Sustainability Science (2023) 18:135–152
https://doi.org/10.1007/s11625-022-01170-7

SPECIAL FEATURE: ORIGINAL ARTICLE

Networks of Action Situations in Social-Ecological Systems Research

Identifying leverage points for shifting Water-Energy-Food nexus cases towards sustainability through the Networks of Action Situations approach combined with systems thinking

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Received: 14 August 2021 / Accepted: 24 April 2022 / Published online: 18 June 2022

Abstract

In the twenty-first century, the world´s demand for natural resources is more pressing and deeply interconnected than ever before. The Water-Energy-Food (WEF) nexus has gained growing interest as a promising concept for complex resource management challenges. However, knowledge about the root causes of cross-sectoral coordination problems and how they can be shifted towards sustainability is still lacking. This paper fills this gap by conceptualising a WEF nexus case with the Networks of Action Situations approach combined with systems thinking. This approach allows a deep analysis of the root causes of coordination gaps, facilitates a joint understanding of the system dynamics to identify leverage points for shifting the WEF nexus towards sustainability, and to envision the impact of potential interventions on the network of action situations and their outcome. The value and the reciprocal benefits of the combined approach introduced are illustrated for a case in Switzerland, Europe. The results show a coordination gap between the different sectors and that not all sectors were considered equally. This leads to a prioritization of energy production over water-bound biodiversity and food production. The root causes for this outcome are a focus to mitigate climate change and awareness of biodiversity but much less awareness of the impacts of climate change on Swiss water bodies. The study identifies five deep leverage points for interventions, which are expected to ensure a shared systemic problem understanding and more balanced coordination between different sectors resulting in the sustainable and equitable provision and utilization of WEF resources.

Keywords Water governance · Social-ecological systems · Renewable energy · Climate change · Adaptation · Mitigation · Biodiversity · Water scarcity · Mental models

Introduction

In the twenty-first century, the world´s demand for natural resources is more pressing and deeply interconnected than ever before and is expected to continue with threats to people and ecosystems at various levels (Liu et al. 2015; Bleischwitz et al. 2018). The implementation of the Sustainable Development Goals (SDGs) shows also the interdependencies between the goals and targets, whereby action toward one goal impacts the performance of one or more others (Pham-Truffert et al. 2020). Accordingly, the key sustainability challenges of the twenty-first century cannot be addressed without recognising the systemic nature of these problems (Biggs et al. 2021). Therefore, comprehensive approaches are needed to understand interdependencies in complex resource systems and to find leverage points for interventions to shift the system towards more sustainable resource uses. The debate on the Water-Energy-Food (WEF) nexus addresses such interlinkages and encourages a more holistic perspective on sustainable development of natural resources (Pahl-Wostl et al. 2020). Considering how water, energy, and food sectors are both interconnected and interdependent, the nexus concept targets the maximization of synergies (mutually beneficial outcomes) and minimization of trade-offs (potentially non-optimal outcome for a single

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sector). It aims to promote "policy coherence through identifying optimal policy mixes and governance arrangements across the water, energy and food sectors" (Weitz et al. 2017, p. 165). To achieve these goals, an integrated perspective across the nexus is necessary to avoid maladaptation and negative externalities (Hoff 2011).

Despite these aims, most scholars focus on the biophysical interlinkages in WEF nexus cases (Albrecht et al. 2018) and call for increased and effective coordination across sectors and levels, but knowledge about the root causes for effective coordination is still lacking (Srigiri and Dombrowsky 2021). Although some scholars identify barriers to achieving policy coherence across the WEF nexus, they do not identify why the barriers are present, what influences them, and how they can be transformed (Weitz et al. 2017). Venghaus and Hake (2018, p. 191) propose that future research should focus "on understanding the relevant action situations of the nexus policy making process including the role and influence of actors and institutions within them".

