrological and habitat connectivity but divert more water to floodplains, thus reducing navigation depth during low-discharge periods. Our analysis shows how this biophysical rule shaped E-AS outcomes for navigation and conservation, and informed governance debates on fairway parameters and engineering measures.

4.3. Integrating ecological dynamics into institutional analysis

The IAD framework captures how governance contexts affect decision-making, with produced outcome feedbacking into these contexts and decision-making. This dynamic perspective has been extended in NAS and PG approaches, which examine feedback pathways among governance outcomes, contextual conditions, and linked decision-making processes over a longer time (Cole et al., 2019; Baldwin et al., 2023b). In these approaches, the biophysical system is often treated as one of the contextual factors that influence or are influenced by decision-making processes and outcomes. However, this may overlook the internal dynamics and interdependencies within the biophysical system itself, which can be critical for explaining complex SES phenomena. For instance, in the case of the Baltic Sea cod population collapse, ecological interactions – namely competition and predation dynamics between cod and sprat – played a crucial role, alongside social drivers such as market and policy, in explaining the regime shift (Schlüter et al., 2019). Considering that, the SE-AS framework explicitly incorporates these ecological dynamics, allowing researchers to go beyond merely tracking changes in biophysical variables or outcomes. This study builds on the longer-term dynamic perspective introduced in earlier works and extends it through the SE-AS framework. Specifically, we embedded key biophysical processes and outcomes into the E-AS and traced their dynamic interactions with other decision-making processes in driving changes to the SE-AS networks.

We suggest that delineating the E-AS provides an entry point for integrating ecological dynamics into governance analysis (Section 2.3.1). The interdisciplinary lens helps identify key biophysical processes that are in two-way relationships with human actions. In other words, the E-AS indicators serve to link biophysical dynamics with operational activities that are embedded in the broader SE-AS network. In this study, the two E-AS outcome measures, HC and navigability, are strongly influenced by historical and ongoing river engineering measures, with navigability further determining navigation capacity. This understanding informed the delineation of river engineering measures and navigation as two key SE-ASs, together with their biophysical linkages to the E-AS.

In addition to identifying biophysically linked SE-ASs and the E-AS, the SE-AS framework also facilitates the analysis of their interactions with S-ASs. This provides a structured way to explore the coupling between social and ecological systems (Fischer et al., 2015; Folke et al., 2016). Our analysis uncovered two key forms of interdependence. First, across all three governance periods, the ecological (HC) and environmental (navigability) analysis reveal the direct impacts of operational activities on the riverine system, demonstrating how quickly the riverine system responds to human actions. Second, we observe key network dynamics involving all three AS typologies in driving governance changes. In Periods 1 and 3, for example, monitoring information about the riverine system resulting from operational activities informed decision-making processes in relevant S-ASs. These include discourse, court ruling, and policymaking in Period 1, and the policy forum in Period 3. These dynamics produced institutional outcomes that, in turn, affected operational activities and, subsequently, the E-AS. These findings illustrate two interrelated insights into social–ecological coupling by applying the SE-AS framework: (1) the capacity to trace bidirectional relations between SE-ASs and the E-AS, and (2) the ability to analyze how institutional changes within S-ASs emerge in response to, and feed back into, ongoing social–ecological interactions.

4.4. Extensions on the ecological complexity and governance data

While the preceding discussion has highlighted key patterns of social-biophysical interdependence in driving governance changes, further analysis of biophysical dynamics could enhance the explanation of the riverbed incision phenomenon. Our findings reveal a slight decrease of LHC and dPC, reflecting reduced hydrological and habitat connectivity, in two floodplain locations (Orth and Regelsbrunn) during Period 3 compared to Period 2 (Section 3.2.3). The LWL analysis shows a similar trend, with continued deepening of the riverbed in the main river channel, albeit at a slower rate. These results suggest persistent riverbed incision, likely attributable to the historical river regulation measures, despite the implementation of bedload-related management in a later period. Recent hydrology research has pointed to climate change as a potential contributing factor to this trend (Klasz and Baumgartner, 2024). Following the SE-AS framework, an extension of this research would involve investigating the role of climate change or other biophysical processes, along with their interaction with the riverine landscape processes and operational activities, in contributing to the observed incision issue.

Moreover, we acknowledge the limitation in the availability of longer-term social data for analyzing governance changes over an extended period. In this study, archival data and the knowledge of two coauthors facilitated the identification of key events and activities, allowing us to establish a governance timeline. Survey and interview data were collected to gain deeper insight into these decision-making processes. Although we interviewed policy actors with extensive knowledge and longer-term involvement in managing the study area, data on past decision-making, particularly from the period preceding the establishment of the national park more than two decades ago, remain limited. As a result, our dataset contains more detailed accounts of governance processes in the latter two periods.

