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Learning from past coevolutionary processes to envision sustainable futures: Extending an action situations approach to the Water-Energy-Food nexus

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ABSTRACT

Despite near-global consensus on the Sustainable Development Goals and the Paris Climate Agreement, unresolved and politically contentious trade-offs have undermined implementation. One exemplary case facing difficult trade-offs are Water-Energy-Food (WEF) nexus cases. Here, we extend the nascent 'Social-Ecological Action Situations' framework to analyse past coevolution of WEF nexus cases (or other social-ecological systems) to envision possible futures where trade-offs are equally considered and minimized. We illustrate the value of the approach for a WEF nexus case in Switzerland with upstream hydropower reservoirs, water-bound biodiversity, and emerging downstream agricultural irrigation needs. The proposed solution-oriented, transformative approach goes beyond existing frameworks by analysing past coevolution of the intertwined system to build system understanding and to envision a future with concrete policies that would result in a higher adaptive capacity of the system and a compromise within the WEF nexus. We argue that this perspective helps to devise policies to address trade-offs in WEF nexus cases and thereby to tackle global crises.

1. Introduction

The 21st century is marked by pressing ecological and social challenges with the potential for emergent systemic risks undermining sustainable development (Reyers et al., 2018). These sustainability challenges result from interactions between mutually reinforcing ecological and social processes at different scales, which are deeply intertwined (Folke et al., 2016; examples in e.g., Schlüter et al., 2019). Consequently, new integrated approaches are needed to understand and address the complex, intertwined, and coevolving social-ecological nature of the challenges (Liu et al., 2015; Reyers et al., 2018). The nexus concept is one approach that aims to emphasize the interconnected nature of sustainability challenges, to identify trade-offs and synergies between different sectoral sub-systems of social-ecological systems, and to encourage a more holistic perspective (Pahl-Wostl et al., 2020). A prominent example of the nexus concept is the Water-Energy-Food (WEF) nexus, which sets the system boundary around trade-offs and synergies of water, energy, and food systems. However, while the nexus concept offers a promising frame, it remains less clear which methodological approach may effectively capture the intertwined social-ecological dynamics in WEF nexus cases (Leach et al., 2018) and how such an approach can help to identify interventions that improve emerging phenomena of WEF nexus cases.

Even though the nexus concept was formulated in response to siloed thinking and critical interlinkages across resources in an integrated manner (Bleischwitz et al., 2018), a comprehensive review by Albrecht et al. (2018) showed that empirical nexus studies often fail to capture the interconnected social-ecological dynamics among sub-systems. Instead, scholars mostly use conventional disciplinary approaches which provide narrow perspectives on interactions among the sub-systems, thus perpetuating a fractured view on nexus cases. Consequently, the conclusions of such studies often do not go beyond fighting the sectorial symptoms of an overall unsustainable nexus. Resulting interventions may then be tangible (e.g., irrigation efficiency) but ultimately fail to address underlying drivers of current trajectories (e.g., food consumption patterns) and therewith a transformation of the system (Abson et al., 2017). However, recent studies have started to address this gap through e.g., integrating qualitative and social science

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methods in nexus studies and consequently contribute to breaking disciplinary silos (Sušnik and Staddon, 2021). Scholars with a background in institutional analysis started to use the nascent Networks of Action Situations (NAS) approach to study nexus cases (Möck et al., 2019; Srigiri and Dombrowsky 2021; Kellner 2022). This approach conceptualises nexus cases as a network of (social) action situations at different levels to identify linkages across water, energy, and food-related action situations, and how the outcome of action situations limit or facilitate synergies and trade-offs along the nexus cases affecting energy, water, and food systems (Kellner 2022). The NAS approach helps to understand the interdependence of WEF-related interactions by actors in various interlinked action situations and the performance of the governance processes in nexus cases (Srigiri and Dombrowsky 2021). The study of Kellner (2022) goes one step further in identifying interventions in the NAS of a nexus case for the transformation towards sustainable and equitable provision and utilization of nexus resources.

However, these studies rooted in institutional analysis treat social and ecological systems as separated but connected through two-way feedbacks (Kellner 2021; Brelsford et al., 2020). Ecological systems are viewed as external drivers of social dynamics. This thinking is increasingly contested amongst social-ecological systems researchers influenced by systems and complexity thinking (Preiser et al., 2021). Systems thinking provides a way of bridging the study of humans and nature as separate elements to understand the continuous interplay "between microlevel elements to form emergent macrolevel patterns" (Biggs et al., 2021, p. 5). In turn, these macrolevel patterns influence the behaviour of the individual elements and their interactions with other elements, thereby creating feedback processes that shape the evolution of the system and enable it to adapt to changing contexts over time (Lansing, 2003). The continuous adaptive responses between elements and between the elements and the resulting emergent phenomenon imply that nexus cases are more than the sum of the social and ecological elements (Reyers et al., 2018). In consequence, they need to be understood as complex adaptive systems (Levin et al., 2013). With this perspective, elements in social-ecological nexus cases are shaping and are being shaped by one another (Folke et al., 2016) in a continuously coevolving manner (Levin et al., 2013; Haider et al., 2021); they are 'intertwined' (Schlüter et al., 2019). This implies that interactions and relations between elements in WEF nexus cases (e.g., resulting river runoff) are more important for understanding the characteristics of the case than the characteristics of individual elements in the systems themselves (e.g., size of hydropower reservoir) (Preiser et al., 2018). This conceptualization allows to capture various stages of the same system and the corresponding emergent phenomenon over time, thereby helping to understand past 'evolution' of the system to learn from and to envision future transformation.

To apply this conceptualization in the study of nexus cases, we propose an approach that is adapted from the nascent Social-Ecological Action Situations (SE-AS) framework (Schlüter et al., 2019). The approach builds on Ostrom's Institutional Analysis and Development (IAD) (Ostrom 2005, 2011; McGinnis 2011a) and social-ecological systems frameworks (Ostrom 2009) and the NAS approach (Kimmich et al., 2022, 2023; McGinnis 2011b). However, the SE-AS framework goes beyond these frameworks by incorporating relations between and agency of social elements (SE) and ecological elements (EE) and interactions across multiple levels to overcome the dichotomy between the social and the ecological, and thus to better account for the intertwined nature of socia-ecological systems. Besides "social" action situations (SE/SE-AS), it integrates "social-ecological" action situations (SE/EE-AS) and "ecological" action situations (EE/EE-AS; Fig. 1).

The integration of SE/EE-AS and EE/EE-AS enables a shift away from the environment as an externality and instead allows to consider configurations of ASs that are linked through coevolving relationships which generate the nexus case phenomena of interest (Schlüter et al., 2019); Fig. 1). This allows capturing those interactions that are most relevant for the phenomenon of interest, which is necessary to define the system boundary of the configuration. Our proposed approach goes one step further than the SE-AS framework by building configurations of action situations across past stages to understand the past coevolution of the system, i.e., how a past emergent social-ecological phenomenon shaped the current configuration of action situations. This then allows us to identify key interventions such as adapted public policies that could steer transformational change towards a desired phenomenon. We apply the approach to an embedded WEF nexus case study in Switzerland, where three hydropower projects in the last 120 years led to contrasting phenomena. In this WEF nexus case, water is constructed to protect water-bound biodiversity, energy to produce hydropower, and food as agricultural food production with irrigation demands. In the case study, public policies and governance processes fail to address the intertwinedness of social and ecological processes of the complex WEF nexus case.