This paper fills this gap by conceptualising a WEF nexus case with the Networks of Action Situations (NAS) approach (McGinnis 2011b; Kimmich et al. 2022) combined with systems thinking (Meadows and Wright 2011). The NAS approach postulates that "actors' decisions depend on the institutional structure of a particular situation and the decisions made in related situations" (Villamayor-Tomas et al. 2015, p. 735). This approach helps to analyse how decisions across sectors and levels of action shape directly or indirectly decision-making in adjacent action situations (Ostrom et al. 2014). Therefore, it enables to diagnose how current dynamics in WEF nexus cases affect water, energy, and food provision and utilization and which governance processes shape these dynamics. Systems thinking is an integrated and holistic way of thinking that helps to understand how different system components interact with each other to generate overall outcomes (Sanneh 2018). This understanding allows the identification of leverage points for system change, which are points in the dynamics of a complex system to intervene for impactful change (Bryant and Thomson 2020). Leverage points can range from 'shallow' leverage points where interventions are relatively easy to implement but have little potential for system change to 'deep' leverage points that might be difficult to implement but have a high potential for system change (Meadows 1999). This systems perspective in combination with the NAS approach helps to identify leverage points in the network of action situations and to envision how its implementation could shift the WEF nexus case towards more sustainable and equitable provision and utilization of WEF resources.

This approach is illustrated empirically through a WEF nexus case in Switzerland, Europe. In this case, water is constructed as a sector to protect water-bound biodiversity, energy to produce hydropower (climate change mitigation), and food as irrigation for agricultural food production (climate change adaptation). Data collection includes semi-structured interviews and document analysis to diagnose the current WEF nexus dynamics. In an iterative expert deliberation process afterward, leverage points were identified, which are expected to shift the WEF nexus case towards sustainability. The objective is to maximize synergies between sectors and minimize trade-offs. In concrete terms, interventions based on the identified leverage points are expected to ensure balanced coordination between hydropower production to mitigate climate change, water-bound biodiversity protection, and irrigation to adapt to climate change. This article is guided by the following research questions: *(1) How do—in a WEF nexus case—decisions at different levels of action shape day-to-day activities affecting the provision and utilization of WEF resources? (2) Which leverage points are expected to shift the WEF nexus towards more sustainable and equitable provision and utilization of WEF resources?*

Analytical approaches

Networks of action situations (NAS) approach

The NAS approach is based on the Institutional Analysis and Development (IAD) framework (Ostrom 2005, 2011; McGinnis 2011a) and the Social-Ecological Systems (SES) framework (Ostrom 2009; McGinnis and Ostrom 2014). Both frameworks are widely considered to be state-of-the-art for analysing resource governance issues and provide powerful tools to build theory about collective action problems and to explain how, why, and under what conditions actors can resolve contested resource claims. However, there are several limitations to these tools. They address small-scale common pool resource systems (Cox et al. 2010) and have not yet been widely applied to more complex problems, where governance may require a mix of policy solutions to prompt action across diverse sectors, jurisdictions, and levels of government (Thiel and Moser 2018; Baldwin et al. 2018). The frameworks enable diagnosing interactions and outcomes in social-ecological systems (Partelow 2018) but typically focus on outcomes within a single policy area (Chhatre and Agrawal 2009). This focus can overlook how governance processes are maintaining trade-offs among different policy areas—such as water, energy, and food. The nascent NAS approach builds on existing strengths of the IAD and the SES frameworks but addresses the above mentioned gaps (McGinnis 2011b). It expands the scope of analysis to encompass multiple sectors and policy outcomes by identifying linkages between multiple action situations (McGinnis 2011b).