4.5. Processes of conflict resolution

Our findings revealed that the governance system has evolved, its structure and function becoming more complex and polycentric over time. The governance changes were largely mobilized around the process of conflict resolution (García et al., 2019) between governmental and nongovernmental actors, resulting in major changes in institutions, actors' participation, and management paradigms (Pahl-Wostl, 2006). In Periods 1 and 2, problems primarily revolved around the S-AS of policymaking, concerning the framing of policy goals and decision-making process. Reactions from civil society (and the private sector in Period 2) led to the following: first, to the reframing of policy goals (shifting from regulated rivers for human and economic benefits to promoting the multifunctionality of the riverine system); and second, to the adoption of participatory decision-making processes. In Period 3, conflicts shifted from the collective-choice level (S-ASs) to the operational-level activities (SE-ASs). Over time, a participatory and adaptive governance system with aligned policy goals emerged.

Within all periods, the dynamics in resolving conflicts occurred within the S-ASs, though the processes differed. Conflicts over policymaking were addressed through discursive and legal actions taken by nongovernmental actors. This observation resonates with the finding of an earlier study highlighting the role of a reliable court system in creating incentives for productive collective action in the case of international aid development (Ostrom et al., 2002). In contrast, conflicts over operational activities were largely resolved due to a new knowledge base generated from the monitoring data, as well as trust established and learning facilitated through participation in the policy forum (Wenger, 1998; Folke et al., 2005). Notably, establishing the policy forum in Period 3 was an outcome of conflict resolution in Period 2. This finding may be explained by the multilevel learning process (Pahl-Wostl, 2009; Pahl-Wostl et al., 2013), with a more careful examination of the learning processes in tackling different types of conflicts over time.

5. Conclusion

In this study, we employed a dynamic analysis centered on the SE-AS analytical framework (Schlüter et al., 2019) to study the governance changes in the river-floodplain area along a 48 km stretch of the Danube east of Vienna, Austria, over the past four decades. Building on previous research examining longer-term governance changes through the NAS and PG approaches, this study extends it in two ways. First, it integrates ecological interactions and dynamics as action situations, rather than contextual factors, within the SE-AS governance network. This perspective helped reveal several key forms of social-biophysical interdependence that drive governance changes. A crucial analytical step was the delineation of the ecological action situation, which drew on interdisciplinary knowledge to identify key biophysical processes and their connections with operational activities. A promising extension of this study would be to assess whether, and how, other key biophysical dynamics (e.g., climate change, highlighted in recent hydrological research) and their interactions with social–institutional processes might explain the persistent incision phenomenon, as well as the capacity of the evolving governance system to address this ongoing challenge. Second, by focusing on the sequence and interplay of social-biophysical drivers, responses, and outcomes, this study offers an operationalizable lens for examining the dynamic processes underlying longer-term governance changes (Baldwin et al., 2023b; Cole et al., 2019). However, understanding the emergence of key network dynamics requires an extension of the methods to study dynamic NAS. The analytic history and narrative approach for counterfactuals analysis, as well as comparative case study methods, could help to trace, understand, and corroborate causal mechanisms that explain dynamic NAS.

CRediT authorship contribution statement

Yanhua Shi: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Sonia Steffany Recinos Brizuela:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization; same contribution as the first author. **Thomas Hein:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Andrea Funk:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Christian Kimmich:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Thomas Hein and Andrea Funk report financial support was provided by via donau Österreichische Wasserstraßen-Gesellschaft mbH (under the IREP project). Other authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.jenvman.2025.127662.

Data availability

Data will be made available on request.

References

Andersson, K.P., Ostrom, E., 2008. Analyzing decentralized resource regimes from a polycentric perspective. Policy Sci. 41 (1), 71–93. http://dx.doi.org/10.1007/s11077-007-9055-6.

Angst, M., Mewhirter, J., McLaughlin, D., Fischer, M., 2022. Who joins a forum—And who does not?—Evaluating drivers of forum participation in polycentric governance systems. Public Adm. Rev. 82 (4), 692–707. http://dx.doi.org/10.1111/puar.1342.

Baldwin, E., McLaughlin, D.M., Jasso, V., Woods, D., Breshears, D.D., López-Hoffman, L., Soto, J.R., Swann, A., Lien, A., 2023a. Diverse stakeholders and their interests matter to the U.S. forest service: a network of action situations analysis of how stakeholders affect forest plan outcomes. Sustain. Sci. 18 (1), 27–42. http://dx.doi.org/10.1007/s11625-022-01173-4.

Baldwin, E., Tang, T., 2021. Hierarchies, markets, and collaborative networks in energy governance: Multilevel drivers of renewable energy deployment. J. Env. Manag. 290, 112614. http://dx.doi.org/10.1016/j.jenvman.2021.112614.