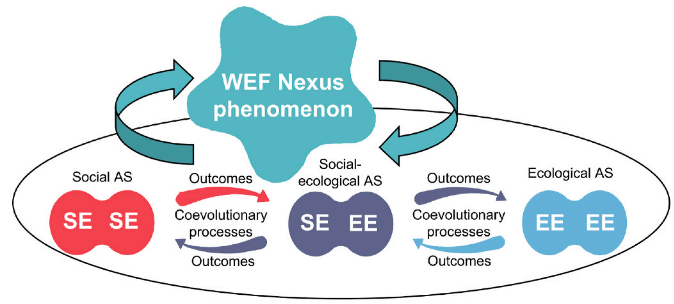

Fig. 1. Social-Ecological Action Situations (SE-AS) framework adapted from Schlüter et al. (2019). This conceptualization of WEF nexus cases enables the study of continuous adaptive responses between elements (e.g., granting a water right (SE-SE), energy and food production (SE-EE), and runoff of a river (EE-EE)) and between the elements and the resulting emergent phenomenon (e.g., coordination failure and governance gaps). WEF Nexus = Water--Energy-Food Nexus; AS = Action Situation; SE = Social Element; EE = Ecological Element.

2. Method

2.1. Case study

The case study is the upper part of the Aare catchment in the canton of Bern, Switzerland, Europe (map see Fig. A.1 in Appendix A). The upstream part of the catchment is mountainous, sparsely populated, and heavily used for hydropower production. A complex system of power infrastructure has been built since 1925: 195 million cubic meters of water can be stored in eight reservoirs, which are operated by the power company Kraftwerke Oberhasli (KWO). The downstream part is more densely populated and used for agricultural crop production (Seeland region). Two natural lakes (Lake Brienz and Lake Thun) are located in the pre-alpine region in between and are used for recreation, shipping, and water sports (Fig. 2).

The hydrological regimes in the upstream part of the catchment are characterized by glacier- and snowmelt processes and therefore high flows in summer and low flows in winter. In contrast, the hydrological regimes in the downstream part of the catchment are rainfall-dominated with wet winters and dry summers. In dry seasons, the downstream catchment, therefore, disproportionally relies on inflow from the runoff-rich upstream catchments, particularly for water-bound biodiversity and

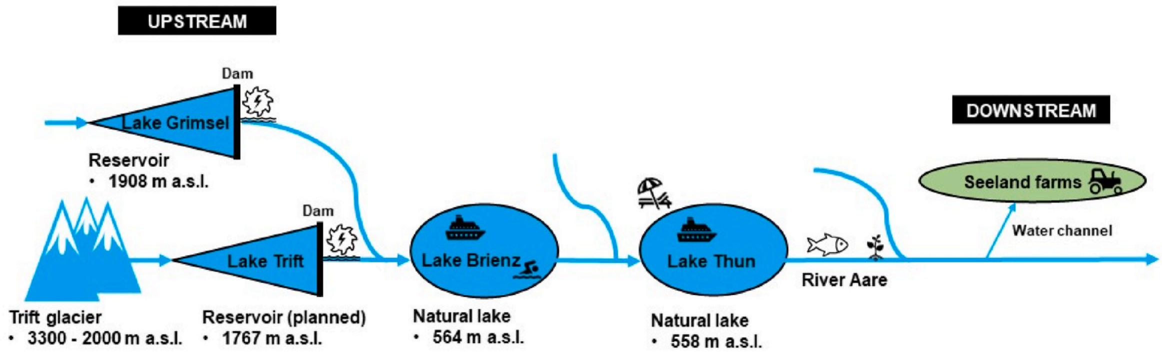

Fig. 2. Schematic overview of the Aare catchment representing the WEF case with (planned) alpine reservoirs for hydropower production, water-bound biodiversity along the river, and Seeland farms in need of irrigation.

crop irrigation.

This article analyses three hydropower projects in the upstream part as part of a WEF nexus to exemplarily study the coevolution of action situations over time: 1) Construction of Lake Grimsel: The power company obtained the concession to use the water for hydropower in 1906 from the canton of Bern. The dam of Lake Grimsel was completed in 1932. 2) Expansion of Lake Grimsel: In 1988, the power company planned to increase the height of the dam, which would allow using available water better throughout the year. Conflicts between the hydropower company and conservationists are ongoing and the project has not been realized more than three decades later. 3) Construction of the Trift dam: Due to climate change, the Trift glacier is shrinking rapidly, and a new periglacial lake is forming. The hydropower company submitted plans to construct a new reservoir at Lake Trift in 2012. A broad participatory process was established together with NGOs and local municipalities to develop a draft hydropower concession. The hydropower company submitted the draft to the authorities in 2017; these will likely grant the concession soon (Mentha et al., 2019). More details on the public policies and corresponding social processes of the three projects are described in Kellner et al. (2019); more details on hydrological conditions and the conflicts around the Trift project are presented in Kellner and Brunner (2021), and details about social acceptance of the Trift project can be found in Kellner (2019). These projects, which (plan to) store water in summer to produce energy in winter interfere with water uses in the pre-alpine lakes, water-bound biodiversity, and the agricultural cropping area downstream. Simultaneously, downstream farmers plan to build further water pipes from the river Aare to their agricultural land to enable irrigation during increasingly dry spring and summer months under climate change. Regardless of this, the Lake Brienz and Thun regulators have no means to influence upstream water release and do not coordinate runoff with downstream water demand for irrigation.

2.2. Data collection and analysis

We used an exemplary case study research design and selected a WEF nexus case, where the mechanisms at play are easily identifiable (Yin 2018). We carried out data collection between early 2017 and early 2021. The data collection included 31 semi-structured face-to-face interviews, partly online due to the pandemic, with the main actors representing public authorities on different levels, politicians, hydropower company, associations involved, downstream farmers, agricultural representatives, and scientists. Table A.1. in Appendix A provides an anonymized list of all formal and informal interviewees and a general structure of the interviews. These expert interviews provided information on specific resource use interests and political strategies, helping to understand ongoing governance processes. The interviews were confidential to create an atmosphere of trust during the interviews and to avoid strategic answers. Additionally, we collected data through participatory observations of meetings (e.g., meetings of NGOs and the hydropower company), document analyses of legal materials (laws, regulations, concessions, and national, cantonal, and regional strategies), and reviews of grey literature on the case (including administrative and NGO reports and newspaper articles). We transcribed interviews and analysed the data following the principles of qualitative content analysis (Mayring 2010). Based on this data, we built configurations of action situations across three stages in an iterative process (Appendix B, Fig. B2). We also held six meetings and one half-day workshop with representatives from the Swiss Federal Offices for Energy, Environment, and Agriculture between the end of 2019 and early 2021 to discuss the results of the data analysis, the identified action situations, and the identified interventions that could steer transformational change (Kellner et al., 2021). From this system understanding, including the interventions discussed with representatives from the Swiss Federal Offices, we were able to envision one potential future configuration of action situations with policy extensions that addresses the current unsustainable nexus phenomenon, which is a prioritization of energy production with potential threats to water-bound biodiversity, and unrecognized potential threats to food production.

A detailed diagnostic procedure for the operationalization of the SE-AS framework and how we built the configurations of action situations is available in Appendix B.

3. Results

The emerging WEF nexus phenomena are changing over time. To understand the current phenomenon, we analysed the coevolutionary processes over the last 120 years. We identified three stages, which are described via three exemplary projects in the same area under the umbrella of evolving cantonal and national public policies. In a fourth stage, we envisioned one potential future with extended policies that could lead to mutual coordination of water uses and minimized trade-offs.