Action situations are defined as venues for repeated interaction between two or more actors (Ostrom 2005). These interactions produce outcomes, which then affect future interactions within the same or related action situations. Action situations are linked or 'adjacent' if the outcome of one action situation directly influences decision-making in one or more additional action situations (McGinnis 2011b). Moreover, action situations might occur on different levels of action: the constitutional, collective, or operational choice level (Kiser and Ostrom 1982; Ostrom et al. 2014), whereby levels of actions are usually not levels of government, even though they could correspond to them. These levels constitute a hierarchical, multi-level structure, in which each upper level determines how decisions are made in action situations at the next, downward level. Actors in action situations at the constitutional choice level determine the overarching rules, like national water protection laws, that shape rulemaking at the collective choice level, where actors make shared policy decisions such as water extraction rules (e.g., irrigation concessions), which influence the operational level, where actors make day-to-day decisions on resource uses, for example, the amount of water pumped by a farmer. However, the outcomes of lower levels can also, in turn, trigger decisions in action situations at upper levels, if, for example, the extraction of water for irrigation is threatened through upstream hydropower production. As a consequence, actors at the operational level may organise activities to influence outcomes of action situations at the constitutional or collective choice level. The configuration of individual action situations and the outcome-based linkages between them constitute a 'network' of action situations. Thus, the NAS approach allows for identifying the levels of action for collective decision-making and the diagnosis of decision-making in individual action situations, and of dynamics between them (Basurto et al. 2020). This helps to conceptualise governance systems in e.g., WEF-nexus cases, where competing interests interact within and across different action situations at different levels. Therefore, the NAS approach is well-suited for 'deep diagnoses' of collective decision-making in multi-actor, multi-interest governance systems such as a WEF nexus case.

Recent developments of the NAS approach have focused on cases of fisheries management, international development cooperation, and social welfare (McGinnis 2011b), coordination of water uses (Dennis and Brondizio 2020; Kellner and Brunner 2021), renewable energy policies and deployment (Grundmann and Ehlers 2016; Baldwin and Tang 2021), energy infrastructure policies (Gritsenko 2018), water and energy governance in irrigation systems (Kimmich 2013; Kimmich and Villamayor Tomas 2019), and telecoupled resource systems (Oberlack et al. 2018; Boillat et al. 2018). However, application of the NAS approach on WEF nexus cases are still rare: Villamayor-Tomas et al. (2015) relate WEF nexus cases with value chain analyses; Möck et al. (2019) layer action situations to integrate spatial scales, resource linkages, and change over time; Srigiri and Dombrowsky (2021) suggest that applying the NAS approach on WEF nexus cases may help to achieve WEF-related SDGs; and Srigiri et al. (2021) identify multiple interlinked action situations that spread across operational, collective and constitutional choice levels in a case study of Ethiopian lower Awash River Basin.

Combining the NAS approach with systems thinking to identify leverage points

This study is the first contribution combining the NAS approach with systems thinking. Figure 1 synthesises the

