sustainability

MDPI

Review

Management of Global Warming Effects in the European Water Framework Directive: Consideration of Social–Ecological System Features in the Elbe River Basin District

Eva Sievers [1,*], Christoph Zielhofer [2] and Frank Hüesker [3]

[1] Institute of Environmental Sciences (CML), Leiden University, 2311 EZ Leiden, The Netherlands
[2] Institute of Geography, Leipzig University, 04103 Leipzig, Germany; zielhofer@uni-leipzig.de
[3] Department of Environmental Politics, Helmholtz-Centre for Environmental Research, UFZ, 04318 Leipzig, Germany; frank.hueesker@ufz.de
* Correspondence: e.m.sievers@umail.leidenuniv.nl

Abstract: In this study, we examined the extent to which global warming management is currently integrated into the European Water Framework Directive (WFD), the central legal framework for water management in the EU. We focused on the Elbe River Basin District and how global warming is addressed in its water management. We used the social–ecological systems (SES) approach as our theoretical framework, representing an eminent analytical frame of biosphere-based sustainability science. In our study, we analysed core characteristics of SES in the context of global warming to evaluate the effectiveness of current water management in the Elbe River basin concerning long-term changing climate conditions. To determine to what extent each SES feature is considered in the Elbe water management, we applied a scale of 1 to 5. Our results show that the SES feature "scale and openness" is best addressed (score 4.0) by the Elbe River basin management, followed by "context dependency" (score 3.9); however, "non-linearity, uncertainty, unpredictability" (score 3.2), "self-organisation and adaptability" (score 3.1), and "dynamics" (score 3.0) have only moderate impacts. SES features can only be considered comprehensively if global warming is accounted for in an integrated way at a European level. In order to ensure effective implementation, explicit regulations and legally binding obligations are most likely required.

Keywords: social–ecological systems approach; EU Water Framework Directive; global warming; Elbe River; climate change adaptation; water management; river basin management; adaptive water resource management; European water governance

check for updates

Citation: Sievers, E.; Zielhofer, C.; Hüesker, F. Management of Global Warming Effects in the European Water Framework Directive: Consideration of Social–Ecological System Features in the Elbe River Basin District. *Sustainability* **2021**, *13*, 9111. https://doi.org/10.3390/su13169111

Academic Editors: Vincenzo Torretta and Elena Rada

Received: 12 July 2021
Accepted: 10 August 2021
Published: 14 August 2021

1. Introduction

Due to the current state of global warming, it is critical, and more important than ever, to take steps to reduce the rate of climate change in order to secure a "safe operating space for humanity" [1]. In Europe, the fifth IPCC Assessment Report indicates a temperature increase throughout all climate regions of Europe if the current warming rate continues [2], likely reaching a 1.5 °C increase compared to pre-industrial levels between 2030 and 2052 [3]. To make projections on anthropogenic greenhouse gas (GHG) emissions, the IPCC adopted four Representative Concentration Pathways (RCPs), which describe different emission scenarios for the 21st century. RCP2.6 outlines a stringent mitigation pathway, requiring GHG emissions to start declining by 2020 [4]. RCP4.5 and RCP6 represent two intermediate pathways, and RCP8.5, the most pessimistic scenario, represents the worst-case climate change scenario, including very high GHG emissions [5]. Depending on the scenario, the global mean temperature will rise by at least 0.3 °C (RCP2.6) to 4.8 °C (RCP8.5) by the end of the 21st century due to increasing GHG emissions [4]. Projections show significant increases in high-temperature extremes and the frequency and intensity of heat waves, drought periods, and heavy precipitation events, subjecting water management to a broad range of changes [6].

New approaches for sustainable development in consonance with planetary boundaries are urgently needed [7]. In this context, biosphere-based sustainability science has emerged as a new research field, providing new analytical concepts, such as the social–ecological systems (SES) framework [8]. The SES approach has evolved into an eminent analytical frame to address pressing questions of future development, resilience, and long-term sustainability [9].

To protect and manage European water resources, EU policy has established the Directive 2000/60/EC, the European Water Framework Directive (WFD), in 2000 [10]. It aims to reconcile the national water policies of EU Member States and establish a coherent legal framework at a European level [11]. River Basin Districts (RBD) following natural geographical river basins and related River Basin Management Plans (RBMP) were drawn up to effectively meet water management needs at smaller scales [12]. The WFD is regarded as the most ambitious and significant piece of European environmental legislation [13]. It requires promoting sustainable water use, minimising pressures on water bodies, preventing further pollution, and mitigating floods and droughts [10]. A WFD Fitness Check Evaluation, carried out in 2019, highlights that the directive has successfully prevented water body deterioration but has not fully achieved its ecological and chemical objectives [12]. Assuming that water use and protection conflicts originate from natural or technical obstacles and have political, social, and cultural dimensions, the integrated water resources management paradigm is thus firmly established in the WFD [14,15]. The river basin approach, which allows comprehensive and transboundary water management at the river basin level, was a new concept introduced into EU policy [12]. As RBDs are responsible for implementing the WFD, significant differences concerning the application of integrated water resources management still exist.

When the WFD was adopted and entered into force in 2000, global warming and its consequences had not been put on the main agenda as potential threats to European water bodies—this highlights the missing awareness of climate-change-related threats at the end of the 1990s [12,16]. In context of the WFD Common Implementation Strategy (CIS), Guidance Document No. 24 “River Basin Management in a Changing Climate” was published in 2009. The intention behind the document was to guide the EU Member States in integrating global warming and climate variability into water policy [17]. Since the second river basin management cycle started in 2015, European Member States agreed that “climate-related threats and adaptation planning should be incorporated in their RBMPs” [18] (p. 271). Although only a recommendation, this indicates a shift in problem awareness, showing that global warming threats have gained more attention in recent years [12]. To quantify and visualise global warming-induced changes, especially on a smaller scale, regional climate models and sets of climate models are increasingly being used [19,20]. Due to their high resolution, regional climate models can capture complex physiographical features and spatial variability [19]. Although uncertainties regarding the prediction accuracy still exist, for example, concerning the ability to represent the temporal variability of precipitation time series [21], regional climate models represent an efficient tool to conduct hydrological analyses on a river basin scale, such as future precipitation, runoff scenarios, or flood risk assessments [19,20]. According to the WFD Fitness Check Evaluation, the WFD generally contributes to managing global warming challenges in the EU by restoring water bodies, regularly reviewing measures and progress, and implementing natural retention measures [12]. Although the WFD is considered legally able to deal with emerging issues such as climate change due to its flexible nature, the WFD Fitness Check states that this is not sufficient for counteracting the effects in total [12]. In the evaluation report, the authors argue that concerns about global warming do not necessarily result in practical action, and mitigation and adaptation planning are not yet covered in a completely integrated way. Furthermore, the authors state that the reference conditions of the WFD do not sufficiently consider global warming effects, as they are not explicitly mentioned as a threat or defined as an objective. Additionally, water scarcity remains poorly covered, as indirect measures are often ineffective, and monitoring is considered insufficient [12]. Regarding coherence, the WFD Fitness Check concludes that stakeholders see climate change as the least-coherent subject within WFD legislation [12]. Although most Member States have successfully carried out a "climate-proofing" of the Programme of Measures by applying the CIS Guidance Document No. 24, climate change adaptation cannot be fully pursued due to a failure to integrate global warming effects into WFD evaluations [12]. According to the European Overview of River Basin Management Plans, most RBDs consider flood risk management, assess direct and indirect climate pressures, and address drought management and water scarcity [18]. Nevertheless, drought management plans do not always correspond to the actual drought risk faced in practice [18]. In summary, the report positively evaluates the WFD's high flexibility in combatting global warming effects. Nonetheless, it cannot address climate change sufficiently, especially when it comes to practical action, coherence with other objectives, and drought management [18].

The aim of this review study was to assess the effectiveness of global warming management within the WFD. To this end, we applied the SES approach to the Elbe RBD following the conceptual "typology of six organising principles" by Preiser et al. [22]. We applied six distinctive SES features to this study: 1. "scale and openness"; 2. "context dependency"; 3. "self-organisation and adaptability"; 4. "non-linearity, uncertainty, unpredictability"; 5. "dynamics"; and 6. "constituted relationally". To evaluate the extent to which each SES feature is considered in the water management of the Elbe River basin, we will address the following research question: With regard to global warming, to what extent does water management in the Elbe River Basin District take features of social–ecological systems into consideration?

2. Theoretical Framework

Social–ecological researchers investigate the dynamic interactions between humans and the environment using both social and natural sciences and are interested in the interface between science, politics, the economy, and the public [23]. As human activity is an increasing pressure on ecosystems and has major impacts on their functioning, a clear distinction between social and natural systems is arbitrary [24]. The SES approach emphasises this intertwined character and supports that environmental preconditions shape social dimensions (economy, politics, technology, culture, etc.). Vice versa, natural systems (terrestrial and aquatic ecosystems) are impacted by human activities [8]; therefore, mutual interaction on different spatial and temporal scales is the consequence (Figure 1) [25].