3.1. Stage I (beginning of the 20th century): construction of Lake Grimsel

Due to increasing energy demand at the beginning of the 20th century, the power company applied for a hydropower concession for Lake Grimsel in 1906. At this time, no national public policies regulated the

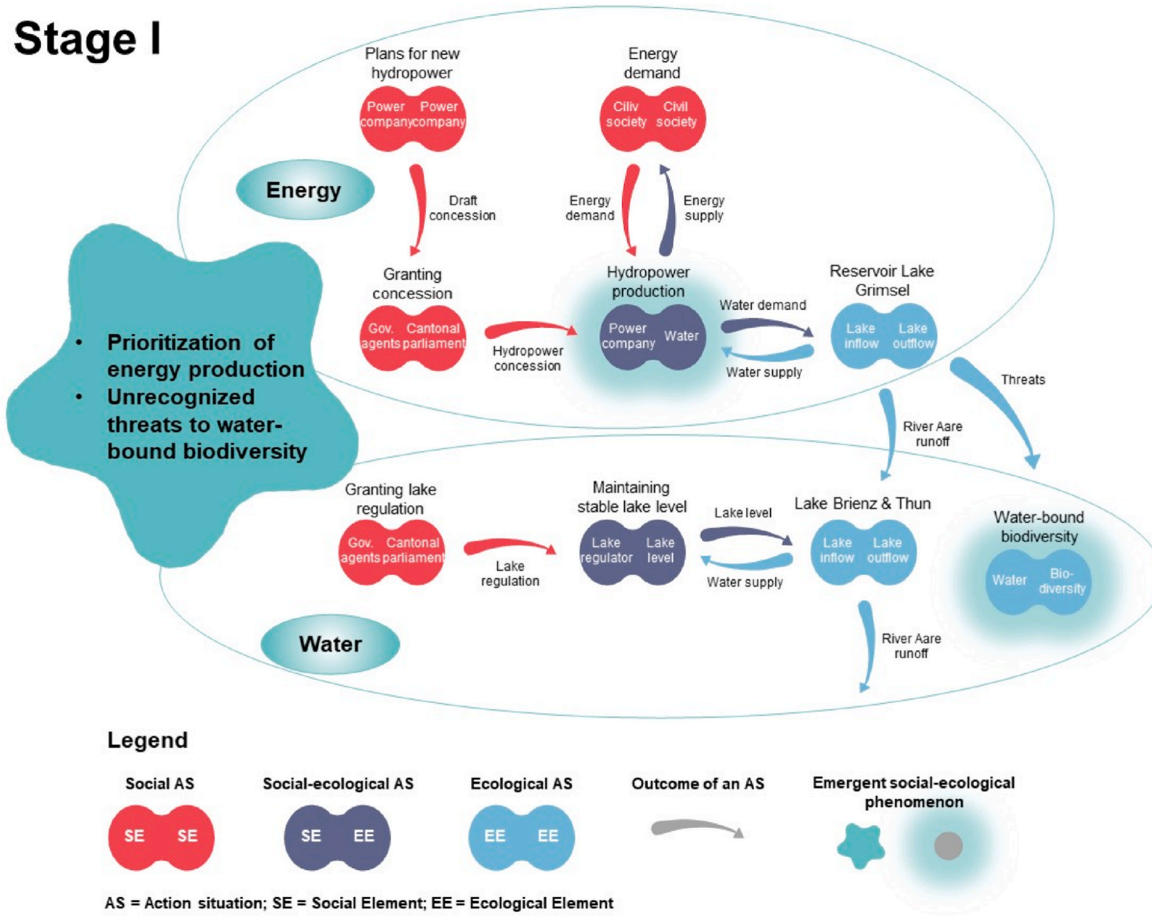

Fig. 3. Stage I of the WEF nexus at the beginning of the 20th century using the case of the construction of Lake Grimsel shows a weak integration of energy and water while irrigated food production was absent. The prioritization of energy production leads to an unrecognized threat to water-bound biodiversity.

use of water or public land, except for forest legislation. Concessions were regulated at the cantonal level. This led to the key social action situation, where the cantonal parliament granted the concession. We could find no evidence for opposition in the document analysis and interviews despite that the new reservoir flooded a raised bog. At this time, protection of water and water-bound biodiversity was not a concern and food production in need of irrigation was not established in the downstream Seeland region. Lake Brienz and Lake Thun were regulated for flood protection and residual water.

The emerging WEF nexus phenomena in that time are the prioritization of energy production over biodiversity and no conflicts about threats to biodiversity (Fig. 3).

3.2. *Stage II (mid to late 20th century): expansion of Lake Grimsel*

Due to increasing awareness of threats for water-bound biodiversity, the number of public policies regulating hydropower production and protecting water and the environment (including bogs) evolved rapidly over the 20th century. For more details see Kellner et al. (2019). Of particular interest are national protection laws which introduced the right for some non-governmental organizations (NGOs) to appeal against rulings of the cantonal authorities or the federal authorities in 1966. This right to appeal gives them a correspondingly powerful position. Furthermore, a mandatory environmental impact assessment for hydropower concessions and lake regulations was introduced in 1983. The minimum amount of residual water at the direct outflow of hydropower reservoirs to protect water-bound biodiversity was introduced in the water protection law in 1991.

In 1988, the power company applied for raising the dam of Lake Grimsel. These plans triggered considerable resistance because parts of the – in the meantime nationally protected – raised bog around the existing Lake Grimsel would be flooded by raising the dam. This situation resulted in various coevolving social action situations including several rounds of appeals, more restrictions for granting a hydropower concession, and court decisions with still unresolved conflicts between energy production and biodiversity. After more than 30 years, until the time of research in early 2022, no concession has been granted.

After finishing two large water corrections in the Seeland region in 1973, agricultural production started to increase in importance, and irrigation concessions to use water from the river Aare and from groundwater were granted.

The emerging WEF nexus phenomena in this period are, firstly, the conflicts about weighing of interests between energy production and biodiversity and, secondly, sufficient water supply for irrigation for food production (Fig. 4).