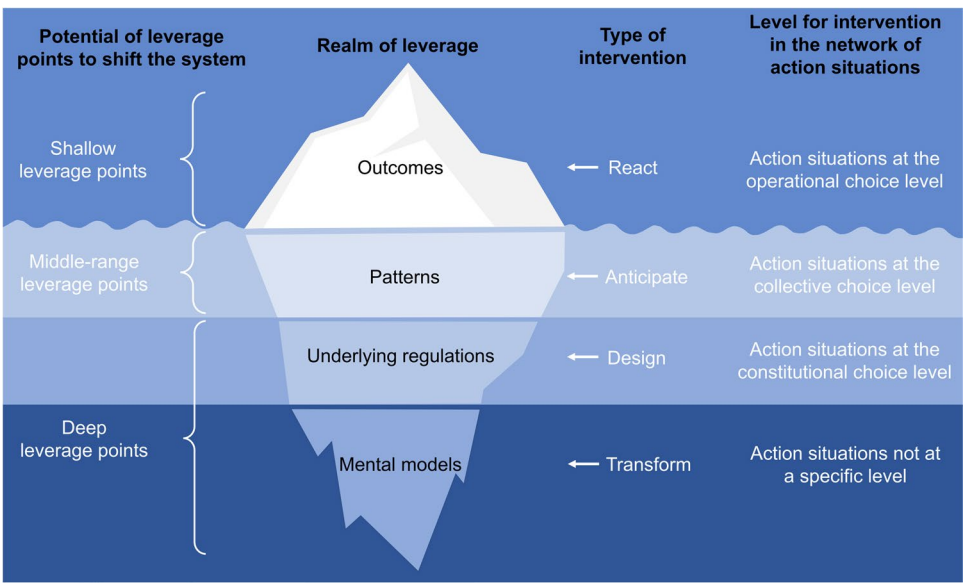

Fig. 1 Combination of the NAS approach with systems thinking. The iceberg model shows how observable outcomes on the surface and vague patterns around the waterline are manifestations of invisible, underlying regulations, and mental models. The figure links the potential of leverage points to shift the system and the type of intervention with the level for intervention in the network of action situations. Adapted from Davelaar (2021)

key elements of the combination using the iceberg model (Bosch et al. 2007; Kim 1999). The iceberg metaphor outlines how observable outcomes on the surface and vague patterns around the waterline are manifestations of invisible, underlying regulations, and mental models such as values, beliefs, or assumptions (Davelaar 2021). "Mental models are deeply held internal images of how the world works, images that limit us to familiar ways of thinking and acting. Very often, we are not consciously aware of our mental models or the effects they have on our behaviour" (Senge 2006).

Figure 1 shows four layers in the iceberg (outcomes, patterns, underlying regulations, mental models). They represent from the perspective of systems thinking consecutive levels of understanding of the system, and from the combined perspective of systems thinking and the NAS approach, levels of potential interventions in the system of concern:

- The outcome level is only the tip of the iceberg, which is the most visible part. From a NAS perspective, this is the outcome of the network of action situations, e.g., a prioritization of hydropower production over irrigation for food production. An intervention, which reacts directly to the outcome, would be an action situation at the operational choice level, e.g., the hydropower company increases the runoff for one day. This would be a shallow leverage point with little potential for shifting the system.
- Trends over time, patterns, are below specific outcomes. From a NAS perspective, these are outcomes of action situations at the collective choice level, e.g., hydropower concessions are usually granted for 80 years even though the law regulates "up to 80 years". This duration could be anticipated with interventions of action situations at the collective choice level. This intervention would be a middle-range leverage point.
- The underlying structures are behind the patterns. From a NAS perspective, these are outcomes of action situations at the constitutional choice level, e.g., environmental laws regulate the right to appeal to non-governmental organizations (NGOs). To change a law, which shapes rulemaking at the collective choice level, would be an intervention at the constitutional choice level, e.g., the extension of the right to appeal for downstream affected actors. The intervention would be a deep leverage point with a high potential for shifting the system.
- These structures are in turn based on underlying mental models of actors, which create the regulations at the constitutional and collective choice level. From a NAS perspective, these are outcomes of action situations at no specific level, e.g., awareness for biodiversity threats but not for water scarcity. An intervention to shift a mental model, e.g., awareness raising for water scarcity, could be localized at each level. The intervention would be a deep leverage point with a high potential for shifting the system.

This combined approach allows the identification of deep leverage points for interventions in the network of action situations of the WEF nexus case and to envision how its implementation could shift the network towards more sustainable and equitable provision and utilization of WEF resources.