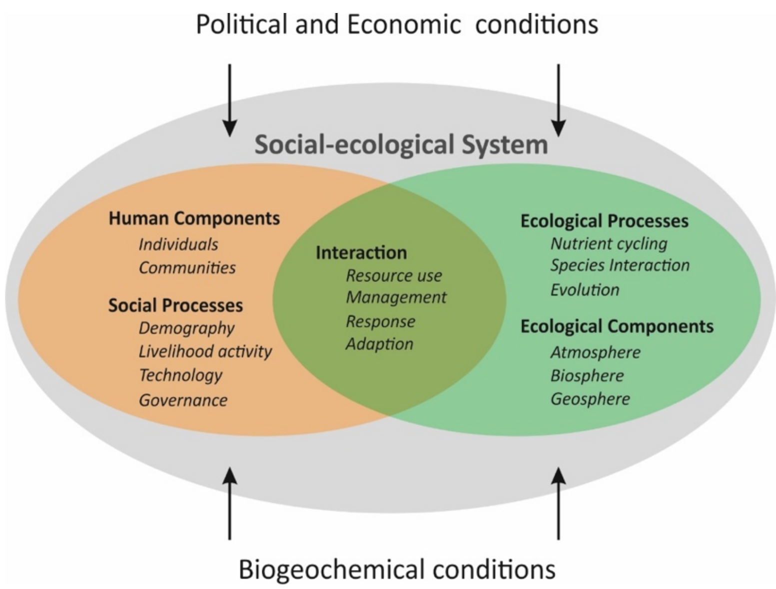

Figure 1. Depiction of a social–ecological system.

The SES approach evolved from biosphere-based sustainability science, which marks the stability and resilience of the biosphere as a crucial precondition for human wellbeing [8]. The SES approach emerged as a prominent "conceptual and analytical framing with which to understand the connections and feedbacks between social and environmental interactions" [9] (p. 1). It emphasises human dependency on ecosystems, supports cross-disciplinary collaboration, and allows researchers to understand systems [7,26]. Finally, increased system knowledge contributes to an acceptable way of managing resources towards resilience and long-term sustainability [27].

Our study orientates at the "typology of six organising principles" accounting for key features of SES, according to the heuristic SES framework established by Preiser et al. [22]. To apply this conceptual typology to the Elbe River basin case study, we adjusted and harmonised the types, or the name of the types, for our research purposes; however, the overall structure is preserved. As such, the six relevant characteristic features of SES for this study are 1. "scale and openness"; 2. "context dependency"; 3. "self-organisation and adaptability"; 4. "non-linearity, uncertainty, unpredictability"; 5. "dynamics"; and 6. "constituted relationally". Properties and requirements associated with specific features are explained in detail in Section 5, at the beginning of each feature's section.

3. Methodological Approach

We reviewed key publications to determine how the WFD in general, and the Elbe RBD in particular, address global warming. We focused on publications of the European Commission and the Elbe River Basin Cooperation, including the WFD [10], the Overview on River Basin Management Plans [18], the WFD Fitness Check Evaluation [12], the River Basin Management Plan for the German part of the river basin [28], the German Programme of Measures [29], and the German background document on climate change effects [30]. Finally, we considered the International River Basin Management Plan for the Elbe RBD [31].

In order to gain further insights into the interface between SES theory and WFD in the context of global warming, we conducted four guided expert interviews [32–35]. Bernd Klauer is deputy head of the Department of Economics at the Helmholtz-Centre for Environmental Research (UFZ, Leipzig, Germany). For many years he has been engaged in social–ecological approaches in environmental and resource economics concerning sustainability and the valuation of nature [36–38]. Moritz Reese is deputy head of the Department of Environmental and Planning Law at the Helmholtz-Centre for Environmental Research (UFZ, Leipzig, Germany). His research focuses on European environmental law, water law, and climate change and adaptation [16,37,39–41]. Laura Herzog is a political scientist working at the Institute of Environmental Systems Research at Osnabrück University. She works on the dynamics of SES and the influence of climate change and land use on aquatic ecosystem services [42,43]. Finally, Christine Wolf is a former member of the Department of Economics and the Department of Environmental Politics at the Helmholtz-Centre for Environmental Research (UFZ, Leipzig, Germany). In her doctoral thesis, she analysed water bodies as SES, integrating the effects of global warming to improve the methods used to evaluate the ecological status of water bodies [44–48]. The interviews were conducted via video call and were recorded and transcribed afterwards (clean verbatim).

To evaluate SES features in Elbe River basin management, we conducted a semi-quantitative assessment for each feature in table form; therefore, we applied a rating scale of 1–5 with a score of 5 indicating full consideration of feature properties, and a score of 1 displaying very limited consideration. We derived the feature properties in the table from Preiser et al. [22], De Vos et al. [9], Berkes et al. [7], and the expert interviews conducted [32–35].

4. The Elbe River Basin District

Since practical management of global warming impacts occurs in RBDs, the analysis of SES features must also occur in RBDs; therefore, we selected one RBD to assess the features.

The choice fell on the Elbe RBD, because it is one of the largest European river basins crossing national borders and representing a transport route of significant international importance. Moreover, the effects of global warming are diverse due to the significant variability between areas along the river's course, including sub-basins with high flood risk and sub-basins with low annual precipitation, potentially facing enhanced drought risk (Figure 2).

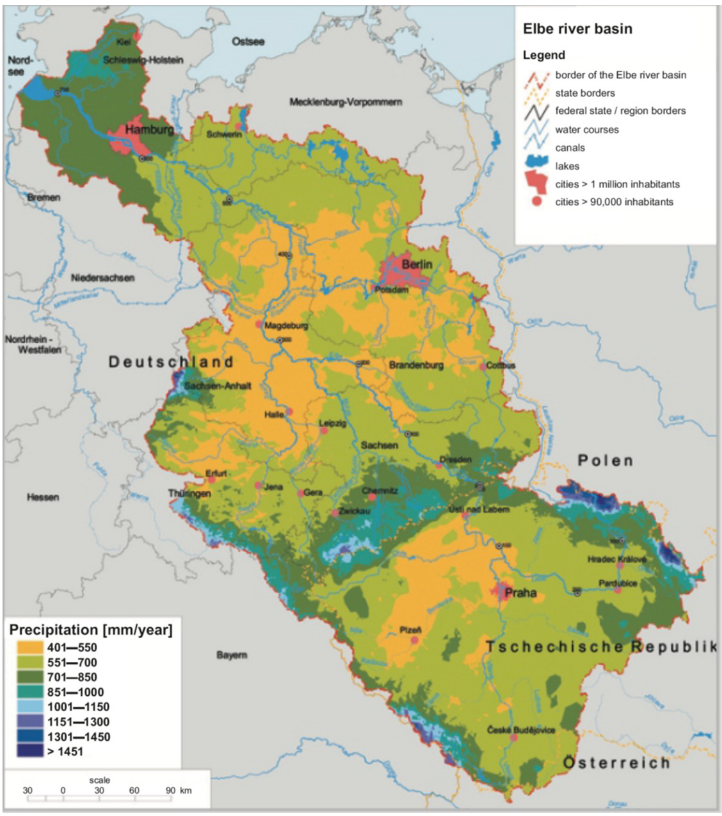

Figure 2. Average annual precipitation in the Elbe River basin for the 1961–1990 series (Source: BfG, ČHMÚ, ICPER).

Furthermore, the GLOWA Elbe research project, which started in 2000, investigated global change effects on the environment and society in the Elbe RBD [32]. Due to the long project duration, and the "pioneering" character concerning global change impacts, the Elbe River basin features a significant projection and modelling database—this provides a favourable starting point for us to assess SES features in the Elbe RBD.

The Elbe is located 1386 m above sea level, rises in the Krkonoše mountains (Czech Republic), and flows for 1094 km, near Cuxhaven (Germany) into the North Sea (Figure 2). The Elbe River basin is part of the temperate climate (Koeppen: Cfb). It is located in the transition zone from the humid oceanic climate of Western Europe and the dry continental climate of Central and Eastern Europe [28]. The river has peak discharges in spring. Furthermore, heavy summer precipitation events can pose a major flood risk, as observed during the Elbe floods of 2002 and 2013 [28]. The river basin covers 148,000 km^2, where 65.54% is located in Germany, 33.68% in the Czech Republic, and two smaller shares are located in Austria (0.62%) and Poland (0.16%). About 25 million people live in the Elbe RBD [31].

In the Elbe River basin, the effects of global warming will be marked by an increase in annual mean air temperature, more frequent and intensified extreme weather events, and changes in seasonal precipitation, i.e., minor increases in winter precipitation (less than 10% by 2050) and medium decreases in summer precipitation [30]. These changes will most likely affect water supply, groundwater resources and recharge, soil water balance, surface runoff, nutrient loads, flow dynamics, hydromorphological conditions, water storage, and flood risk in the Elbe RBD [28].

5. Results and Discussion

For each SES feature, we present the results in separate sections. Each section starts with a detailed explanation of feature properties, followed by an elaboration on the feature's role in the context of the WFD and global warming. Subsequently, the analysis specifically for the Elbe RBD follows. It starts with a section covering aspects of the Elbe River basin management that successfully consider respective SES feature properties, followed by a section indicating areas where the consideration is still insufficient. Finally, we present the scores of the semi-quantitative assessment, summarising how feature properties were considered.