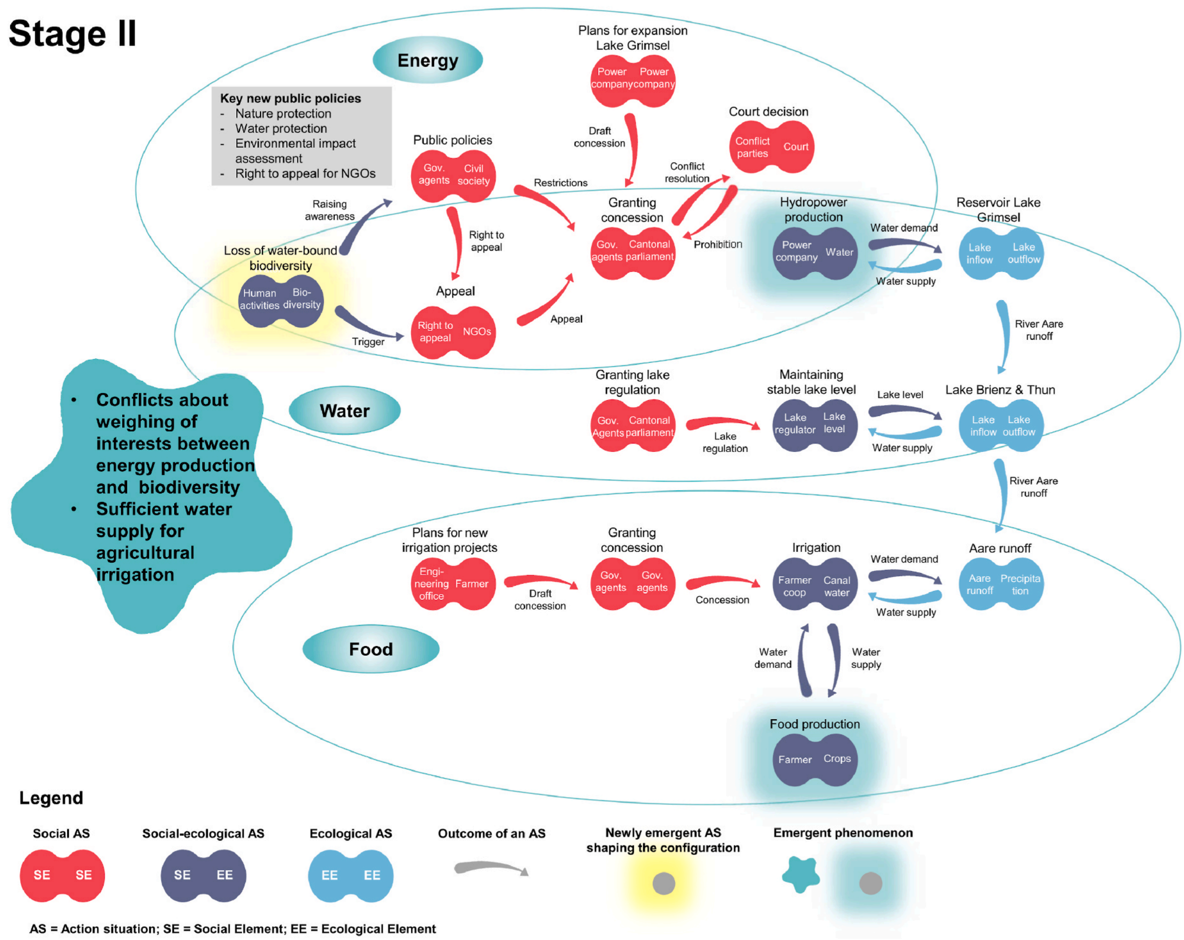

Fig. 4. Stage II of WEF nexus in the mid to late 20th century using the case of the expansion of Lake Grimsel shows an integration of energy and water while food production remains largely separated. The emergent issue of loss of water-bound biodiversity leads to a conflict between energy production and biodiversity, while sufficient water was available for irrigated food production.

3.3. Stage III (beginning of the 21st century): construction of the Trift dam

Anthropogenic activities have resulted in climate change, with consequences for the average global temperature, the volume loss and retreat of glaciers (Hugonnet et al., 2021), the formation of new (peri-) glacial lakes (Mölg et al., 2021), raising snow lines, precipitation amount and seasonality, runoff, and evapotranspiration (Arnell 2003; IPCC 2021, 2022). This has led to the evolution of new national and cantonal public policies for climate change mitigation and adaptation. To mitigate climate change, Switzerland has adopted an Energy Act in 1998 (with many revisions afterwards) and a 'Swiss Energy Strategy 2050' in 2017 aiming to phase out nuclear energy and to increase renewable energy, in particular hydropower. To adapt to climate change, cantonal and national adaptation strategies were adopted in 2010 and 2012, respectively. They aim to coordinate the different uses of surface and underground waters, water reservoirs, and lakes (BAFU 2012a, 2014; AWEL 2018). Further, a national biodiversity strategy was adopted in 2012 (BAFU 2012b).

In parallel with the evolution of new public policies, other key action situations coevolved to mitigate climate change but not to adapt to climate change. The retreating Trift glacier and the formation of a new lake in front prompted the power company to plan a new hydropower dam 10 km away from Lake Grimsel. As a response to the long-standing Grimsel conflict, being aware of the power of NGOs to block a project, they initiated a participatory process to develop a draft 80-year concession involving actors who could potentially file an appeal (NGOs and affected local communities). In contrast, downstream affected farmers had no power in these dynamics because of a lack of right to appeal and were, consequently, not invited to the process. The focus of this process was to find a compromise between energy production and biodiversity conservation. Downstream irrigation needs were not part of the discussion. In contrast to the area around Lake Grimsel, the project area is not (yet) protected and environmental NGOs would have little legal basis to block the process. In this light, and due to goals to increase renewable energy for climate change mitigation in their statutes, the environmental NGOs showed a high willingness to compromise. They determined that establishment of hydropower in the Trift area would be ecologically justifiable (Kellner 2019). However, adaptation strategies, aiming at cross-sectoral coordination of water uses, were not considered. The draft concession was submitted to the canton in 2017 but has not been granted by early 2022 due to formal aspects. The hydropower company did not include a mandatory time schedule for the project implementation in the draft concession and the canton of Bern did not integrate the project into its Cantonal Structure Plan. However, the concession is expected to be granted soon (Mentha