Water-energy-food (WEF) nexus

Even though the nexus concept was formulated in response to siloed thinking, and emphasizes the understanding of interlinkages in a more integrated way (Bleischwitz et al. 2018), many scholars use mostly adapted conventional disciplinary approaches, such as mixed systems modelling, biophysical, or economic approaches (Albrecht et al. 2018; Yung et al. 2019; Liu et al. 2018). They focus on biophysical interdependencies among different sub-systems (Yung et al. 2019), resource-efficient technologies (Chang et al. 2016), or address potential synergies and trade-offs among sectors with improved technologies (Pahl-Wostl et al. 2020). This leads to knowledge about the physical interconnections between the sub-systems, but an integrated perspective across the nexus needs also knowledge about the institutional linkages (Villamayor-Tomas et al. 2015). However, the governance of WEF nexus cases has received comparatively little attention so far (Pahl-Wostl et al. 2020), and there is a need for more knowledge about institutions, policy goals, and policy instruments that guide actions leading to sustainable outcomes of WEF nexus cases (Srigiri and Dombrowsky 2021). This study aims to contribute to this knowledge in conceptualizing a WEF nexus case with the NAS approach combined with systems thinking.

Methods

This study is part of the broader study "Effects of climate change on Swiss water bodies. Hydrology, water ecology, and water management" of the Swiss Federal Offices (FOEN 2021). The goal of this water governance study was to provide an overview of the current situation in Switzerland and to identify potential interventions leading to more coordination between sectors. However, the mission of this study was not to find a consensus for implementation. This study relies on an exemplary case study research design. The case study region is located in Switzerland, which is an interesting case to investigate WEF nexus sustainability challenges because Switzerland (1) has a Swiss Energy strategy 2050 aiming to phase out nuclear energy and strives for energy security

(Energy Act SR 730.0); (2) has integrated food security in the Federal Constitution of the Swiss Confederation (SR 101, Art. 104a); (3) has established a biodiversity strategy and a biodiversity action plan (BAFU 2017, 2012c); (4) has elaborated national and cantonal climate adaptation strategies, which aim to coordinate the different uses of surface and underground waters, water reservoirs, and lakes (BAFU 2012a, 2014a; AWEL 2018) and guiding principles for integrated water management (BAFU 2012b; Water Agenda 21 2011); and (5) is strongly affected by climate change (Zekollari et al. 2019).

Data collection was carried out between 2018 and early 2021. The data collection included interviews, document analysis, and an iterative expert deliberation process with experts from the Swiss Federal Offices for Energy, Environment, and Agriculture and scientists. For the diagnosis of the current WEF nexus, 21 semi-structured face-to-face interviews were conducted, partly online due to the pandemic, with the main actors representing public authorities on different levels, the hydropower company, associations involved, downstream farmers, agricultural representatives, and scientists. The interviews followed an interview guide, where questions could be adapted to individual knowledge and experiences of the interview participant. The development of the interview guide was informed by insights of the document analysis. The interviews were designed to yield in-depth information on the involved actors, negotiations about the water rights at the collective choice level, political strategies, specific resource use interests, and operationalisation of the water rights. They fostered a specific understanding of the WEF nexus governance processes. Additional information sources included document analyses of legal materials to understand action situations on the constitutional and collective choice level (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) to inform the interview guide and to support the identification of the different action situations. The interviews were transcribed and the collected data were analysed by a qualitative content analysis (Mayring 2010).

Multiple approaches exist for the diagnostic procedure in NAS analysis (Oberlack et al. 2018): some approaches are informed by a theoretical lens (i.e., governance functions, value chains), others identify the boundaries of a NAS and the action situations according to the research question, in particular to the outcome of interest for which the NAS is developed. In both approaches, the action situations and their interactions in the network serve as an explanation for the root causes of the outcome of interest. In this study, the WEF nexus concept guided the NAS boundaries and the links between action situations. First, the boundary along the action situations of social interactions that influenced the outcome of the WEF nexus case was delineated. Second, the main actors involved were identified and how these actors interact with each other to address their claims and how they are influenced through the outcomes of adjacent action situations. Third, the main action situations and their interactions to explain the prioritization of specific sectors in the WEF nexus case were summarized.