Baldwin, E., Thiel, A., McGinnis, M., Kellner, E., 2023b. Empirical research on polycentric governance: Critical gaps and a framework for studying long-term change. Policy Stud. J. 00 (0), 1–30. http://dx.doi.org/10.1111/psj.12518.

Baudoin, L., Gittins, J.R., 2021. The ecological outcomes of collaborative governance in large river basins: Who is in the room and does it matter? J. Env. Manag. 281, 111836. http://dx.doi.org/10.1016/j.jenvman.2020.111836.

Biggs, R., Schlüter, M., Schoon, M.L. (Eds.), 2015. Principles for Building Resilience: Sustaining Ecosystem Services in Social-Ecological Systems. Cambridge University Press, Cambridge.

Bodin, Ö., Alexander, S.M., Baggio, J., Barnes, M.L., Berardo, R., Cumming, G.S., Dee, L.E., Fischer, A.P., Fischer, M., Mancilla Garcia, M., Guerrero, A.M., Hileman, J., Ingold, K., Matous, P., Morrison, T.H., Nohrstedt, D., Pittman, J., Robins, G., Sayles, J.S., 2019. Improving network approaches to the study of complex social–ecological interdependencies. Nat Sustain. 2 (7), 551–559. http://dx.doi.org/10.1038/s41893-019-0308-0, URL https://www.nature.com/articles/s41893-019-0308-0. Number: 7 Publisher: Nature Publishing Group.

Bodin, Ö., Saura, S., 2010. Ranking individual habitat patches as connectivity providers: Integrating network analysis and patch removal experiments. Ecol. Model. 221 (19), 2393–2405. http://dx.doi.org/10.1016/j.ecolmodel.2010.06.017.

Bondar-Kunze, E., Dittrich, A.-L., Gmeiner, P., Liedermann, M., Hein, T., 2024. The effect of ship-induced wave trains on periphytic algal communities in the littoral zone of a large regulated river (river danube, Austria). Sci. Total Environ. 954, 176068. http://dx.doi.org/10.1016/j.scitotenv.2024.176068.

Brondizio, E.S., Ostrom, E., Young, O.R., 2009. Connectivity and the governance of multilevel social-ecological systems: The role of social capital. Annu. Rev. Env. Resour. 34 (1), 253–278. http://dx.doi.org/10.1146/annurev.environ.020708.100707.

Bundesstrombauamt, 1951. Die kennzeichnenden Wasserstände der österreichischen Donau – KWD-1949. Technical Report, Bundesstrombauamt.

Bundesstrombauamt, 1959. Die kennzeichnenden Wasserstände der österreichischen Donau – KWD-1956. Technical Report, Bundesstrombauamt.

Bundesstrombauamt, 1970. Die kennzeichnenden Wasserstände der österreichischen Donau – KWD-1970. Technical Report, Bundesstrombauamt.

Bundesstrombauamt, 1978. Die kennzeichnenden Wasserstände der österreichischen Donau – KWD-1976. Technical Report, Bundesstrombauamt.

Carlisle, K.M., Gruby, R.L., 2018. Why the path to polycentricity matters: evidence from fisheries governance in Palau. Env. Policy Gov. 28 (4), 223–235. http://dx.doi.org/10.1002/eet.1811.

Carlisle, K., Gruby, R.L., 2019. Polycentric systems of governance: A theoretical model for the commons. Policy Stud. J. 47 (4), 927–952. http://dx.doi.org/10.1111/psj.12212.

Cole, D.H., Epstein, G., McGinnis, M.D., 2019. The utility of combining the IAD and SES frameworks. Int. J. Commons 13 (1), 244–275, URL https://www.jstor.org/stable/26632720.

Danube Commission, 1988. Recommendations on Minimum Requirements for Standard Fairway Parameters, Hydrotechnical and Other Improvements on the Danube. Technical Report, Danube Commission (Donaukommission), Budapest, Hungary, Minimum fairway depth of 2.5 m below Low Navigation and Regulation Level (LNRL) – standard applied to free-flowing sections of the Danube.

DeBoer, J.A., Thoms, M.C., Delong, M.D., 2024. Chapter 10 - The anthropocene: Rivers and resilience. In: Thoms, M., Fuller, I. (Eds.), Resilience and Riverine Landscapes. Elsevier, pp. 209–228. http://dx.doi.org/10.1016/B978-0-323-91716-2.00028-5.

Delaroche, M., Dias, V.M.A., Massoca, P.E., 2022. The intertemporal governance challenges of Brazil's Amazon: managing soybean expansion, deforestation rates, and urban floods. Sustain. Sci. 18, 43–58. http://dx.doi.org/10.1007/s11625-022-01149-4.