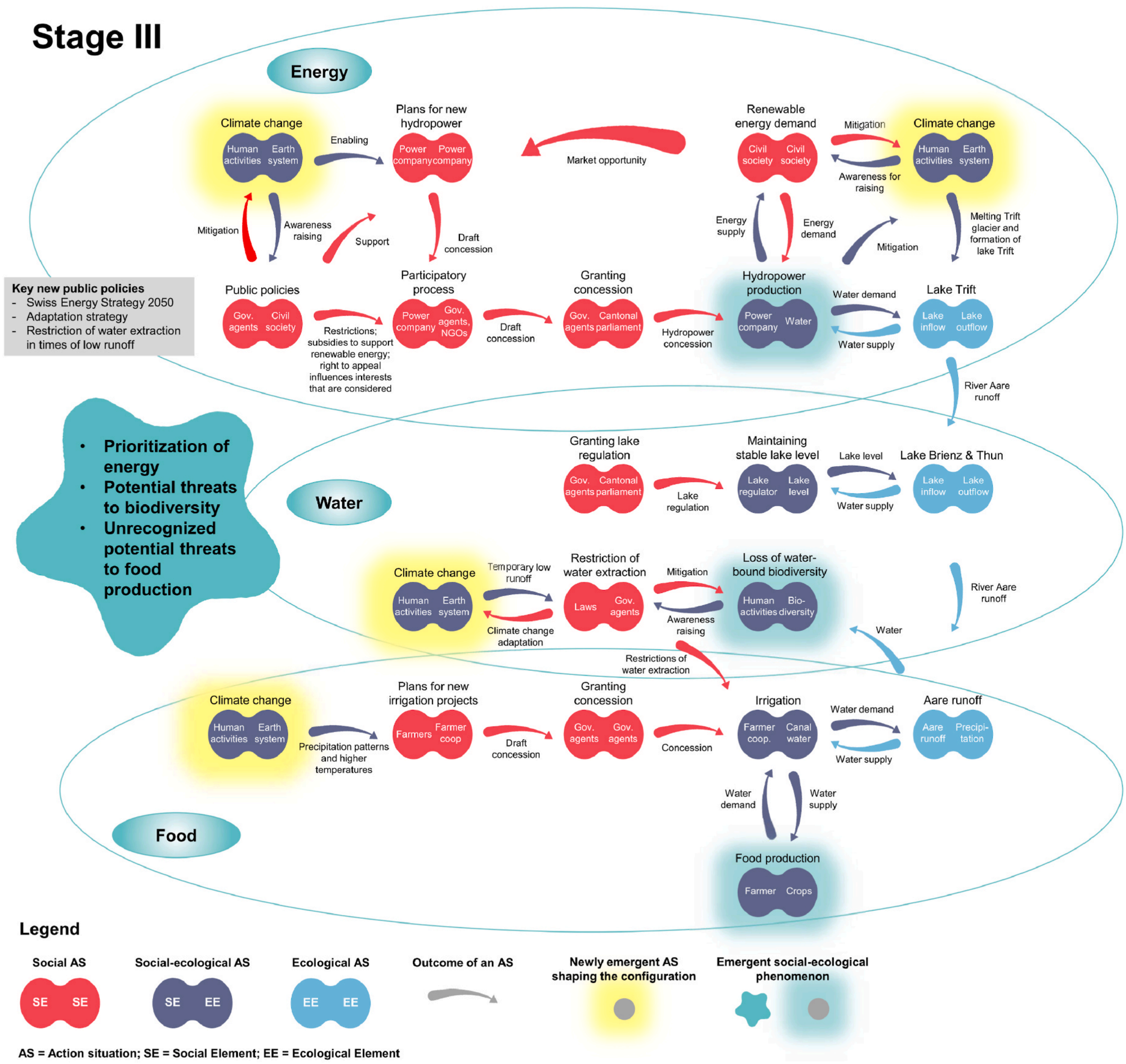

Fig. 5. Stage III of the WEF nexus at the beginning of the 21st century using the case of the construction of the Trift dam shows weak integration between energy and water and unilateral coordination between water and food production. The emergent issue of climate change results in climate change mitigation and adaptation strategies and growing demand for hydropower, leading to the prioritization of energy production, potential threats to biodiversity, and unrecognized potential threats to food production.

et al., 2019). The concession will allow to store and release water without restrictions except for a minimum amount of residual water at the direct outflow of the reservoir. This leads to the opportunity to produce hydropower flexibly, thereby providing energy during winter and stabilizing the electricity grid, without considering water scarcity further downstream.

The lake regulations consider flood protection and residual water but do not take into account situations of water scarcity for other downstream uses. If the lakes do not have sufficient inflow from upstream, temporal low runoff and higher water temperatures downstream in the River Aare in dry seasons can occur, in line with past events (Kaderli 2021), all disrupting the balance of ecosystems. This disruption could lead to a decline in water-bound biodiversity: generalists and warm-water species would benefit and new non-natives would invade, likely leading to impoverished communities with low multifunctionality (FOEN 2021). However, to ensure sufficient runoff to safeguard water-bound biodiversity, the cantonal authorities can limit or prohibit temporally the extraction of water for irrigation.

To adapt to higher temperatures and changing precipitation patterns, plans of Seeland farmers for new irrigation projects coevolve. They want to use more water from the river Aare to irrigate their agricultural land. Interviews revealed that they were not aware of potential future limitations for extraction due to low Aare runoff, which could lead to a loss of harvest and income for farmers in dry years. As a consequence of this lack of awareness, no conflicts about upstream water regulations, in particular the requested 80-year concession of the hydropower dam, have been mentioned.

Even though the energy, water, and food systems are part of one water cascade depending on the same upstream water supply and water uses, they are not coordinated and follow sectoral approaches. This

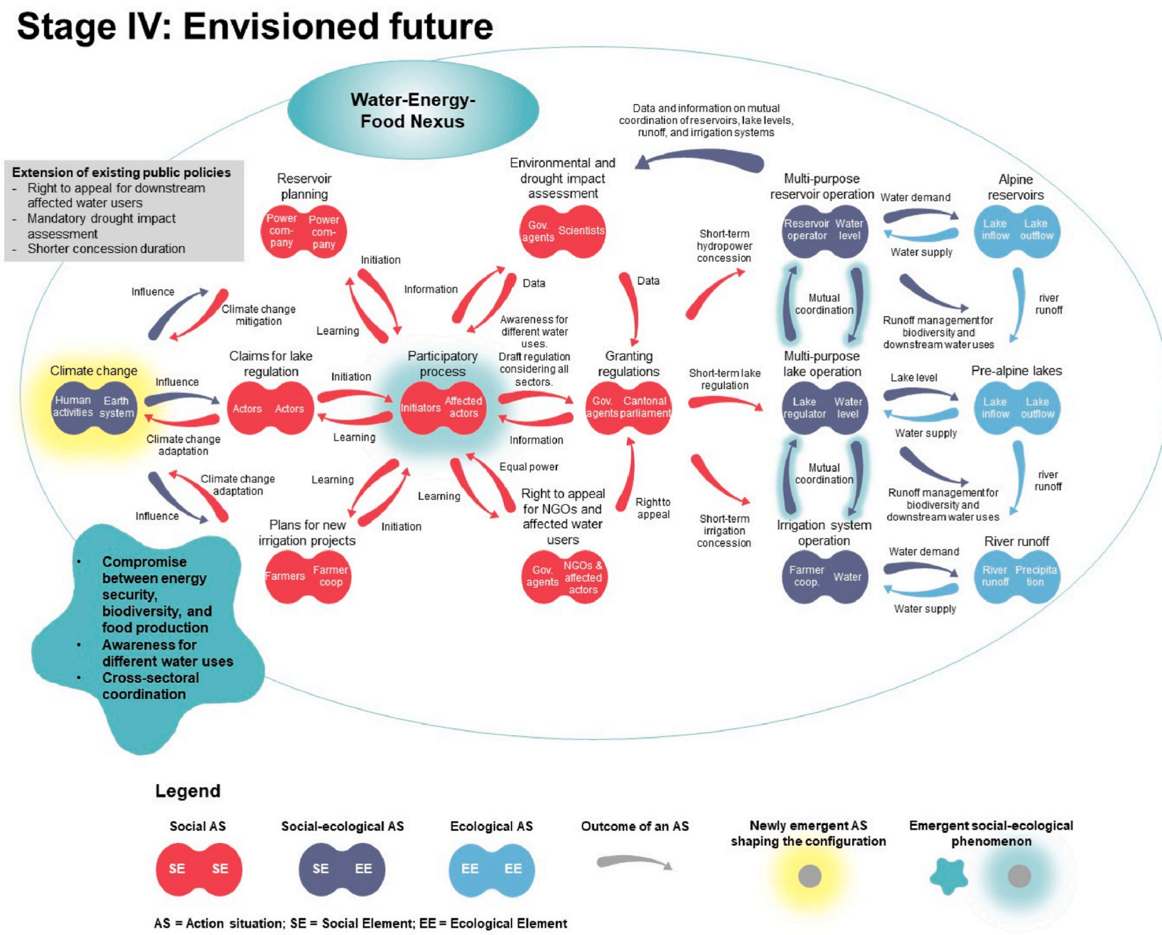

Fig. 6. Stage IV of the WEF nexus shows an envisioned future with the extension of existing public policies that is expected to result in mutual coordination of water uses for all three sectors. This coordination would result in compromises between energy security, water-bound biodiversity, and food production.

becomes visible in Fig. 5, where the ecological action situations are linked through the cascade whereas the social action situations are not linked. Social-ecological action situations, which manage water uses, do not consider other uses.

The emerging WEF nexus phenomenon is a prioritization of energy production with potential threats to water-bound biodiversity, and unrecognized potential threats to food production.

3.4. Stage IV: envisioning futures with participatory processes leading to mutual coordination of competing water uses

The analyses of the different stages show that the system adapted to evolving threats for biodiversity. In contrast, new public policies addressing climate change adaptation were developed and adopted but not considered in the WEF nexus case. The Trift case shows that trade-offs between hydropower production and biodiversity conservation could be managed through a participatory process in combination with equal power between the representatives of the two sectors due to the right to appeal of the NGOs. However, due to (a) a lack of awareness of the impact on other water needs downstream and (b) no right to appeal for downstream water users, farmers and other downstream water users were not integrated into this process, leading to an unequal consideration of the different sectors. Data about future downstream water scarcity were also not available for decision-making.