5.1. Social–Ecological System Feature 1: "Scale and Openness"

5.1.1. "Scale and Openness": Feature Properties

SES are hierarchically structured, incorporating sub-systems embedded in larger systems, and act on different levels of spatial and temporal *scale.* Furthermore, SES are characterised both by internal exchange and by external interaction between the system and its environment [22,49]. This applies to institutions, since local institutions are nested in national and international institutions, as well as to natural systems, since local water systems are embedded in larger river systems [7]. Defining a system's spatial and temporal boundaries can be difficult, owing to the radical *openness* and influence the system has on its broader environment [22]. Moreover, global feedback loops (e.g., global warming) influence local feedback loops and vice versa [8]. Social–ecological challenges at different temporal and spatial *scales* require adapted solutions that fit the level of scale. Subsequently, there is not one all-encompassing solution [7]; however, institutions often refer to political boundaries and, therefore, to different spatial scales than the scales found in "natural" systems (e.g., river basins). Hence, spatial and temporal *scale* mismatches can occur when dealing with SES [50], which also affects the WFD. In addition to the general understanding of *scale* as "level", *scale* can further be understood in terms of "scope" [34].

5.1.2. "Scale and Openness" in Context of the European Water Framework Directive and Global Warming

The WFD considers multiple spatial *scales* both for the natural and institutional dimension. Looking at the institutional dimension, this is reflected by various administrative scales involved (EU, national, river basin), the clear division of authorities' competences and the opportunity to call in a "higher scale" when necessary [34]. In terms of global warming, this is significant, because the EU level is generally evaluated as being most effective to tackle climate change, but the river basin level is needed to particularly address the changes in practice [12]. Regarding the natural dimension, the river basin approach categorises water bodies after "natural boundaries" and parameters, rather than following administrative boundaries, particularly emphasising the consideration of *scale*. Depending on the scope of the social–ecological challenge faced, different *scales* can be addressed (e.g., local, regional, or transnational), enabling solutions to be adaptable and fit the *scale*. This can be important, for example, in terms of upstream and downstream issues that are likely to become more relevant regarding global warming [35]. However, it remains a challenge to ensure coherence between different *scales* and associated needs [12]. In relation to global warming, *scale* in terms of scope is especially relevant. Global warming is not explicitly mentioned as a pressure in the WFD itself, which is from today's perspective insufficient and not proportionate to fundamentally tackle the resulting impacts [32,34]. So far, global warming is only addressed in a very schematic and cursory way, which is no longer adequate to the *scale* of global warming impacts [33]. In addition, *openness* is mostly given, since Member States have a great scope of action to implement the Directive and assign responsible authorities. Reference conditions are defined in an *open* way, rather than specific measures that are prescribed [34]. Regarding climate change mitigation and adaptation, the scope of action therefore also depends on the degree of problem awareness and political will of each Member State [16]. Moreover, temporal *scales* represent a constant challenge, as climate change adaptation planning often misses the time horizon of WFD requirements, including planning cycles of only six years. Consequently, time lags between political action and delayed ecosystem responses can occur, which may be hard to bridge [35]. Furthermore, the WFD focuses more on water quality than on water quantity issues, indicating that global warming impacts are not considered to their full extent, which represents a constraint on *scale* in terms of scope [32]. According to the WFD Fitness Check, limitations to water scarcity become apparent in terms of monitoring, water use and abstraction, and energy efficiency. Looking at global warming, these limitations will most likely become more significant [18], representing other insufficient consideration of *scale* in terms of scope.

5.1.3. Successful Consideration of "Scale and Openness" in the Elbe River Basin Management

The hierarchically structured planning frame applied in the Elbe River basin is well equipped to consider both internal exchange between sub-systems and effects outside the systems' boundaries, representing the core properties of *scale*. For example, the trade-offs between flood protection, ecology, population and economic growth, and the possible effects of global warming are taken into account [28]—this also includes many anticipated consequences regarding different water body types and adaptation areas, for example, wastewater treatment, drinking water supply, and flood risk management [31]. *Openness* and impacts across *scales* are accounted for because local improvements of river continuity, morphology, or a reduction in heat pollution positively affect overarching water bodies' resilience [28]. Conflicts between *scales* (e.g., between overarching national strategies and regional needs) are acknowledged; therefore, an integrated approach should be adopted [28,30]. The distinction between water management questions relevant for the entire Elbe River basin, or questions of regionally high importance, demonstrate that problem-solving addresses different *scales*, and solutions fit the *scale* [31]. For example, locally impacting pressures, or local changes in biodiversity (e.g., invasive species) resulting from increasing water temperatures, can be addressed by adopting regional or case-specific solutions [28]. Finally, the "climate check" of the Programme of Measures is conducted on different planning levels and examines the impact of specific measures, taking local and regional conditions and interactions with other measures into consideration [28].

5.1.4. Insufficient Consideration of "Scale and Openness" in the Elbe River Basin Management

Although competing water uses are acknowledged, conflicts between *scales* are not entirely covered by the Elbe River basin management. For example, if superordinate strategies, such as national energy or biomass strategies are to be implemented, which result in increasing needs for agricultural irrigation, local water scarcity situations may erupt [30]. Thus, in the future, tensions may particularly arise between objectives of water protection, agriculture, energy supply, and flood protection [30,31]. These conflicts can easily be amplified by reduced overall water availability, which is caused by decreased summer precipitation due to global warming. Therefore, ensuring the coherence of objectives and sector-specific needs while taking various *cross-scale* impacts into account still remains challenging.

5.1.5. "Scale and Openness": Semi-Quantitative Assessment

The feature "scale and openness" is best considered by the water management within the Elbe River basin. This is particularly the result of the hierarchical structure of River Basin Management Plans and its corresponding assessment. It is acknowledged that the effects have impact across *scales*, the systems are radically *open*, and the measures need to fit the *scale* to be effective. In the semi-quantitative evaluation, "scale and openness" achieved a total outcome of 4.0 (Table 1).

Table 1. Properties constituting the feature "scale and openness" following the approaches of Berkes et al. [7], Preiser et al. [22], and De Vos et al. [9].

"Scale and Openness" Feature Properties	Score [1]
Hierarchical structure, embedded sub-systems nested in larger systems	5
Internal and external exchange and mutual interactions	4
Effects impacting across scales	5
Application of solutions that fit the scale	5
Radical openness	5
Temporal scale	3
Scale in terms of scope	1
"Scale and openness" total	**4.0**

[1] To evaluate how much each feature property is considered in the Elbe River basin management, we applied an ordinal scale ranging from 1–5, with 5 = very high, 4 = high, 3 = moderate, 2 = low, 1 = very low consideration.

5.2. Social–Ecological System Feature 2: "Context Dependency"

5.2.1. "Context Dependency": Feature Properties

Changes in a system affect both its *context* and its sub-systems. When changing the external environment (e.g., physical environment, policies, economic development, etc.), *context dependency* indicates that the system itself changes because it emerges as a result of *context* and relation. Once *context* has changed, sub-systems reorder—equally, the *context* changes when sub-systems evolve [9,22]. Consequently, the structure of SES comprises two elements: the internal dynamic interactions between systems' compartments and interactions between the SES and the external environment [9]. Berkes et al. [7] state that an isolated examination of an SES is inadequate without considering its context. SES possess a unique *context*, and as a result, multiple *context-dependent* identities exist [27]. As internal and external interactions have equal importance to the system structure, SES are necessarily defined by the *context*; therefore, transformative space should be created to implement systemic change processes [9].

5.2.2. "Context Dependency" in Context of the European Water Framework Directive and Global Warming

According to the analysis, the WFD is generally capable of considering different *contexts*. Concerning water body assessment, Member States have great room to manoeuvre, and RBDs are classified in a *context-dependent* manner [34,35]. Regarding global warming, this is particularly important as its consequences show many different facets depending on geographic conditions. The opportunity to use exemptions and less stringent objectives takes *context-dependent* conditions and occurrences into account [33,35]. Concerning global warming, it remains questionable if, for example, recurring drought periods can still be categorised as "unpredictable" and "surprising", which is required by the WFD to claim for an exemption. When circumstances that were previously seen as exemptions become standard in the face of increasing temperatures, reference conditions need to be adapted for the future [33]. Further limitations are provided regarding the ecological status, as parts of the assessment are rigid and invariable, further indicating a need for adaptation because of increasing temperatures [33,35]. Although *context dependency* plays a central role in assessing water bodies, specific climate impact assessments that recognize the *contexts* of water bodies are rare—this results in limited significance on a regional scale [33]. Following this, if drought management plans exist for certain river basins, they are often not implemented according to the actual, *context*-specific drought risk [32].

5.2.3. Successful Consideration of "Context Dependency" in the Elbe River Basin Management

The Elbe River basin has different *contexts*, which is especially important concerning global warming. For example, adapted and *context-specific* management concepts are applied to areas with particularly low water availability, i.e., Black Elster, Upper Havel, and Spree region [29,30]—this shows that the Elbe River basin generally acknowledges *context* and considers multiple *context-dependent identities* by implementing measures which take into account the local and regional preconditions and pressures. Furthermore, different scales are addressed, and the mutual interactions between measures are recognised [28]. Moreover, the River Basin Management Plan suggests that local improvements of river continuity, morphology, or a reduction in heat pollution have positive effects on the super-ordinate living conditions and the resilience of water bodies. Owing to that, the systems' adaptive capacity for absorbing external shocks (e.g., in hot or dry periods) is higher, so extreme stress situations can be better tolerated [28]. Aiming to develop a coherent planning frame for the Elbe River basin represents an attempt to create transformative space allowing for systemic change processes. Interactions between flood protection, ecology, economy, and global warming effects should be considered, thus enabling transformation [28]. Systems adapting to changes in *context* can be identified, for example, as trans-regional water supplies provide a balance between water surplus and water scarcity regions [30]. As a result of decreasing water availability in summers due to global warming, this balance becomes more relevant.