To determine potential interventions for shifting the current WEF nexus case towards sustainability, an iterative expert deliberation process was conducted to identify leverage points (inspired by Chan et al. 2020). First, based on the understanding of the dynamics in the current WEF nexus, a preliminary set of leverage points was identified. Second, the results were presented to 14 experts from the Swiss Federal Offices and 4 scientists in a total of six meetings and a half-day workshop between 2020 and early 2021. In the meetings, the experts and scientists discussed first the dynamics of the current WEF nexus case based on the NAS and subsequently the suggested leverage points and their potential impact to shift the WEF nexus case. The discussions revealed that they were not aware of the prioritization of specific sectors in the WEF nexus case and different sectoral interests of the experts according to their representing Federal Offices. The different perspectives of the discussion and the identified leverage points formulated as policy recommendations were integrated into a practical report to the Swiss Federal Offices (Kellner et al. 2021). A mandate to continue this process to find a consensus and to implement the identified interventions was not included in this study.

Case study

The case study is located in Switzerland, Europe, in the region around Lake Zurich. In the upper part of the catchment are the artificial Lake Sihl and the natural Lake Zurich and downstream the agriculturally intense region Furttal (Fig. 2).

Lake Sihl (hydropower production)

Lake Sihl is an artificial lake to produce hydropower in the district of Einsiedeln in the canton of Schwyz and lies at an altitude of 889 m above sea level. The lake is crossed by the River Sihl, which is dammed on the north bank and can store a total volume of 96 million m^3. Permission to build this lake and produce hydropower was granted to the operators of the hydropower station at a municipal meeting in 1926. The operator is the Swiss Federal Railways AG (SBB), the state-owned railway company in Switzerland, which operates various hydropower plants to generate traction current. The construction of the dam and power plant 'Etzelwerk' began in 1932 and the valley was flooded in 1937 covering

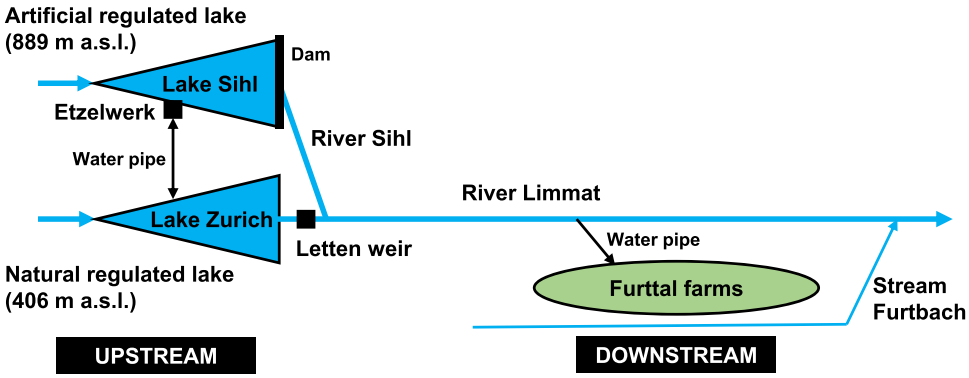

Fig. 2 Schematic map of the water system in the Swiss WEF nexus case around Lake Zurich. In the upper part of the catchment, the artificial Lake Sihl and the natural Lake Zurich are located in parallel and directly connected through a water pipe to pump water and to produce hydropower (Etzelwerk). The run-of-river power plant Letten weir is downstream of Lake Zürich. An agriculturally intense region (Furttal) with irrigation demand is located in the downstream part of the lakes

fens and raised bogs, over 90 buildings, and over 50 farms and their land, displacing over 500 people.

Lake Sihl is connected to the underlying Lake Zurich through a water pipe. The Etzelwerk produces 270 GWh of traction power annually for the SBB by turbining water from Lake Sihl into Lake Zurich. The Etzelwerk can also pump water up from Lake Zurich into Lake Sihl for short-term storage of purchased electricity. Below the dam, the River Sihl flows out of the lake entering the River Limmat. In addition to generating electricity, Lake Sihl is used for various water sports, local recreation, and flood protection. The 80-year concession for electricity production at the Etzelwerk expired in 2017. Due to long and difficult negotiations, which did not address water scarcity, a 5-year transition concession until 2022 was granted and a new draft concession was submitted to the authorities in 2020.