Based on our system understanding and discussions with representatives from Swiss Federal Offices, we identify key interventions to address the current unsustainable emergent phenomenon. These would steer transformational change towards the equal consideration of all three sectors. Specifically, we identify three extensions of existing public policies (Fig. 6): 1) Extension of the right to appeal against concessions and lake regulations to downstream affected actors (inspired by the existing right to appeal for environmental NGOs); 2) Introduction of a mandatory drought impact assessment at a relevant scale for current and future downstream drought scenarios (inspired by the existing mandatory environmental impact assessment); 3) Reduction of the duration of water concessions (inspired by a recent Swiss Federal Court decision regarding the duration of water rights; (Swiss Federal Court, 2019). These policies are expected to lead to i) the implementation of participatory processes when planning for new hydropower dams, the expansion of existing dams, or the renewal of existing hydropower concessions, new claims for lake regulation, or new plans for irrigation or the renewal of existing irrigation concessions; ii) equal power between all three sectors; and iii) sufficient data to find options for coordination between energy security, biodiversity, and food production to ensure just and ecological water uses. These changes are expected to foster learning processes and information sharing, allow responding to climate and socio-economic changes in a timely manner, create water rights with a higher social-ecological system fit, and – consequently –

lead to a higher adaptive capacity of the WEF nexus.

4. Discussion

The results show that deep interdisciplinary system knowledge is necessary to understand the evolution of the WEF nexus phenomena over time. This understanding of past WEF evolution helps to envision interventions to transform the WEF nexus towards long-term sustainability regarding energy production, biodiversity conservation, and food production. The contributions of our approach are threefold: 1) We conceptualize the WEF nexus as an intertwined system to understand the phenomenon of interest; 2) we understand past coevolution in intertwined systems to envision transformative solutions; and 3) we envision transformative solutions as a basis for transformation and future research.

4.1. Conceptualization of the WEF nexus as an intertwined system to understand the phenomenon of interest

Here, we conceptualize the WEF nexus as an intertwined system of coevolutionary processes between social and ecological actions situations. Treating human elements - such as farmers - and ecological elements - such as river runoff - as equal is an important step to better account for the intertwined nature of WEF nexus cases (Schlüter et al., 2019). This systemic perspective goes beyond former social-ecological systems frameworks which mainly conceptualized biophysical conditions as context factors to social interactions.

The approach - including the development of the visualization - supports a structured analysis of the interplay of social-ecological interactions (Haider et al., 2021). It enables a deep diagnosis of the coevolving interactions across spatial (Aare catchment) and temporal (120 years) scales as well as sectors (energy, water-bound biodiversity, food production). The presented case shows how the continuous interplay between microlevel elements (e.g., hydropower production) forms emergent macrolevel phenomena (e.g., prioritization between sectors), which, in turn, influence microlevel elements (e.g., new public policies), creating feedback processes that shape the evolution of the WEF nexus and enable it to adapt and change over time (Lansing, 2003). With this, the focus shifts from the characteristics of individual elements to the characteristics of the relations and interactions between system elements and macro patterns (Preiser et al., 2018). This allows to uncover complex causation and relevant coevolving dynamics of social-ecological processes (e.g., responses to biodiversity loss) and shows how the system adapts to changing ecological or social action situations (e.g., new public policies; (Folke et al., 2016; Orach and Schlüter 2021). Ultimately, these dynamics result in altered social-ecological phenomena, which are more than the sum of the ecological or social elements (Reyers et al., 2018). With this, the framework also goes beyond existing approaches studying social-ecological water systems with systems thinking, e.g., the hydrosocial cycle by Linton and Budds (2014). They integrate water's social and political nature into the hydrological cycle "to conceptualize the hydrosocial cycle as a socio-natural process by which water and society make and remake each other over space and time" (Linton and Budds 2014, p. 170). While addressing the coevolution between social and ecological processes, they do not explicitly integrate the relations and interactions between system elements and macro patterns.

In addition, the coloured visualizations of the configurations allow for an integrated understanding of the case that goes beyond individual action situations. It gives a quick overview and additional information due to the coloured patterns and the connections or disconnections within or between colours (e.g., coordination of water rights). A survey at the end of a workshop in January 2021 about this study with Swiss Federal Offices for Environment, Energy, and Agriculture (n = 8) showed that five participants agreed that such visualizations helped a lot to identify and understand the social-ecological interactions in a better way, and three participants agreed that it helped, but not to understand details. This result confirmed the discussion about the visualization during the workshop.

We argue that this conceptualization also goes beyond other nexus approaches, which call for increased and effective coordination across sectors and levels (Albrecht et al., 2018), while knowledge about the barriers for effective coordination is still lacking (Srigiri and Dombrowsky 2021). Even though some nexus studies identify barriers to achieve policy coherence across nexus sectors, they do not identify why the barriers are present, what influences them, and how they can be transformed (Weitz et al., 2017). The SE-AS framework allows also to integrate power relations as the presented case shows.

However, we identified also challenges and limitations using the SE-AS framework. On the one hand, the SE-AS framework provides a system understanding of dynamics in complex social-ecological systems, e.g., WEF nexus cases. On the other hand, it offers fewer details of individual action situations compared, for example, to the IAD framework or the NAS approach, e.g., Kellner (2022). This trade-off is difficult to balance and it is not always clear to an analyst what details need to be integrated to explain the emergent phenomenon. It is important that the frameworks do not get too complex because we would lose the capacity of the frameworks to help us study complex systems. The question is how do we make the simplest framework that can deal with complex systems? Second, it can be difficult to differentiate between external drivers of the social-ecological system of interest which cannot be influenced by actors or ecological processes within the social-ecological system and internal drivers which can be influenced through social-ecological interactions and need to be represented as action situations (Schlüter et al., 2019)? For example, Schlüter et al. (2019) categorize climate change as an external driver whereas we integrate it in our configuration as an ecological action situation which could be influenced (e.g., climate change mitigation policies) and influences social action situations (e.g., awareness raising). Third, the SE-AS framework defines interactions between action situations as the outcome of action situations (Schlüter et al., 2019). The NAS approach, for example, differentiates between an outcome of an action situation and interactions between action situations (Kimmich et al., 2022). The distinction between outcomes and interactions remains rather vague. For example, several climate change adaptation strategies were developed at the beginning of the 21st century in Switzerland which is an important outcome of a social action situation. However, if no interaction evolves with other action situations, it is questionable whether it should be integrated into the configuration or not even though the neglect explains also the unsustainable emergent phenomenon. Herzog et al. (2022) observed similar challenges by stating that it depends on the researcher's perspective what is defined as a process of interaction or as an outcome. This could be also relative to time or a question of resolution to capture the action situations and their interrelations.

4.2. Understanding past coevolution in intertwined systems to envision transformative solutions

The proposed conceptualization of WEF nexus cases resulting in the understanding of past coevolution helps to envision transformative solutions. Our suggestions – e.g., the extension of the right to appeal to downstream affected actors – are inspired by past policy changes – e.g., the right to appeal for environmental NGOs – that led to the consideration of water-bound biodiversity in hydropower concessions. Our envisioned future aims to steer the implementation of participatory processes to develop draft water rights, which integrate WEF nexus sectors through mutual coordination. This will require a compromise between hydropower production, water-bound biodiversity, and food production with irrigation needs. Such an absence of a win-win situation, even in an envisioned future, highlights that trade-offs are common in social-ecological systems (Cavender-Bares et al., 2015) and that compromises may be the optimal solution in the absence of co-benefits.