5.2.4. Insufficient Consideration of "Context Dependency" in the Elbe River Basin Management

Establishing a coherent planning frame for the Elbe River basin can function as a transformative space; however, creating transformative space is neither explicitly formulated as being a deliberate goal, nor are systemic change processes highlighted as being particularly desirable for the Elbe River basin [28]. Furthermore, to fully consider *context dependency*, systems must adapt as soon as conditions of *contextual* change are present; however, flexible adaptation to changing *contexts* is limited if system structures are relatively fixed and rigid—this is the case, for example, with trans-regional water supply and sewage infrastructure comprising long periods of use and requiring expensive maintenance, making it quite inflexible to adapt to evolving *contexts* [30].

5.2.5. "Context Dependency": Semi-Quantitative Assessment

The feature "context dependency" is addressed second-best by the Elbe River basin management—this is due to the high consideration of both the environment and the sub-systems and the recognition of the context to understand a system. In the semi-quantitative assessment, "context dependency" achieved a total score of 3.9 (Table 2).

Table 2. Properties constituting the feature "context dependency" following the approaches of Berkes et al. [7], Preiser et al. [22], and De Vos et al. [9].

"Context Dependency" Feature Properties	Score [1]
Systems depend on both environment and sub-systems	5
No system understanding without recognising the context	5
Multiple context-dependent identities exist	4
Changes inside the system influence both environment and sub-systems	4
System functions adapt to change in context; context change = system change	4
Create transformative spaces for activating systemic change processes	2
System is a result of context and relation	3
"Context dependency" total	**3.9**

[1] To evaluate how much each feature property is considered in the Elbe River basin management, we applied an ordinal scale ranging from 1–5 with 5 = very high, 4 = high, 3 = moderate, 2 = low, 1 = very low consideration.

5.3. Social–Ecological System Feature 3: "Self-Organisation and Adaptability"

5.3.1. "Self-Organisation and Adaptability": Feature Properties

A distinctive feature of SES is their ability to respond to feedbacks and *adapt* over time. Internal and external interactions drive their response. The way system compartments shape the overall structure of SES depends on *self-organising* patterns [22]. These patterns of organisation, emerging as a result of change, provide the system its capacity to *adapt* to altered conditions. To allow for *self-organisation,* transformative space needs to be created, and *adaptive* practices should be implemented to prevent rigid planning [9]. The time lag that occurs via the interaction between human decision making and ecological feedback often makes it difficult to properly consider *adaptation* [51]. The systems' *re-organisation* is path-dependent; considering the history of SES is crucial for an integrated system understanding. The path-dependency of SES ("system memory") contributes to social and institutional learning based on responses to change. Knowledge resulting from co-evolutionary feedback learning is a rich source for improving *adaptation* and should be fostered [7].

5.3.2. "Self-Organisation and Adaptability" in the Context of the European Water Framework Directive and Global Warming

The flexible, quality-orientated, and cyclically evolving river basin approach enables the *adaptation* of management concepts [16,35]. The wide range of evaluation criteria allows for *adapting* to specific preconditions [32]; however, the directive's provisions do not regulate how objectives and reference conditions are to be *adapted* concerning the conditions of climate change. Currently, only a mid-term and concomitant *adaptation* to already noticeable global warming impacts is possible. Nevertheless, including global warming impacts in the assessment, objectives, reference conditions, and planning measures would be required to enable early and cost-efficient *adaptation* for long-term structural decisions [16]. When circumstances make it necessary to claim an exemption, conditions, effects and measures need to be summarised to *adapt* the next river basin management plan. To claim for temporary deterioration, the circumstances must be "exceptional" or "could not reasonably have been foreseen" [10] (Art. 4), which, considering climate change, is relative. When exemptions potentially become the new normal, the evaluation system must be *adapted* [34]—this also requires the WFD to more extensively *adapt* to issues of water quantity, for example, by applying the "good" quantitative status to surface water bodies [32]. Furthermore, providing the autonomy to draw up Programmes of Measures provides space for *self-organisation*; however, the consideration of *self-organisation* and the opportunity to *adapt* to change are quite limited, for example, by principles such as restoring the previous state after an unforeseen external shock. Because of global warming, a system developing towards another stable state could be favourable for *adaptation*; however, this *openness* is not certain [34]. Furthermore, the six-year duration of planning cycles does not meet the requirements for *self-organisation* on an ecological scale and misses the long-term perspective of climate change impacts [35]. The time lag between the institutional and ecological dimensions reflects a common problem of SES management [51]; therefore, the WFD lacks long-term *adaptability*.

5.3.3. Successful Consideration of "Self-Organisation and Adaptability" in the Elbe River Basin Management

The planning frame of the Elbe River basin generally allows for implementing *adaptive* practices, guards against rigid planning, and creates room for *adaptability* and *self-organisation* on the institutional side [28]. For example, due to specific needs for action regarding water scarcity in the Upper Havel, Black Elster, and Spree region, the Programme of Measures can be *adapted*, and additional measures can be applied [28]. Furthermore, it is required to assess whether each measure remains effective under, and *adapts* to, adverse climate change conditions [28]. Facing global warming challenges, flexible responses such as "no-regret" measures (e.g., the creation of reservoirs, attenuation dams, and buffer strips) are prioritised [28]. Nevertheless, more ambitious and far-reaching measures, specifically designed to tackle warming impacts, could improve the consideration of *adaptation and self-organisation*, especially concerning the ecological dimension. By improving the overall health of water bodies, the Elbe River basin management considers path-dependent *self-organisation* to a certain extent. For example, improving river continuity fosters recolonisation after a drought period. Moreover, varying morphological structures provide refuge and facilitate survival under adverse conditions, thus increasing resilience against global warming impacts [28]. Social and institutional learning is largely considered in the Elbe River basin. Hence, emerging issues, such as the quantitative status of groundwater bodies, are to be addressed in the next planning cycle, for example, by developing experience-based concepts for specific groundwater recharge [28]. In addition, the Elbe River Basin Cooperation has created a website with learning and teaching material for schools, with the intent to provide the next generation with climate change-related knowledge [28].

5.3.4. Insufficient Consideration of "Self-Organisation and Adaptability" in the Elbe River Basin Management

Although the Elbe River basin management attempts to allow opportunities for *self-organisation*, it is not made explicit that path-dependency, transformation, or *re-organisation* are fostered, or even considered. While a development towards aquatic ecosystem resilience is classified as important, *self-organisation* itself is not a guiding principle for the ecological part [28]. The International River Basin Management Plan acknowledges that studies on climatic and hydrological trends and investigations into the effects of global warming on discharge regimes clearly indicate the need to pay more attention to water quantity management in the Elbe RBD [31]; however, there is no measure in the Programme of Measures that directly addresses global warming or determines global warming as the main reason for practical action [29].

The lack of practical implementation methods also becomes evident when looking at stakeholder *adaption*. Taking into account climate change impacts in the Elbe River basin is considered crucial for various stakeholders (e.g., municipalities, water companies, water-related industries, etc.) to ensure early *adaptation*; however, no specific provisions on how this is to be achieved are given [30]. *Adaptation* remains on a very theoretical and basic level, which does not appear to be sufficient to address global warming.

5.3.5. "Self-Organisation and Adaptability": Semi-Quantitative Assessment

In water management within the Elbe River basin, "self-organisation and adaptability" is considered the second least important—this is mainly due to the weak consideration of transformative space and *adaptation* to feedback loops on a temporal scale, and the entirely lacking consideration of path-dependent *self-organisation* at tipping points. Consequently, "self-organisation and adaptability" achieved a total outcome of 3.1 in the semi-quantitative assessment (Table 3).

Table 3. Properties constituting the feature "self-organisation and adaptability" following the approaches of Berkes et al. [7], Preiser et al. [22], and De Vos et al. [9].

"Self-Organisation and Adaptability" Feature Properties	Score [1]
Systems contain self-organising principles	4
Transformative space allows opportunity for self-organisation	2
In response to changes in the environment, system behaviour adapts	4
Implementation of adaptive practices, prevention of rigid planning	4
Path-dependent self-organisation at tipping points	1
Adaptation to feedback loops on temporal scale	2
Social and institutional learning through path-dependency	5
"Self-organisation and adaptability" total	**3.1**

[1] To evaluate how much each feature property is considered in the Elbe River basin management, we applied an ordinal scale ranging from 1–5 with 5 = very high, 4 = high, 3 = moderate, 2 = low, 1 = very low consideration.