Epstein, G., Vogt, J.M., Mincey, S.K., Cox, M., Fischer, B., 2013. Missing ecology: integrating ecological perspectives with the social-ecological system framework. Int. J. Commons 7 (2), 432–453, URL https://www.jstor.org/stable/26523137.

Council of the European Communities, 1992. Council directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora. pp. 7–50, URL http://data.europa.eu/eli/dir/1992/43/oj/eng. Official Journal of European Communities, L206.

Council of the European Communities, 2000. Directive 2000/60/EC of the European parliament and of the council of 23 October 2000 establishing a framework for community action in the field of water policy. pp. 1–72, URL http://data.europa.eu/eli/dir/2000/60/oj/eng. Official Journal of European Communities, L137.

Council of the European Communities, 2013. Regulation (EU) no 1315/2013 of the European parliament and of the council of 11 December 2013 on union guidelines for the development of the trans-European transport network and repealing decision no 661/2010/EU text with EEA relevance. pp. 1–128, URL http://data.europa.eu/eli/reg/2013/1315/oj. Official Journal of European Communities, L348.

Fischer, J., Gardner, T.A., Bennett, E.M., Balvanera, P., Biggs, R., Carpenter, S., Daw, T., Folke, C., Hill, R., Hughes, T.P., Luthe, T., Maass, M., Meacham, M., Norström, A.V., Peterson, G., Queiroz, C., Seppelt, R., Spierenburg, M., Tenhunen, J., 2015. Advancing sustainability through mainstreaming a social–ecological systems perspective. Open Issue, Curr. Opin. Env. Sustain. Open Issue, 14, 144–149.http://dx.doi.org/10.1016/j.cosust.2015.06.002,

Folke, C., Biggs, R., Norström, A.V., Reyers, B., Rockström, J., 2016. Social-ecological resilience and biosphere-based sustainability science. Ecol. Soc. 21 (3), URL https://www.jstor.org/stable/26269981.

Folke, C., Hahn, T., Olsson, P., Norberg, J., 2005. Adaptive governance of social-ecological systems. Annu. Rev. Env. Resour. 30, 441–473. http://dx.doi.org/10.1146/annurev.energy.30.050504.144511.

Funk, A., Baldan, D., Bondar-Kunze, E., Brizuela, S.R., Kowal, J., Hein, T., 2023. Connectivity as a driver of river-floodplain functioning: A dynamic, graph theoretic approach. Ecol. Indic. 154, 110877. http://dx.doi.org/10.1016/j.ecolind.2023.110877.

Funk, A., Gschöpf, C., Blaschke, A.P., Weigelhofer, G., Reckendorfer, W., 2013. Ecological niche models for the evaluation of management options in an urban floodplain—conservation vs. restoration purposes. Env. Sci. Policy 34, 79–91. http://dx.doi.org/10.1016/j.envsci.2012.08.011.

Funk, A., Tschikof, M., Grüner, B., Böck, K., Hein, T., Bondar-Kunze, E., 2021. Analysing the potential to restore the multi-functionality of floodplain systems by considering ecosystem service quality, quantity and trade-offs. River Res. Appl. 37 (2), 221–232. http://dx.doi.org/10.1002/rra.3662.

García, M.M., Hileman, J., Bodin, Ö., 2019. Collaboration and conflict in complex water governance systems across a development gradient: addressing common challenges and solutions. Ecol. Soc. 24 (3), URL https://www.jstor.org/stable/26796968.

Gritsenko, D., 2018. Explaining choices in energy infrastructure development as a network of adjacent action situations: The case of LNG in the Baltic sea region. Energy Policy 112, 74–83. http://dx.doi.org/10.1016/j.enpol.2017.10.014.

Gunderson, L.B.A.C., Chaffin, B.C., Arnold, C.A.T., Fremier, A.K., Garmestani, A.S., Craig, R.K., Gosnell, H., Birge, H.E., Allen, C.R., Benson, M.H., Morrison, R.R., Stone, M.C., Hamm, J.A., Nemec, K., Schlager, E., Llewellyn, D., 2017. Regime shifts and panarchies in regional scale social-ecological water systems. Ecol. Soc. 22 (1), http://dx.doi.org/10.5751/ES-08879-220131.

Gutschik, R., Horvath, P., Weinzierl, R., 2007. Konflikte um infrastrukturprojekte in österreich: Erkenntnisse für politik und gesellschaft. SWS-Rundsch. 47 (2), 218–242, URL https://nbn-resolving.org/urn:nbn:de:0168-ssoar-164569.