Importantly, participation alone cannot result in the envisioned future: it may build on the assumption of limited knowledge of individual participants, and may be prone to reinforcing existing interests and thus may also have adverse effects on adaptive decision-making (Kirschke and Newig 2021). Therefore, our envisioned solution is not the implementation of such processes itself, but the implementation of key public policy extensions: 1) the extension of the right to appeal to steer willingness to implement participatory processes and to have equal power of all participants, 2) mandatory drought and environmental impact assessments to provide sufficient knowledge for decision making, and 3) reduction of the duration of water concessions to increase the adaptive capacity of the nexus. Similar policies have had strong effects in the past coevolution of the system (Stages l – lll). By adapting them to the new situation under climate change, we expect these 'extended policies' to lead to a participatory process with balanced powers. This three-fold approach is likely more effective to address complex problems than one-fits-all solutions (Kirschke and Newig 2021).

To foster the implementation of our proposed interventions, the results were summarized in a report for the Swiss Federal Offices (Kellner et al., 2021) and, were presented at several events of the Swiss administration, as well as at public events. These activities were already partly successful. A cantonal politician attending one of the presentations recognized the need to act. He tabled a motion in the cantonal parliament which directly builds on our policy extension two, the mandatory drought and environmental impact assessments to provide sufficient knowledge for decision making (Motion 2021). The parliament of the canton of Bern passed this motion in March 2022.

4.3. Envisioning transformative solutions as a basis for transformation and future research

Complex social-ecological systems are inherently unpredictable (Biggs et al., 2021) since they are characterised by coevolution, non-linear effects, learning, creativity, and novelty (Preiser et al., 2018). In times of global change, we face unexpected and unknown disruptive events, e.g., COVID (Berbés-Blázquez et al., 2022). Therefore, we propose interventions that balance power relations and promote learning processes, information sharing, and flexibility, increasing the adaptive capacity of the system. Despite this, any envisioned future should not be considered as a prediction but rather as one of many ways that would result in more sustainable phenomena. Importantly, the envisioned transformative solution to integrate all affected actors in the process and to give them balanced powers, may also shape the nexus case itself and stimulate future research. Visualizations of past coevolutionary processes and envisioned futures can be used in existing and future participatory processes to stimulate discussions outside sectorial silos, thereby positively contributing to a mutual understanding of different sectorial perspective and to a common understanding of the problem by diverse actors. This may allow to see the intertwined system as a whole, and setting a prerequisite for developing and implementing water rights with equal consideration of all three WEF sectors (Scharmer and Käufer 2013). Furthermore, the configurations of action situations may also serve as a basis to identify and study specific action situations or coevolutionary processes in more depth. Here, agent-based modelling (Schulze et al., 2017) could allow researchers to explore various scenarios in the nexus context.

5. Conclusion

The nexus concept was formulated in response to siloed thinking and emphasizes the examination of critical interlinkages across resources by focusing on trade-offs and synergies between sub-systems. Despite this intention, scholars predominantly apply approaches which provide a narrow perspective on interactions among water, energy, and food systems (Albrecht et al., 2018; Khan et al., 2022). Consequently, conclusions of these studies often fail to address underlying drivers of current trajectories and therewith a transformation of the system toward sustainability.

We present an approach which tries to understand the causes of unsustainable WEF nexus phenomena by analysing past coevolution of the intertwined system using the nascent 'Social-Ecological Action Situations' framework. We then envision a transformative solution. The approach incorporates the intertwined nature of social-ecological systems and understands processes as coevolutionary. This perspective goes beyond former nexus studies, which conceptualize biophysical conditions mainly as context factors to social interactions or vice versa. Further, it understands nexus cases as complex coevolving systems and focuses, consequently, on interactions between system elements and macro patterns and not on individual elements themselves. We argue that this perspective on WEF nexus cases is crucial to find interventions that could increase the adaptive capacity of the system and transform the WEF nexus towards long-term sustainability through balancing power relations and increasing learning processes and information sharing which also leads to a compromise between energy production, biodiversity conservation, and food production. This is key to achieve the Paris Agreement, the post-2020 biodiversity targets, and Sustainable Development Goals (Liu et al., 2018; Chan et al., 2020).

CRediT authorship contribution statement

Elke Kellner: Formal analysis, Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Dominic A. Martin:** Methodology, Visualization, Writing – review & editing.

Declaration of competing interest

The 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.

Data availability

The data that has been used is confidential.

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Appendix A

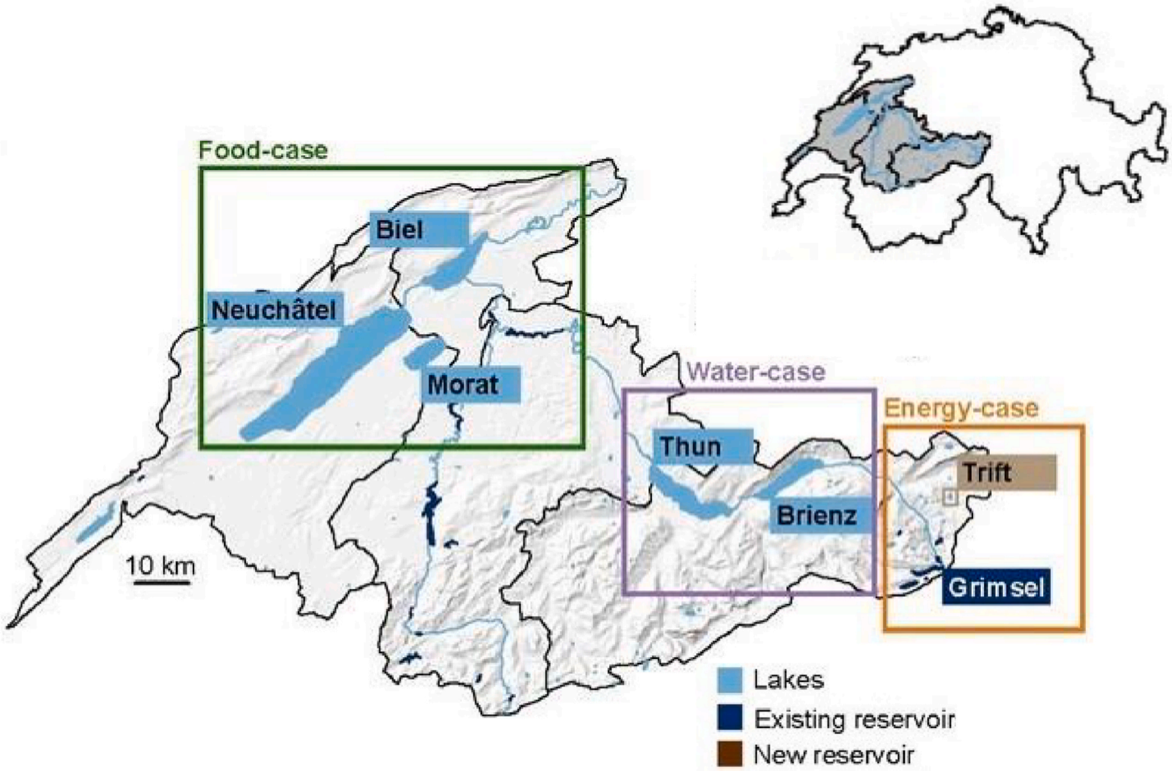

Fig. A.1. Map of the study region in Switzerland: The energy-case with the existing Grimsel reservoir and the planned Trift reservoir, the water-case with the lakes Brienz and Thun and the food-case downstream in the region of Seeland.

Table A.1
List of formal interviewees.