5.4. Social–Ecological System Feature 4: "Non-Linearity, Uncertainty, Unpredictability"

5.4.1. "Non-Linearity, Uncertainty, Unpredictability": Feature Properties

SES are characterised by emergent properties resulting from strong coupling and interaction between system components, which thus cannot be considered in isolation [7]. *Non-linear* causality and effects incorporated by SES result from emergent properties and complex functioning [22]. For example, outputs of SES can represent inputs, and minor effects might result in huge impacts, and vice versa [9]. Consequently, SES trigger evolution and cannot be traced in linear equations or models due to complex causal pathways [22]. Furthermore, newly constituting emergent properties result in SES consisting of more than the mere sum of their system properties. Owing to that, SES are inherently *unpredictable* and deeply *uncertain* [9]. In virtue of often suddenly and unexpectedly exceeded tipping points, the *predictability* of SES is generally limited [25,52]. Consequently, managing for emergence and fostering flexible responses is favourable [9].

5.4.2. "Non-Linearity, Uncertainty, Unpredictability" in Context of the European Water Framework Directive and Global Warming

The WFD provides the opportunity to claim justified and temporary deterioration, generally acknowledging that *unpredictable* events occur and *uncertainties* exist; however, specifications refer (implicitly) to a distinct cause–effect relationship, such as "hot spell–drought" or "extreme precipitation–flood". The resulting definite correlation between cause and effect does not do justice to the complex functioning and the *non-linear* trajectories that apply to global warming [34]. For example, the assessment of chemical status does not cover interactions between substances and joint effects, which might become more significant in light of global warming [32]. Furthermore, the taxonomic biodiversity approach of the WFD focusing on species composition impedes flexible management for mitigating shocks and addressing unforeseen developments—this allows for internal changes and transformation, but only to a limited extent [33]. Furthermore, this is amplified by the fact that water bodies' resilience is not the main objective of the WFD; thus, *unpredictability* and *uncertainty* can only be taken into account to a limited extent [32]. Hence, the WFD lacks an unambiguous and scientifically determinable state of resilience to enable management for emergence and flexibility [33]. Moreover, to consider *non-linearity* resulting from cross-scale impacting feedback loops, huge time lags can be problematic, especially between implementing measures and visible improvement [35]. Lastly, the WFD does not consider *non-linear* functioning resulting from emergent properties, although this is part of the complexity of climate change—this represents a central shortcoming for the overall consideration of *non-linearity, uncertainty, and unpredictability.*

5.4.3. Successful Consideration of "Non-Linearity, Uncertainty, Unpredictability" in the Elbe River Basin Management

Management plans of the Elbe River basin acknowledge the presence of *uncertainties* regarding the effects of global warming. Thus, measures tolerating ranges of impacts to improve water status regardless of climate development are fostered. Additionally, management options and outcomes are redefined [28]. Adaptation measures are flexible, adjustable, and robust, indicating the possibility of management for the emergence and unexpected outcomes. Overall, water management in the Elbe River basin increases water bodies' health and resilience, and the capacity to absorb *unpredictable* shocks; therefore, it contributes to climate adaptation [28]. To align water management with global warming management in the river basin, a "climate check" of the Programme of Measures is conducted [28]. Due to the significant spatial variation within the Elbe region revealing different facets of global warming that lead to *uncertainty*, differentiated technical solutions need to be applied, such as for water supply and sewage [30]. On account of expecting variability, *non-linear* trajectories are generally anticipated.

5.4.4. Insufficient Consideration of "Non-Linearity, Uncertainty, Unpredictability" in the Elbe River Basin Management

In general, uncertainties are expected; however, there is a need to consider and strengthen the adaptive capacities of natural and social systems in the Elbe region [53]. Among other things, *non-linearity*, *uncertainty,* and *unpredictability* are considered as lacking in scientific knowledge, and the consequences of varying climate projections are recognised. However, *non-linearity, uncertainty, and unpredictability* are neither acknowledged as inherent system properties nor explicitly managed [28,30]. The same applies to emergent properties, thus revealing strong limitations with respect to considering this SES feature in the Elbe River basin.

5.4.5. "Non-Linearity, Uncertainty, Unpredictability": Semi-Quantitative Assessment

The feature "non-linearity, uncertainty, unpredictability" obtains moderate consideration in the water management within the Elbe River basin—this is particularly the result of management for emergence, the expectation of unintended consequences, the flexibility of responses, and the redefinition of outcomes, which are considered to a high degree; however, there is only a weak consideration of *non-linear* cause–effect relationships and none for emergent properties. Hence, "non-linearity, uncertainty, unpredictability" achieved a total outcome of 3.2 in the semi-quantitative assessment (Table 4).

Table 4. Properties constituting the feature "non-linearity, uncertainty, unpredictability" following the approaches of Berkes et al. [7], Preiser et al. [22], and De Vos et al. [9].

"Non-Linearity, Uncertainty, Unpredictability" Feature Properties	Score [1]
Non-linear cause–effect relationships	2
Management for the emergence and expect unintended consequences	5
Systems are deeply uncertain	3
Systems are inherently unpredictable	3
Flexible responses are fostered, outcomes can be redefined	5
Emergent properties lead to non-linear functioning	1
"Non-linearity, uncertainty, unpredictability" total	**3.2**

[1] To evaluate how much each feature property is considered in the Elbe River basin management, we applied an ordinal scale ranging from 1–5 with 5 = very high, 4 = high, 3 = moderate, 2 = low, 1 = very low consideration.

5.5. Social–Ecological System Feature 5: "Dynamics"

5.5.1. "Dynamics": Feature Properties

SES are subjected to *dynamic* development, including periodic and cyclic changing sequences [7]. When feedback loops exceed a specific tipping point at critical thresholds, systems may branch off into another stable state [22]—the importance of resilience is underlined, as it is the only way to avoid undesirable regimes [7]. The process of cyclic transformation "may provide a window of opportunity" to adapt and evolve new properties [51] (p. 2717). Slow and fast variables of non-linear feedback loops can either reduce or reinforce system *dynamics* [22]. To consider *dynamics*, spatial and temporal cross-scale impacts must be captured, and systemic thresholds must be identified; thus, methods addressing SES *dynamics* and building systemic resilience are favourable [9].

5.5.2. "Dynamics" in Context of the European Water Framework Directive and Global Warming

The WFD prescribes to review, and if necessary, update River Basin Management Plans every six years, indicating the consideration of *dynamics* in the field of status assessment, thus appearing conceptually well-suited to capture *dynamic* change [16]. *Dynamics* and emerging trends can easily be identified and addressed in the short term; however, the WFD does not determine how to capture long-term *dynamics*, i.e., how to address altered conditions, newly constituted *dynamics*, and transformation [33,34]. Furthermore, it is not specified how one can adapt reference conditions, for example, when water temperatures permanently increase [12,33]; however, to properly capture the long-term *dynamics* of global warming, it would be necessary to measure the effects systematically. Considering and addressing alternative stable states to predict tipping points requires determining impacts in advance. So far, such a systematic assessment of *dynamics* is not yet integrated into the WFD [33]. Moreover, the opportunity to claim an exemption or a temporary status deterioration aims at restoring the previous state as quickly as possible. Consequently, no openness is given for the system *dynamics* to develop towards another alternative stable state, even if that might be favourable, especially in global warming management [34]. Additionally, SES naturally go (also in the absence of a severe event) through periodic and cyclic changing sequences [22], which is not acknowledged in the WFD. A gap between the objectives of the WFD and the *dynamic* needs of global warming management exists. Neither tipping points nor resilience become an explicit part of the directive.

5.5.3. Successful Consideration of "Dynamics" in the Elbe River Basin Management

Water management in the Elbe River basin applies vulnerability and sensitivity analyses to address the *dynamics* of a system, for example, regarding water scarcity management [30]. Applying such methods, including cross-sectoral stakeholders, water balance equations, and cost–benefit analyses, is useful to consider the properties of *dynamics*, particularly in view of emerging challenges due to global warming. Since "no regret measures" are applied in the Elbe River basin, short-term flexibility towards *dynamics* is guaranteed [28].

5.5.4. Insufficient Consideration of "Dynamics" in the Elbe River Basin Management

Since the institutional framework of the WFD does not require otherwise, global warming impacts are covered under "other anthropogenic pressures" in Elbe River basin management plans [28]. Accordingly, only limited consideration of *dynamics* is possible. For instance, invasive species resulting from increasing water temperatures can be recorded and addressed in the Programme of Measures—this represents a short- to medium-term compensation for the *non-dynamic* reference conditions [29]. Concerning the long-term perspective, however, *dynamics* are not adequately considered, which indicates a major constraint for considering the *dynamics* of global warming. Moreover, the conducted vulnerability and sensitivity analyses consider different pressures, stakeholders, and interactions; however, they do not specifically investigate *dynamics* as a feature itself [30]—this results in no or only vague assessments of tipping points and regime shifts and in outcomes that often have no implications.

5.5.5. "Dynamics": Semi-Quantitative Assessment

The feature "dynamics" is addressed the least by the Elbe River basin management. This is due to the moderate consideration of resilience-building mechanisms and uncertain outputs resulting from "windows of opportunity". Furthermore, cyclic changing sequences of resource *dynamics* are only considered marginally, and identifying thresholds and indicators to detect possible regime shifts is entirely neglected. In the semi-quantitative assessment, "dynamics" achieved a score of 3.0 (Table 5).

Table 5. Properties constituting the feature "dynamics" following the approaches of Berkes et al. [7], Preiser et al. [22], and De Vos et al. [9].