Lake Zurich

Lake Zurich is a natural lake located in the cantons of Zurich, St. Gallen, and Schwyz at an altitude of 406 m above sea level. The main inflow is the River Linth and the outflow is the River Limmat. Lake Zurich is regulated according to the lake regulation, which was granted in 1977 for an unlimited period. It can store a total volume of 3′900 million m^3. However, the usable storage capacity is only 104 million m^3, as defined through the lake regulation. The lake level is regulated about two kilometres downstream through the Letten weir. Just below the Letten weir, the River Sihl flows into the River Limmat, which also influences the control of the Letten weir, especially during heavy precipitation and flood risk in the underlying River Limmat valley. To dampen the flood peaks of the River Sihl, part of the water is already retained in Lake Sihl. However, comparable regulations for low water levels and drought management are not mentioned in the lake regulations.

Furttal farms

The Furttal is an intensively used agricultural region, which serves to supply the agglomeration area of the city of Zurich with fresh agricultural products (Müller Ingenieure AG 2017). The farmers need irrigation water for special crops (mainly vegetables) in the open and in greenhouses. In the case of contract cultivation of canned vegetables, the possibility of irrigation is also part of the customer contracts. So far, irrigation water has mainly been taken from the little Stream Furtbach and its side streams, from groundwater close to the surface, drinking water, and spring water from the valley sides (Baudirektion Kanton Zürich 2008). Some farms also have small irrigation reservoirs. Since the discharge of the Stream Furtbach fell below critical levels, especially in dry summers, the cantonal Office for Waste, Water, Energy, and Air did not want to renew existing concessions after 2022 to protect the water quality of the Stream Furtbach and to ensure sufficient runoff for biodiversity. The farmers consequently decided in 2014 to establish an irrigation cooperative and received in 2019 permission to build water pipes from the River Limmat to the agricultural land and a concession to use a specific amount of water from River Limmat for irrigation. To ensure sustainable water consumption, the amount of water is limited to a specific amount per second, day, and year. Construction work started in 2021 and completion is scheduled for spring 2022 (Eppenberger 2021).

However, droughts in 2003, 2015, and 2018 showed negative consequences for the Limmat runoff (BAFU 2016, 2019), and climate and hydrological models predict that climate change is altering in the next years the entire water balance: low runoff is projected to become more frequent, precipitation is increasing in winter and decreasing in summer and water temperatures are also going to increase (FOEN 2021; Michel et al. 2020). This is also shown for the case