No	Function	Category	Date
1	Regional NGO	NGO	06.06.2017
2	Regional NGO		09.06.2017
3	Cantonal NGO		June 07, 2017
4	Cantonal NGO		22.08.2018
5	National NGO		10.06.2017
6	National NGO		13.06.2017
7	National NGO		15.06.2017
8	National NGO		26.10.2017
9	Commune President	Politicians	22.06.2017
10	Commune President		22.06.2017
11	Commune President		22.06.2017
12	Cantonal politician		30.10.2017
13	Cantonal politician		20.10.2017
14	Cantonal politician		16.10.2017
15	Cantonal politician		24.10.2017
16	Cantonal politician		06.10.2017
17	Cantonal politician		10.10.2017
18	Regional administration	Administration	15.08.2017
19	Cantonal administration		30.10.2017
20	Cantonal administration		14.12.2017
21	Cantonal administration		20.12.2018
22	Cantonal administration		14.04.2020
23	National administration		11.04.2019
24	National administration		14.10.2020
25	Hydropower Company	Business	13.08.2017
26	Hydropower Company		14.11.2018
27	Agricultural representative		09.04.2020
28	Downstream farmer and agricultural representative		15.04.2020
29	Cantonal agricultural consulting institute		20.04.2020
30	Scientist	Science	19.01.2021
31	Scientist		21.01.2021

Several informal interviews with farmers during fieldwork in April 2020.

General interview guide

The interviews followed a common interview guide where questions have been adapted to the individual knowledge and experiences of the interview participants. The general structure was the following.

1) Interviewee's professional background
2) History of the case
3) Actors, interests, actors' strategies, conflicts
4) Governance (institutions and processes)
5) Conflict regulation, participation, justice, decision-making
6) Network
7) Individual learning processes
8) Future, climate change, adaptive capacity
9) Important actors for interviews

Appendix B

We propose a diagnostic procedure to operationalize the SE-AS framework (Table B.1). It modifies the list of guiding questions that Schlüter et al. (2019) developed. All steps need to be performed in an iterative process.

Table B.1
Diagnostic procedure to operationalize our approach. Adapted from Schlüter et al. (2019) and Kellner and Brunner (2021).

Step	Topic	Description
1	Emergent social-ecological phenomenon	Define the current emergent social-ecological phenomenon, which should be explained.
2	Key action situations generating the phenomenon	Identify the social, social-ecological, and ecological action situations that are considered as key for generating the emergent social-ecological phenomenon from a theoretical or empirical perspective.
3	Action situations influencing key action situations	Identify action situations that influence the key action situations.
4	Newly emergent action situations	Identifying emergent action situations that shape the configuration

We propose to start with the current emergent social-ecological phenomenon and to then move on to the identification of the action situations that are considered as key for generating the phenomenon from a theoretical or empirical perspective. Subsequently, we propose to delineate action situations that influence key action situations. Afterwards, we propose to identify newly emergent action situations that shape the configuration. The identified action situations create the system boundary.

Once the current configuration of action situations is created, we propose to step back in history to create a past configuration of action situations. It is important to consider that the past emergent social-ecological phenomenon shapes the current configuration of action situations (Fig. B.1). The understanding of past and current configurations, in turn, helps to envision possible sustainable future configurations.

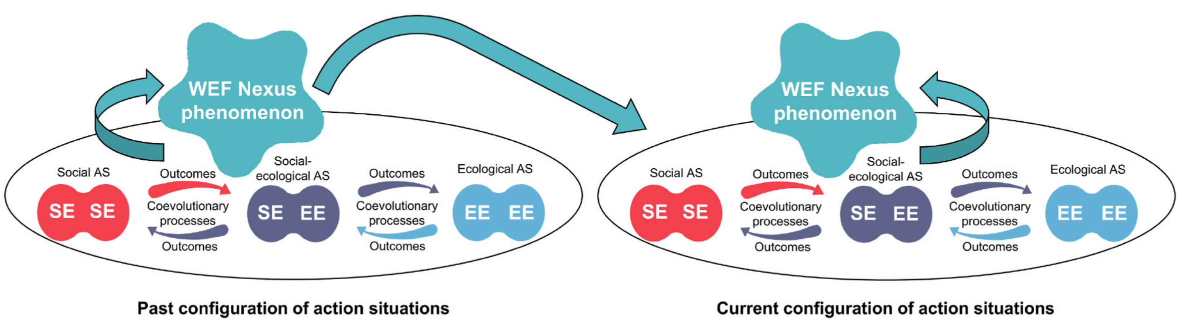

Fig. B.1. The past social-ecological phenomenon shapes the current configuration of action situations. WEF Nexus = Water-Energy-Food Nexus; AS = Action Situation; SE = Social Element; EE = Ecological Element.

Experiences have shown that it is not possible to do such a configuration of action situations properly step by step or to think about social action situations, ecological action situations, social-ecological action situations, and outcomes separately. It is an iterative process of repeating cycles. Therefore, developing the past configuration helps to improve the current configuration and vice versa (Fig. B.2).

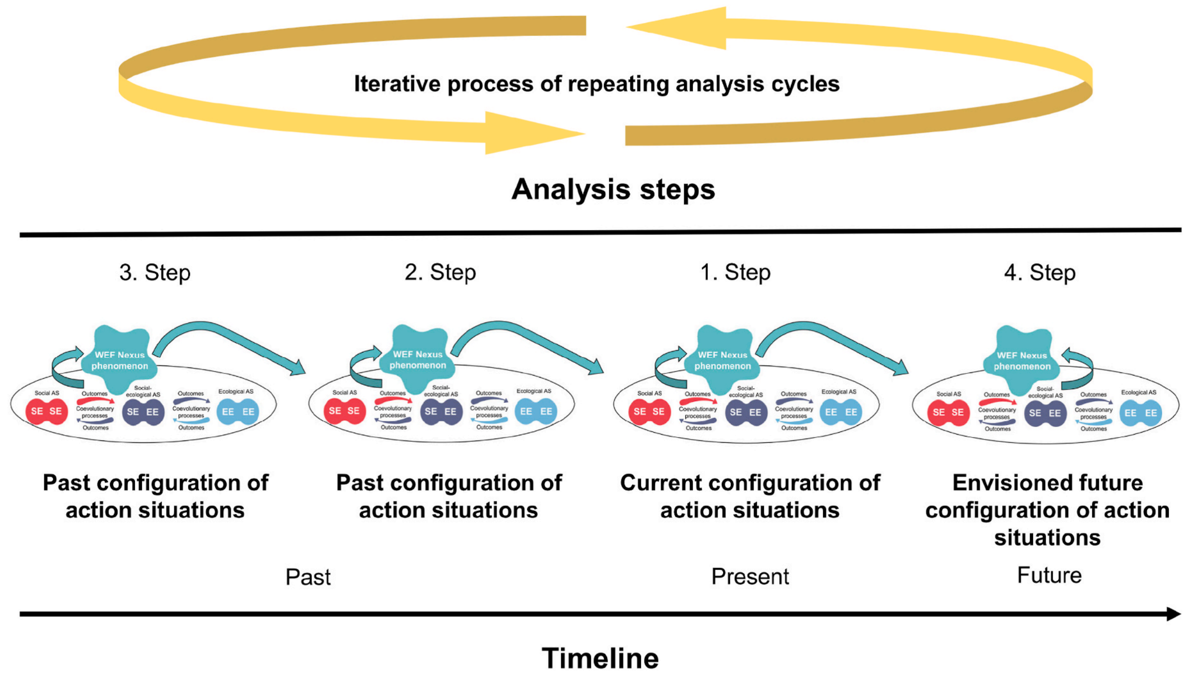

Fig. B.2. Iterative process of repeating cycles to create past and current configurations of action situations and to envision a possible future configuration

All steps may be performed by disciplinary or interdisciplinary research teams or in transdisciplinary co-production of knowledge, depending on projects, research goals, and capacities.

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