"Dynamics" Feature Properties	Score [1]
Cyclic changing sequences of resource dynamics	2
Application of methods addressing system dynamics	4
Assess mechanisms that build or inhibit systemic resilience	3
Uncertain outputs resulting from the "window of opportunity"	3
Identify thresholds and indicators that could help detect possible regime shifts	1
Feedback loops of slow and fast variables determine system dynamics	5
"Dynamics" total	**3.0**

[1] To evaluate how much each feature property is considered in the Elbe River basin management, we applied an ordinal scale ranging from 1–5 with 5 = very high, 4 = high, 3 = moderate, 2 = low, 1 = very low consideration.

5.6. Social–Ecological System Feature 6: "Constituted Relationally"

5.6.1. "Constituted Relationally": Feature Properties

SES are defined by *interactions* and *relations* rather than by the system components themselves. As *relations* determine the system structure, analysing SES must focus on the nature of *interactions* and processes instead of regarding system parts as isolated sections. Accordingly, system properties are dynamic and modifiable, depending on time and scale [22]. *Relations* represent meshing processes and their respective outcomes. Emergent properties play an important role, as they solely arise as a result of multiple interacting *relationships*. Problems caused by *interactions* cannot be identified individually [9]. Fostering collaborative processes and management for diversity allows for interactions, builds trust, and creates social networks [9]. Hierarchies of *interactions* and *relations* form different types of networks comprising multiple scales [22].

5.6.2. "Constituted Relationally" in Context of the European Water Framework Directive and Global Warming

Different evaluation criteria exist within the ecological status assessment category, and values are considered in *relation* to each other, e.g., due to the "one-out-all-out" principle [35]; however, looking at the chemical status assessment category, the *interaction* between substances and joint effects are not taken into account [32]. Furthermore, little consideration is given to *interactions* outside or between different status assessment categories, such as ecological vs. chemical status or ecological vs. quantitative status. As status assessment categories remain independent of one another, accounting for *interactions* and identifying adequate measures is challenging; thus, the traceability of measures' efficiency and *relation* is lacking [35]. In the context of global warming, the lack of consideration of *interactions* will become particularly problematic as warming will impact all assessment categories. As a result, mutual *interactions* will be considerably more complex, which is why we think that the management of *interactions* should be given an even higher importance in the future. European water management is generally aware of global warming effects, which is, for example, reflected in CIS Guidance Documents and technical background documents at the river basin level; however, the lack of explicit reference to global warming in objectives and measures of the WFD barely allows for adequate consideration of *interactions* with its effects. Hence, the incentive to properly consider *relationality* at the river basin level is not given if the regulatory framework for addressing *interactions* with global warming impacts is lacking.

Moreover, when turning to the institutional part of the directive, it addresses both the horizontal and vertical *interactions* between authorities. Furthermore, public information and consultation requirements emphasise the involvement of different stakeholder groups [34]. The directive fosters collaborative processes and creates trust and social networks, which are core properties of the feature *constituted relationally*; however, conflicting cross-sectoral water uses, competing objectives of different stakeholder groups, and complex and costly transdisciplinary exchange processes (including emergent properties) point to a not yet sufficient consideration of *relationality* [34]. In the face of global warming, managing *interactions* between different water demands is crucial to prevent water shortages [12].

5.6.3. Successful Consideration of "Constituted Relationally" in the Elbe River Basin Management

Elbe River Basin Management Plans generally consider the *interactions* between flood protection, ecology, economy, and climate change when determining water availability in the respective river basin [28]. Precipitation amounts, region-specific conditions, types and trends of water and land use, and demographic and economic developments are examined in *relation* to each other [31]. In contrast to the general picture of the WFD Fitness Check Evaluation from 2019, the Elbe River basin also explicitly mentions the water quantity of surface waters and *interactions* with increasing water demand and changing use patterns [31]. Nevertheless, this in no way reduces the need to establish clear indicators to enable a systematic assessment approach, which is crucial in light of global warming impacts [32]. The conducted "climate check" of the Programme of Measures covers the effectiveness of individual measures, as well as the *interactions* between them in the context of concrete, on-location planning regarding changing climate conditions. In this way, dynamic and modifiable system components are taken into account and are set in *relation* to time and scale [28]. To allow for *interactions*, diversity should be fostered, which is done in the Elbe River basin by varying the hydromorphological structures, improving river continuity, establishing refuges and buffer strips, and applying "no-regret measures", all contributing to an overall enhanced water body resilience [28].

5.6.4. Insufficient Consideration of "Constituted Relationally" in the Elbe River Basin Management

The SES approach assigns equal importance to system components and *interactions*. Indeed, *interactions* are addressed in the Elbe River basin management; however, they are not awarded the same attention. Great uncertainty about the interactions between global warming effects and water balance in the Elbe region remains [28]; thus, potentially conflicting future water demands and conflicts over setting priorities were identified. Local water scarcity may be a problem if superordinate strategies, such as national energy or biomass initiatives, are to be implemented—this may result in limited water availability for agriculture, inland fisheries, energy supply, and industry; however, ecological water needs, for example, for wetlands or ecological flows, may also be affected [30]. If these conflicts remain unsolved, they likely represent a lack of considering the nature of *interactions.*

5.6.5. "Constituted Relationally": Semi-Quantitative Assessment

The feature "constituted relationally" is addressed moderately by the water management within the Elbe River basin—this results from a moderate consideration of systems not being defined by their properties but rather by their interactions and from management that focuses on diversity. In the semi-quantitative assessment, "constituted relationally" achieved a total outcome of 3.5 (Table 6).

Table 6. Properties constituting the feature "constituted relationally" following the approaches of Berkes et al. [7], Preiser et al. [22], and De Vos et al. [9].

"Constituted Relationally" Feature Properties	Score [1]
Nature and structure of relationships are considered explicitly	2
System is not defined by its properties but rather by their interactions	3
Process-dependent interactions on multiple spatial and temporal scales	4
Foster collaborative processes, build trust and social networks	5
Management for diversity to allow interactions	3
Address dynamic and modifiable components of the system	4
"Constituted relationally" total	**3.5**

[1] To evaluate how much each feature property is considered in the Elbe River basin management, we applied an ordinal scale ranging from 1–5 with 5 = very high, 4 = high, 3 = moderate, 2 = low, 1 = very low consideration.

6. Requirements from the Governance Perspective

In the political science literature, there is considerable agreement among decision makers and experts "about which bottlenecks are the most crucial when it comes to shortcomings in WFD implementation: insufficient land reserves, lack of intersectoral communication and integration, insufficient staff capacities and inadequate financing" [54] (p. 21). Furthermore, "rapid turnover is also a bottleneck—even if not a characteristic of the system itself—because it causes congestion in a system as well as inefficiencies or significant delays" [54] (p. 21). Other studies show how resilient existing territorial institutional arrangements are and how difficult in terms of power, and how time-consuming it is to implement real water governance measures and processes on a river basin scale [55]. Similarly, effective and legitimate participatory models during WFD implementation develop slowly [56].

These governance categories do not reflect the spirit of our SES features; assessments such as the EU Fitness Check do even less. To put it in other words, implementing more (in number) and more far-reaching (in impact) measures targeted at global warming effects increasing actual practical action sets very high standards for water governance in practice. Fulfilling our criteria is an urgent task for future water governance. Nevertheless, the WFD itself has, as our research results related to the Elbe basin show, the institutional potential to fit to all SES features.

Analysing global warming impacts in the WFD and corresponding river basin management might draw lessons from the implementation of its daughter directive on flood risk management, the EU Floods Directive (FD). Established later in 2007, the FD did not oblige water governance stakeholders to systematically consider climate change projections in management plans. The result is that Member States and River Basin Districts include climate change projections in management plans, but not in a harmonised manner [57–59]. For example, comparative studies show that too many different methods for assessing climate change impacts are in place by 2020. Each basin and member state projects differently, which leads to even more certainties for flood management in times of global warming [57]. However, global warming effects impact flood risk directly and to such a broad extent that its full consideration in management is urgently necessary. Consequently, the FD Fitness Check finds that more coordinated flood prevention in line with climate change projections is needed.

7. Conclusions

For each SES feature, we present the results in separate sections. Each section starts with a detailed explanation of the feature properties, followed by an elaboration on the feature's role in the European Water Framework Direction and global warming context. Subsequently, the analysis specifically for the Elbe RBD follows; therefore, we provide a section that presents aspects where the respective SES feature is successfully taken into account in the Elbe River basin, followed by a section indicating areas where the consideration is still insufficient. Furthermore, we present scores of the semi-quantitative assessment providing an overview of how feature properties were considered.

Our research question—With regard to global warming, to what extent does water management in the Elbe River Basin District take the features of social–ecological systems into consideration?—is answered by the scored properties of the SES features; therefore, we consulted experts and analysed the framework and existing plans. At that stage, and for that basin, we find that the WFD implementation process does not address global warming issues explicitly enough. Provisionally, we can only conclude with rather general recommendations regarding the six features, using our results as guidelines for future WFD implementation cycles:

In the future, only the full recognition, for example, of *scale and openness* can ensure effective water management in the Elbe River basin. The hierarchical structure already allows for different water management needs such as drinking water supply, wastewater treatment, energy supply, and irrigation water for agriculture to be reconciled. Broader, cross-scale impacting effects can be considered. If this is to be further improved and ensured in the future, local level needs and objectives across sectors must be consistent with overarching goals; therefore, it is necessary to consider the scope of global warming in a more fundamental way.