Habersack, H., Jäger, E., Hauer, C., 2013. The status of the Danube River sediment regime and morphology as a basis for future basin management. Int. J. River Basin Manag. 11 (2), 153–166. http://dx.doi.org/10.1080/15715124.2013.815191.

Hein, T., Blaschke, A.P., Haidvogl, G., Hohensinner, S., Kucera-Hirzinger, V., Preiner, S., Reiter, K., Schuh, B., Weigelhofer, G., Zsuffa, I., 2006. Optimised management strategies for the biosphere reserve Lobau, Austria - based on a multi criteria decision support system. Ecohydrol. Hydrobiol. 6 (1), 25–36. http://dx.doi.org/10.1016/S1642-3593(06)70123-9.

Hein, T., Hauer, C., Schmid, M., Stöglehner, G., Stumpp, C., Ertl, T., Graf, W., Habersack, H., Haidvogl, G., Hood-Novotny, R., Laaha, G., Langergraber, G., Muhar, S., Schmid, E., Schmidt-Kloiber, A., Schmutz, S., Schulz, K., Weigelhofer, G., Winiwarter, V., Baldan, D., Canet-Marti, A., Eder, M., Flödl, P., Kearney, K., Ondiek, R., Pucher, B., Pucher, M., Simperler, L., Tschikof, M., Wang, C., 2021. The coupled socio-ecohydrological evolution of river systems: Towards an integrative perspective of river systems in the 21st century. Sci. Total Environ. 801, 149619. http://dx.doi.org/10.1016/j.scitotenv.2021.149619.

Hein, T., Schwarz, U., Habersack, H., Nichersu, I., Preiner, S., Willby, N., Weigelhofer, G., 2016. Current status and restoration options for floodplains along the Danube river. Sci. Total Environ. 543, 778–790. http://dx.doi.org/10.1016/j.scitotenv.2015.09.073.

Herzog, L., Tanguay, L., Beisner, B.E., Pahl-Wostl, C., Audet, R., Schlüter, M., 2022. Studying human-nature relations in aquatic social-ecological systems using the social-ecological action situations framework: how to move from empirical data to conceptual models. Ecol. Soc. 27 (3), http://dx.doi.org/10.5751/ES-13268-270307.

Wasserstandsnachrichten und Hochwasserprognosen, 2024. Messstellendaten (translation: Measurement point data). URL https://www.noel.gv.at/wasserstand/#/de/Messstellen/Details/207274/Wasserstand/Jahr. (Accessed 22 May 2024).

Wasserstandsnachrichten und Hochwasserprognosen, 2025. Erläuterungen (translation: Explanations). URL https://www.noel.gv.at/wasserstand/#/de/Static/Erlauterungen/2. (Accessed 10 August 2025).

Kellner, E., 2023. Identifying leverage points for shifting water-energy-food nexus cases towards sustainability through the networks of action situations approach combined with systems thinking. Sustain. Sci. 18 (1), 135–152. http://dx.doi.org/10.1007/s11625-022-01170-7.

Kellner, E., Martin, D.A., 2023. Learning from past coevolutionary processes to envision sustainable futures: Extending an action situations approach to the water-energy-food nexus. Earth Syst. Gov. 15, 100168. http://dx.doi.org/10.1016/j.esg.2023.100168.

Kimmich, C., 2013. Linking action situations: Coordination, conflicts, and evolution in electricity provision for irrigation in Andhra pradesh, India. Ecol. Econ. 90, 150–158. http://dx.doi.org/10.1016/j.ecolecon.2013.03.017.

Kimmich, C., 2016. Can analytic narrative inform policy change? The political economy of the Indian electricity–irrigation nexus. J. Dev. Stud. 52 (2), 269–285, Publisher: Routledge _eprint: https://doi.org/10.1080/00220388.2015.1093119.

Kimmich, C., Baldwin, E., Kellner, E., Oberlack, C., Villamayor-Tomas, S., 2022. Networks of action situations: a systematic review of empirical research. Sustain. Sci. 18, 11–26. http://dx.doi.org/10.1007/s11625-022-01121-2.

Kimmich, C., Sagebiel, J., 2016. Empowering irrigation: A game-theoretic approach to electricity utilization in Indian agriculture. Util. Policy 43, 174–185. http://dx.doi.org/10.1016/j.jup.2016.10.002.

Kimmich, C., Villamayor-Tomas, S., 2019. Assessing action situation networks: A configurational perspective on water and energy governance in irrigation systems. Water Econ. Policy 05 (01), 1850005. http://dx.doi.org/10.1142/S2382624X18500054.

Klasz, G., Baumgartner, C., 2024. Trends bei wasserständen und mittleren abflüssen in der donau östlich von wien und donaunahen grundwasserständen: Starke effekte durch sohlerosion und klimawandel. Österr. Wasser- Abfallwirtsch. http://dx.doi.org/10.1007/s00506-024-01090-z.

Klasz, G., Reckendorfer, W., Baumgartner, C., Gabriel, H., Gutknecht, D., 2013. River-bed degradation and overbank deposition: A human induced geomorphic disequilibrium in the Donau-Auen National Park. In: 5th Symposium for Research in Protected Areas. Mittersill, pp. 379–384, URL https://www.zobodat.at/pdf/NP-Hohe-Tauern-Conference_5_0379-0384.pdf. Conference Volume.

Levy, J.S., 2015. Counterfactuals, causal inference, and historical analysis. Secur. Stud. 24 (3), 378–402, Publisher: Routledge _eprint: https://doi.org/10.1080/09636412.2015.1070602.

Lubell, M., 2013. Governing institutional complexity: The ecology of games framework. Policy Stud. J. 41 (3), 537–559. http://dx.doi.org/10.1111/psj.12028.

Lubell, M., Morrison, T.H., 2021. Institutional navigation for polycentric sustainability governance. Nat. Sustain. 4 (8), 664–671. http://dx.doi.org/10.1038/s41893-021-00707-5.

Lubell, M., Robins, G., Wang, P., 2014. Network structure and institutional complexity in an ecology of water management games. Ecol. Soc. 19 (4), URL https://www.jstor.org/stable/26269667.

Mahoney, J., Barrenechea, R., 2019. The logic of counterfactual analysis in case-study explanation. Br. J. Sociol. 70 (1), 306–338, URL https://onlinelibrary.wiley.com/doi/abs/10.1111/1468-4446.12340. _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1111/1468-4446.12340.

McGinnis, M.D., 2011. Networks of adjacent action situations in polycentric governance. Policy Stud. J. 39 (1), 51–78. http://dx.doi.org/10.1111/j.1541-0072.2010.00396.x.

McGinnis, M.D., Ostrom, E., 2012. Reflections on Vincent Ostrom, public administration, and polycentricity. Public Adm. Rev. 72 (1), 15–25, URL https://www.jstor.org/stable/41433139.

Méndez, P.F., Clement, F., Palau-Salvador, G., Diaz-Delgado, R., Villamayor-Tomas, S., 2022. Understanding the governance of sustainability pathways: hydraulic megaprojects, social–ecological traps, and power in networks of action situations. Sustain. Sci. 18, 303–321. http://dx.doi.org/10.1007/s11625-022-01258-0.

Möck, M., Vogeler, C.S., Bandelow, N.C., Schröder, B., 2019. Layering action situations to integrate spatial scales, resource linkages, and change over time: The case of groundwater management in agricultural hubs in Germany. Policy Stud. J. 50, 111–142. http://dx.doi.org/10.1111/psj.12377.

Morrison, T., 2017. Evolving polycentric governance of the Great Barrier Reef. Proc. Natl. Acad. Sci. USA 114 (15), E3013–E3021. http://dx.doi.org/10.1073/pnas.1620830114.

National Park Act, 1996. Federal act on the establishment of and participation in the national park corporation Donau-Auen GmbH (in German: Bundesgesetz über die Gründung und Beteiligung an der Nationalparkgesellschaft Donau-Auen GmbH.). URL https://www.ris.bka.gv.at/Dokumente/BgblPdf/1996_653_0/1996_653_0.pdf.

Orach, K., Schlüter, M., 2021. Understanding the dynamics of fish politics: The role of diverse actor interactions in transformations towards co-management. Env. Sci. Policy 124, 195–205. http://dx.doi.org/10.1016/j.envsci.2021.06.010.

Ostrom, E., 1990. Governing the commons: the evolution of institutions for collective action. In: Political Economy of Institutions and Decisions, Cambridge University Press, Cambridge.

Ostrom, E., 2005. Understanding Institutional Diversity. Princeton University Press, Princeton NJ.

Ostrom, E., 2010. Polycentric systems for coping with collective action and global environmental change. Glob. Env. Chang. 20 (4), 550–557. http://dx.doi.org/10.1016/j.gloenvcha.2010.07.004.

Ostrom, E., 2011. Background on the institutional analysis and development framework. Policy Stud. J. 39 (1), 7–27. http://dx.doi.org/10.1111/j.1541-0072.2010.00394.x.

Ostrom, E., Gardner, R., Walker, J., Walker, J., 1994. Rules, Games, and Common-pool Resources. University of Michigan Press.

Ostrom, E., Gibson, C., Shivakumar, S., Andersson, K., 2002. Aid, incentives, and sustainability: an institutional analysis of development cooperation. Sida Studies in Evaluation.

Ostrom, V., Tiebout, C.M., Warren, R., 1961. The organization of government in metropolitan areas: A theoretical inquiry. Am. Polit. Sci. Rev. 55 (4), 831–842. http://dx.doi.org/10.2307/1952530.