The overall consideration of *context dependency* in the Elbe River basin is good. Challenges that still occur in relation to context are related to inflexible infrastructure.

To consider slow and fast variables that result in *non-linearity, uncertainty, and unpredictability*, and to better understand global warming impacts and the interplay between different sectors in the Elbe River basin, different methods, such as vulnerability and impact analyses and generalised modelling, should be applied. These methods increase SES understanding despite restricted system knowledge [9]. So far, such analyses have not yet been applied on a larger scale in the Elbe River basin, and are still associated with great uncertainties, resulting in only limited consideration of the feature at present [30].

To increase the consideration of *dynamics*, which is of particular importance for the long-term perspective, it is necessary to identify potential tipping points; therefore, we must determine the direct impacts of global warming in the Elbe River basin first, which can be achieved by conducting a consistent climate impact assessment at the river basin level [33]. In this context—and regarding vulnerability and sensitivity analyses—it is essential to consider dynamics as an independent but interacting property. Furthermore, it must be ensured that the gained insights into alternative stable states have wider practical implications than the current insight. The assessments must be carried out systematically at a consistent level to obtain the bigger picture.

To analyse the context of water availability and water demand, which is *constituted relationally* (including global warming impacts and different kinds of water use), long-term management models are already applied in the Elbe River basin today [30]. Such models are a good starting point to consider interactions. Within these models, however, the focus should be shifted towards further exploring the nature of these interactions—this is particularly important, for example, when it comes to identifying areas where explicit management for consistency is to be strengthened to prevent future water use conflicts. Methods such as network analysis and agent-based modelling are potentially adequately supportive of relationality [22].

For improving WFD implementation in general, it seems reasonable for us to explicitly include global warming impacts in assessment, objectives, reference conditions, and planning of measures. From our perspective, it would be necessary to add an obligatory precautionary component (exceeding the timeframe of 6 years) to provide the WFD with a long-term perspective—this would allow us to clarify and identify global warming effects, recognise self-organisation capacities, and evaluate *adaptation* measures appropriately.

The preparation of the new planning cycle at the Elbe River basin, which was published in early 2021 (directly after our research period), already addresses the impact of global warming more explicitly. How SES features are addressed here should be analysed with the typology we have presented in this paper.

Author Contributions: Conceptualization, E.S.; writing—original draft preparation, E.S., C.Z. and F.H.; writing—review and editing, E.S., C.Z. and F.H.; visualization, E.S. and C.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors would like to express their sincere thanks to the anonymous reviewers for their constructive comments on an earlier version of this manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Steffen, W.; Richardson, K.; Rockström, J.; Cornell, S.E.; Fetzer, I.; Bennett, E.M.; Biggs, R.; Carpenter, S.R.; De Vries, W.; De Wit, C.A.; et al. Planetary Boundaries: Guiding human development on a changing planet. *Science* **2015**, *347*, 736–746. [CrossRef]
2. Kovats, R.S.; Valentini, R.; Bouwer, L.M.; Georgopoulou, E.; Jacob, D.; Martin, E.; Rounsevell, M.; Soussana, J.F. Europe. In *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, 1st ed.; Arros, V.R., Field, C.B., Dokken, D.J., Mastrandrea, M.D., Mach, K.J., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., et al., Eds.; Cambridge University Press: Cambridge, NY, USA, 2014; pp. 1267–1326.
3. Intergovernmental Panel on Climate Change (IPCC). Summary for Policymakers. In *Global Warming of 1.5 °C. An IPCC Special Report on the Impacts of Global Warming of 1.5 °C above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty*, 1st ed.; Masson-Delmotte, V., Zhai, P., Pörtner, H.O., Roberts, D., Skea, J., Shukla, P.R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., et al., Eds.; Intergovernmental Panel on Climate Changem, 2018; in press.
4. Intergovernmental Panel on Climate Change (IPCC). Summary for Policymakers. In *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, 1st ed.; Pachauri, R.K., Meyer, L.A., Eds.; 2014; in press.
5. Schwalm, C.R.; Glendon, S.; Duffy, P.B. RCP8.5 tracks cumulative CO_2 emissions. *Proc. Natl. Acad. Sci. USA* **2020**, *117*, 19656–19657. [CrossRef] [PubMed]
6. European Environmental Agency. *Climate Change Adaptation and Disaster Risk Reduction in Europe. Enhancing Coherence of the Knowledge Base, Policies and Practices*; Issue 7/2017; Publications Office of the European Union: Luxembourg, 2017.

7. Berkes, F.; Colding, J.; Folke, C. *Navigating Social–Ecological Systems. Building Resilience for Complexity and Change*, 1st ed.; Cambridge University Press: Cambridge, UK, 2002.
8. Folke, C.; Biggs, R.; Norström, A.V.; Reyers, B.; Rockström, J. Social–ecological resilience and biosphere-based sustainability science. *Ecol. Soc.* **2016**, *21*, 41. [CrossRef]
9. De Vos, A.; Biggs, R.; Preiser, R. Methods for understanding social–ecological systems: A review of place-based studies. *Ecol. Soc.* **2019**, *24*, 16. [CrossRef]
10. European Commission. *Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 Establishing a Framework for the Community Action in the Field of Water Policy*; OJ L327; European Commission: Brussels, Belgium, 2000.
11. European Environmental Agency. *European Waters. Assessment of Status and Pressures 2018*; Issue 7/2018; Publications Office of the European Union: Luxembourg, 2018.
12. European Commission. *Fitness Check Evaluation of the Water Framework Directive and the Floods Directive*, 1st ed.; Publications Office of the European Union: Luxembourg, 2019.
13. Voulvoulis, N.; Arpon, K.D.; Giakoumis, T. The EU Water Framework Directive: From great expectations to problems with implementation. *Sci. Total Environ.* **2017**, *575*, 358–366. [CrossRef]
14. Beveridge, R.; Monsees, J.; Moss, S.T. *Das IRS Handbuch zur Analyse der Institutionellen und Politischen Kontexte von Projekten zum Wasserressourcen-Management*, 1st ed.; Leibnitz-Institut für Regionalentwicklung und Strukturplanung: Erkner, Germany, 2012; 57p.
15. German Environmental Agency. *Gewässer in Deutschland: Zustand und Bewertung*, 1st ed.; Germany Environment Agency: Dessau, Germany, 2017.
16. Reese, M.; Möckel, S. Die Handlungsfelder staatlicher Anpassungspolitik und Ansatzpunkte rechtlicher Steuerung. Gewässerqualität. In *Rechtlicher Handlungsbedarf für die Anpassung an die Folgen des Klimawandels-Analyse, Weiter- und Neuentwicklung Rechtlicher Instrumente*, 1st ed.; Reese, M., Möckel, S., Bovet, J., Köck, W., Eds.; German Environment Agency: Dessau, Germany, 2016; Volume 2.
17. European Commission. *Common Implementation Strategy for the Water Framework Directive (2000/60/EC). Guidance Document No. 24 River Basin Management in a Changing Climate*, 1st ed.; Publications Office of the European Union: Luxembourg, 2009.
18. European Commission. *European Overview-River Basin Management Plans. Implementation of the Water Framework Directive (2000/60/EC) and the Floods Directive (2007/60/EC). Second River Basin Management Plans. First Flood Risk Management Plans*, 1st ed.; European Commission: Brussels, Belgium, 2019.
19. Chokkavarapu, N.; Mandla, V.R. Comparative study of GCMs, RCMs, downscaling and hydrological models: A review toward future climate change impact estimation. *SN Appl. Sci.* **2019**, *1*, 1698. [CrossRef]
20. Kling, H.; Fuchs, M.; Paulin, M. Runoff conditions in the upper Danube basin under an ensemble of climate change scenarios. *J. Hydrol.* **2012**, *424–425*, 264–277. [CrossRef]
21. Stefanidis, S.; Dafis, S.; Stathis, D. Evaluation of Regional Climate Models (RCMs) Performance in Simulating Seasonal Precipitation over Mountainous Central Pindus (Greece). *Water* **2020**, *12*, 2750. [CrossRef]
22. Preiser, R.; Biggs, R.; De Vos, A.; Folke, C. Social–ecological systems as complex adaptive systems: Organizing principles for advancing research methods and approaches. *Ecol. Soc.* **2018**, *23*, 46. [CrossRef]
23. Becker, E. Soziale Ökologie: Konturen und Konzepte einer neuen Wissenschaft. In *Wissenschaftstheoretische Perspektiven für die Umweltwissenschaften*, 1st ed.; Matschonat, G., Gerber, A., Eds.; Markgraf: Weikersheim, Germany, 2003; pp. 165–195.
24. Berkes, F.; Folke, C.; Colding, J. *Linking Social and Ecological Systems: Management Practices and Social Mechanisms for Building Resilience*, 1st ed.; Cambridge University Press: Cambridge, UK, 1998; 476p.
25. Leach, M.; Rockström, J.; Raskin, P.; Scoones, I.; Stirling, A.C.; Smith, A.; Thompson, J.; Millstone, E.; Ely, A.; Around, E.; et al. Transforming innovation for sustainability. *Ecol. Soc.* **2012**, *17*, 11. [CrossRef]
26. Tengö, M.; Brondizio, E.S.; Elmqvist, T.; Malmer, P.; Spierenberg, M. Connecting diverse knowledge systems for enhanced ecosystem governance: The multiple evidence base approach. *Ambio* **2014**, *43*, 579–591. [CrossRef] [PubMed]
27. Ostrom, E. A General Framework for Analyzing Sustainability of Social–ecological Systems. *Science* **2009**, *325*, 419–422. [CrossRef] [PubMed]
28. River Basin Cooperation Elbe. *Aktualisierung des Bewirtschaftungsplans nach § 83 WHG bzw. Artikel 13 der Richtlinie 2000/60/EG für den Deutschen Teil der Flussgebietseinheit Elbe für den Zeitraum von 2016 bis 2021*, 1st ed.; RBC Elbe Secretariat: Magdeburg, Germany, 2015.
29. River Basin Cooperation Elbe. *Aktualisierung des Maßnahmenprogramms nach § 82 WHG bzw. Artikel 11 der Richtlinie 2000/60/EG für den Deutschen Teil der Flussgebietseinheit Elbe für den Zeitraum von 2016 bis 2021*, 1st ed.; RBC Elbe Secretariat: Magdeburg, Germany, 2015.
30. River Basin Cooperation Elbe. *Hintergrunddokument zu den Wichtigen Wasserbewirtschaftungsfragen "Ausrichtung auf ein nachhaltiges Wassermengenmanagement" und "Berücksichtigung der Folgen des Klimawandels"*, 1st ed.; RBC Elbe Secretariat: Magdeburg, Germany, 2015.
31. International Commission for the Protection of the Elbe River (ICPER). *International River Basin Management Plan for the Elbe River Basin District*, 1st ed.; ICPER Secretariat: Magdeburg, Germany, 2015.
32. Klauer, B. (Helmholtz-Centre for Environmental Research-UFZ, Leipzig, Germany). Personal communication, 2020.
33. Reese, M. (Helmholtz-Centre for Environmental Research-UFZ, Leipzig, Germany). Personal communication, 2020.
34. Herzog, L. (Osnabrück University, Osnabrück, Germany). Personal communication, 2020.

35. Wolf, C. (Helmholtz-Centre for Environmental Research-UFZ, Leipzig, Germany). Personal communication, 2020.
36. Klauer, B.; Schiller, J.; Bathe, F. Concept for cost-effective improvement of river morphology. *J. Environ. Plan. Manag.* **2014**, *58*, 1944–1960. [CrossRef]
37. Klauer, B.; Sigel, K.; Schiller, J. Disproportionate costs in the EU Water Framework Directive—How to justify less stringent environmental objectives. *Environ. Sci. Policy* **2016**, *59*, 10–17. [CrossRef]
38. Reese, M.; Bedtke, N.; Gawel, E.; Klauer, B.; Köck, W.; Möckel, S. Wasserrahmenrichtlinie-Wege aus der Umsetzungskrise. *Wasser Abfall* **2019**, *21*, 47–54. [CrossRef]
39. Swart, R.; Biesbroek, R.; Binnerup, S.; Carter, T.R.; Cowan, C.; Henrichs, T.; Loquen, S.; Mela, H.; Morecroft, M.; Reese, M.; et al. *Europe Adapts to Climate Change: Comparing National Adaptation Strategies (PEER Report 1)*, 1st ed.; Partnership for European Environmental Research: Helsinki, Finland, 2009; p. 283.
40. Reese, M. Das neue Recht des Hochwasserschutzes vor den Herausforderungen des Klimawandels. *Nat. Recht* **2011**, *33*, 19–28. [CrossRef]
41. Reese, M.; Köck, W. Flussgebietsweites Sedimentmanagement unter der EG-Wasserrahmenrichtlinie am Beispiel der Elbe. *Wasser Abfall* **2019**, *21*, 33–40. [CrossRef]
42. Widmer, A.; Herzog, L.; Moser, A.; Ingold, K. Multilevel water quality management in the international Rhine catchment area: How to establish social–ecological fit through collaborative governance. *Ecol. Soc.* **2019**, *24*, 27. [CrossRef]
43. Herzog, L.M.; Ingold, K. Threats to Common-Pool Resources & the Importance of Forums: On the Emergence of Cooperation in CPR Problem Settings. *Policy Stud. J.* **2019**, *47*, 77–113.
44. Berger, V.; Fan, F.M.; Gabel, F.; Galvão, P.H.; Gies, M.; Grabner, D.; Langhans, S.; Macedo-Moura, P.; Abel de Souza Machado, A.; Manzione, R.L.; et al. *How Do We Want to Live Tomorrow? Perspectives on Water Management in Urban Regions*, 1st ed.; Nissen, J., Azara, F., Cortesão Barnsley Scheuenstuhl, M.C., Eisinger, M., Eds.; Centre for Water and Environmental Research: Essen, Germany, 2017; p. 24.
45. Ziv, G.; Mullin, K.; Boeuf, B.; Fincham, W.; Taylor, N.; Villalobos-Jiménez, G.; von Vittorelli, L.; Wolf, C.; Fritsch, O.; Strauch, M.; et al. Water quality is a poor predictor of recreational hotspots in England. *PLoS ONE* **2016**, *11*, e0166950. [CrossRef]
46. Wolf, C. Wie viel ist streng genug? Ein Verfahrensvorschlag zur Festlegung des Bestmöglichen Ökologischen Gewässerzustandes für Zielabsenkungen nach Art. 4.5 der EG-Wasserrahmenrichtlinie unter Berücksichtigung Struktureller, Funktionaler und Ökosystemleistungsrelevanter Aspekte. Ph.D. Thesis, Osnabrück University, Osnabrück, Germany, 2019.
47. Wolf, C.; Völker, J.; Klauer, B. Der ökologische Zustand nach WRRL–Potenziale einer ergänzenden funktionalen Zustandsbewertung. *WasserWirtschaft* **2019**, *4*, 22–26. [CrossRef]
48. Weitere, M.; Altenburger, R.; Anlanger, C.; Baborowski, M.; Bärlund, I.; Beckers, L.-M.; Borchardt, D.; Brack, W.; Brase, L.; Busch, W.; et al. Disentangling multiple chemical and non-chemical stressors in a lotic ecosystem using a longitudinal approach. *Sci. Total Environ.* **2021**, *769*, 144324. [CrossRef]
49. Ostrom, E. A diagnostic approach for going beyond panaceas. *Proc. Natl. Acad. Sci. USA* **2007**, *104*, 15181–15187. [CrossRef]
50. Virapongse, A.; Brooks, S.; Metcalf, E.C.; Zedalis, M.; Gosz, J.; Kliskey, A.; Alessa, L. A social–ecological systems approach for environmental management. *J. Environ. Manag.* **2016**, *178*, 83–91. [CrossRef]
51. Martin, R.; Schlüter, M.; Blenckner, T. The importance of transient social dynamics for restoring ecosystems beyond ecological tipping points. *Proc. Natl. Acad. Sci. USA* **2020**, *117*, 2717–2722. [CrossRef]
52. Levin, S.; Xepapadeas, T.; Crépin, A.S.; Norberg, J.; De Zeeuw, A.; Folke, C.; Hughes, T.; Arrow, K.; Barrett, S.; Daily, G.; et al. Social–ecological systems as complex adaptive systems: Modeling and policy implications. *Environ. Dev. Econ.* **2013**, *18*, 111–132. [CrossRef]
53. Krysanova, V.; Hesse, C.; Martinkova, M.; Koskova, R.; Blazkova, S. Case Study: Elbe. In *The Adaptive Water Resource Management Handbook*, 1st ed.; Mysiak, J., Henrikson, H.J., Sullivan, C., Bromley, J., Pahl-Wostl, C., Eds.; Earthscan: London, UK, 2010; pp. 89–102.
54. Zingraff-Hamed, A.; Schröter, B.; Schaub, S.; Lepenies, R.; Stein, U.; Hüesker, F.; Meyer, C.; Schleyer, C.; Schmeier, S.; Pusch, M.T. Perception of Bottlenecks in the Implementation of the European Water Framework Directive. *Water Altern.* **2020**, *13*, 3.
55. Hüesker, F.; Moss, T. The Politics of Multi-Scalar Action in River Basin Management: Implementing the EU Water Framework Directive (WFD). *Land Use Policy* **2015**, *42*, 38–47. [CrossRef]
56. Jager, N.W.; Challies, E.; Kochskämper, E.; Newig, J.; Benson, D.; Blackstock, K.; Collins, K.; Ernst, A.; Evers, M.; Feichtinger, J.; et al. Transforming European Water Governance? Participation and Member States. *Water* **2016**, *8*, 156. [CrossRef]
57. Holguin, N.; Mugica, A.; Ukar, O. How Is Climate Change Included in the Implementation of the European Flood Directive? Analysis of the Methodological Approaches of Different Countries. *Water* **2021**, *13*, 1490. [CrossRef]
58. Brillinger, M.; Henze, J.; Albert, C.; Schwarze, R. Integrating nature-based solutions in flood risk management plans: A matter of individual beliefs? *Sci. Total Environ.* **2021**, *795*, 148896. [CrossRef] [PubMed]
59. Lastrada, E.; Cobos, G.; Torrijo, F.J. Analysis of Climate Change's Effect on Flood Risk. Case Study of Reinosa in the Ebro River Basin. *Water* **2020**, *12*, 1114.