Pahl-Wostl, C., 2006. The importance of social learning in restoring the multifunctionality of rivers and floodplains. Ecol. Soc. 11 (1), URL https://www.jstor.org/stable/26267781.

Pahl-Wostl, C., 2009. A conceptual framework for analysing adaptive capacity and multi-level learning processes in resource governance regimes. Glob. Env. Chang. 19 (3), 354–365. http://dx.doi.org/10.1016/j.gloenvcha.2009.06.001.

Pahl-Wostl, C., Becker, G., Knieper, C., Sendzimir, J., 2013. How multilevel societal learning processes facilitate transformative change: A comparative case study analysis on flood management. Ecol. Soc. 18 (4), art58, URL https://www.jstor.org/stable/26269425.

Pahl-Wostl, C., Sendzimir, J., Jeffrey, P., Aerts, J., Berkamp, G., Cross, K., 2007. Managing change toward adaptive water management through social learning. Ecol. Soc. 12 (2), URL https://www.jstor.org/stable/26267877.

Poeppl, R.E., Keesstra, S.D., Maroulis, J., 2017. A conceptual connectivity framework for understanding geomorphic change in human-impacted fluvial systems. Geomorphology 277, 237–250. http://dx.doi.org/10.1016/j.geomorph.2016.07.033.

Reckendorfer, W., Baranyi, C., Funk, A., Schiemer, F., 2006. Floodplain restoration by reinforcing hydrological connectivity: expected effects on aquatic mollusc communities. J. Appl. Ecol. 43 (3), 474–484. http://dx.doi.org/10.1111/j.1365-2664.2006.01155.x.

Reckendorfer, W., Funk, A., Gschöpf, C., Hein, T., Schiemer, F., 2013. Aquatic ecosystem functions of an isolated floodplain and their implications for flood retention and management. J. Appl. Ecol. 50 (1), 119–128. http://dx.doi.org/10.1111/1365-2664.12029.

Reckendorfer, W., Schmalfuß, R., Baumgartner, C., Habersack, H., Hohensinner, S., Jungwurth, M., Schiemer, F., 2005. The integrated river engineering project for the free-flowing Danube in the Austrian Alluvial Zone National Park: contradictory goals and mutual solutions. Large Rivers 15 (1-4), 613–630. http://dx.doi.org/10.1127/lr/15/2003/613.

Saura, S., Estreguil, C., Mouton, C., Rodríguez-Freire, M., 2011. Network analysis to assess landscape connectivity trends: Application to European forests (1990–2000). Ecol. Indic. 11 (2), 407–416. http://dx.doi.org/10.1016/j.ecolind.2010.06.011.

Saura, S., Pascual-Hortal, L., 2007. A new habitat availability index to integrate connectivity in landscape conservation planning: Comparison with existing indices and application to a case study. Landsc. Urban Plan. 83 (2–3), 91–103. http://dx.doi.org/10.1016/j.landurbplan.2007.03.005.

Schiemer, F., Baumgartner, C., Tockner, K., 1999. Restoration of floodplain rivers: The ’Danube restoration project’. Regul. Rivers Res. Manag. 15 (1–3), 231–244. http://dx.doi.org/10.1002/(SICI)1099-1646(199901/06)15:1/3<231::AID-RRR548>3.0.CO;2-5.

Schiemer, F., Hein, T., Reckendorfer, W., 2007. Ecohydrology, key-concept for large river restoration. Ecohydrol. Hydrobiol. 7 (2), 101–111. http://dx.doi.org/10.1016/S1642-3593(07)70176-3.

Schlüter, M., Haider, L., Lade, S., Lindkvist, E., Martin, R., Orach, K., Wijermans, N., Folke, C., 2019. Capturing emergent phenomena in social-ecological systems: an analytical framework. Ecol. Soc. 24 (3), http://dx.doi.org/10.5751/ES-11012-240311.

Scholten, A., Rothstein, B., 2017. Navigation on the Danube - Limitations by low water levels and their impacts. Technical Report EUR 28374 EN, Luxembourg (Luxembourg): Publications Office of the European Union, URL https://publications.jrc.ec.europa.eu/repository/handle/JRC104224.

Sendzimir, J., Flachner, Z., Pahl-Wostl, C., Knieper, C., 2010. Stalled regime transition in the upper Tisza river basin: the dynamics of linked action situations. Env. Sci. Policy 13 (7), 604–619. http://dx.doi.org/10.1016/j.envsci.2010.09.005.

Senge, P.M., 1990. The Fifth Discipline : the Art and Practice of the Learning Organization. Doubleday/Currency, New York.

Srigiri, S.R., Dombrowsky, I., 2022. Analysing the water-energy-food nexus from a polycentric governance perspective: Conceptual and methodological framework. Front. Env. Sci. 10, 725116. http://dx.doi.org/10.3389/fenvs.2022.725116.

Tan, R., Xiong, C., Kimmich, C., 2023. An agent-situation-based model for networked action situations: Cap-and-trade land policies in China. Land Use Policy 131, 106743. http://dx.doi.org/10.1016/j.landusepol.2023.106743, URL https://www.sciencedirect.com/science/article/pii/S0264837723002090.

Thiel, A., 2016. The Polycentricity Approach and the Research Challenges Confronting Environmental Governance. Humboldt-Universität zu Berlin, IRI THESys, pp. 1–27, THESys Discussion Paper No. 2016-1. URL https://edoc.hu-berlin.de/handle/18452/3784.

Tögel, R., Baumgartner, C., 2016. Pilotprojekt bad deutsch-altenburg – projektmotivation, maßnahmen, prozessbeteiligung. Österr. Wasser- Abfallwirtsch. 5–6 (68), 193–198. http://dx.doi.org/10.1007/s00506-016-0314-7.

Tschikof, M., Stammel, B., Weigelhofer, G., Bondar-Kunze, E., Costea, G., Pusch, M., Srdević, Z., Benka, P., Vizi, D.B., Borgs, T., Hein, T., 2024. Cross-scale and integrative prioritization of multi-functionality in large river floodplains. J. Env. Manag. 358, 120899. http://dx.doi.org/10.1016/j.jenvman.2024.120899.

Turnbull, L., Hütt, M.-T., Ioannides, A.A., Kininmonth, S., Poeppl, R., Tockner, K., Bracken, L.J., Keesstra, S., Liu, L., Masselink, R., Parsons, A.J., 2018. Connectivity and complex systems: learning from a multi-disciplinary perspective. Appl. Netw. Sci. 3 (1), 11. http://dx.doi.org/10.1007/s41109-018-0067-2.

viadonau, 2012. Die kennzeichnenden Wasserstände der österreichischen Donau (KWD 2010). Technical Report, viadonau Österreichische Wasserstraßen-Gesellschaft mbH Wien.

viadonau, 2018. Catalogue of measures for the Danube to the east of Vienna. URL https://www.viadonau.org/fileadmin/user_upload/FGP_Masznahmenkatalog_EN_small.pdf. (Accessed 22 May 2024).

viadonau, 2020. Die kennzeichnenden Wasserstände der österreichischen Donau (KWD 2020). Technical Report, viadonau Österreichische Wasserstraßen-Gesellschaft mbH Wien.

viadonau, 2024. Implementation status. URL https://www.viadonau.org/en/company/project-database/integrated-river-engineering-project-catalogue-of-measures/implementation-status-1. (Accessed 22 May 2024).

Villamayor-Tomas, S., Grundmann, P., Epstein, G., Evans, T., Kimmich, C., 2015. The water-energy-food security nexus through the lenses of the value chain and the institutional analysis and development frameworks. Water Altern. 8 (1), 735–755, URL https://www.water-alternatives.org/index.php/alldoc/articles/vol8/v8issue1/274-a8-1-7/file?auid=1133.

Voutsa, V., Battaglia, D., Bracken, L.J., Brovelli, A., Costescu, J., Díaz Muñoz, M., Fath, B.D., Funk, A., Guirro, M., Hein, T., Kerschner, C., Kimmich, C., Lima, V., Messé, A., Parsons, A.J., Perez, J., Pöppl, R., Prell, C., Recinos, S., Shi, Y., Tiwari, S., Turnbull, L., Wainwright, J., Waxenecker, H., Hütt, M.T., 2021. Two classes of functional connectivity in dynamical processes in networks. J. R. Soc. Interface 18 (183), 20210486. http://dx.doi.org/10.1098/rsif.2021.0486.

Wasserstraßendirektion, 1986. Die kennzeichnenden Wasserstände der österreichischen Donau – KWD-1985. Technical Report, Wasserstraßendirektion.

Wasserstraßendirektion, 1998. Die kennzeichnenden Wasserstände der österreichischen Donau – KWD-1996. Technical Report, Wasserstraßendirektion.

Waterway Act, 2004. Federal act on mission and organization of the federal waterway administration (in German: Bundesgesetz über die Gründung und Beteiligung an der Nationalparkgesellschaft Donau-Auen GmbH). URL https://www.ris.bka.gv.at/Dokumente/BgblAuth/BGBLA_2004_I_177/BGBLA_2004_I_177.pdfsig.

Wenger, E., 1998. Communities of Practice: Learning, Meaning, and Identity. Cambridge University Press, Cambridge, UK.