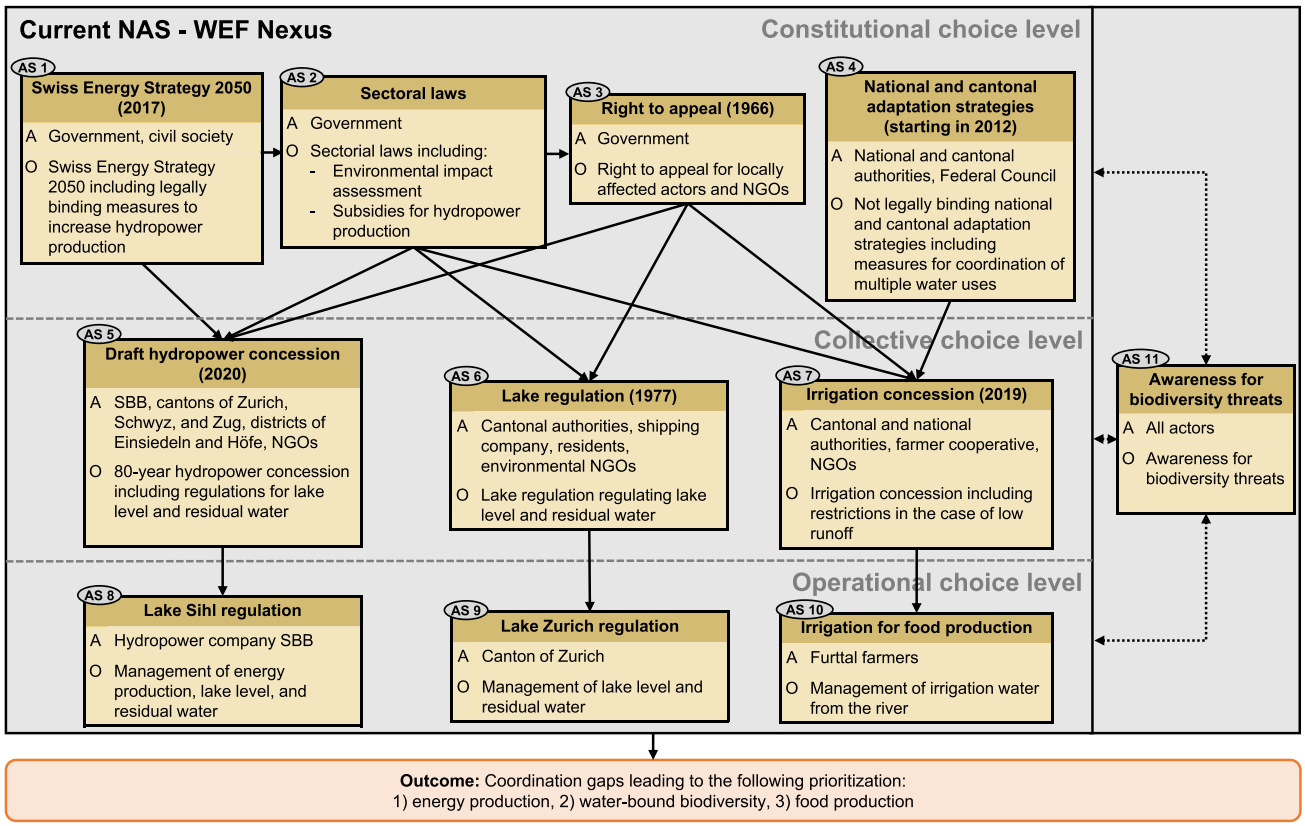

Fig. 3 Network of Action Situations (NAS) of the Swiss Water-Energy-Food (WEF) nexus case. The figure shows (i) how the action situations at the constitutional choice level influence decision-making in action situations at the collective choice level with consequences for the subsequent decision-making at the operational choice level, and (ii) how the awareness for biodiversity threats influences all action situations. These dynamics influence the outcome, which are coordination gaps leading to the prioritization of the energy sectors over the water (biodiversity) and food sectors. *AS* action situations, *A* actors, *O* outcome. *Black arrows* modes of coordination, *dotted arrows* information sharing

study region including Limmat runoff (Lustenberger et al. 2021).

Results

Prioritization between the water, energy, and food sectors in the WEF nexus case

The results reveal a coordination gap between the different sectors and that not all sectors were equally considered, leading to prioritization of upstream over downstream water uses (Fig. 3). This result emerged in three action situations (AS): the draft hydropower concession (AS 5), lake regulation (AS 6), and irrigation concession (AS 7). These action situations are influenced through action situations on the constitutional choice level (AS 1–4) and are crucial for the subsequent decision-making at the operational choice level regarding Lake Sihl regulation (AS 8), Lake Zurich regulation (AS 9), and irrigation for food production (AS 10). All action situations are influenced through the awareness for biodiversity threats (AS 11), which has influenced public policies and the emergence of influential environmental NGOs in the last few decades. Each action situation is described in detail in S1 of the electronic supplementary material.

The priority is hydropower production (AS 8). Even though the hydropower company must fulfil requirements for water-bound biodiversity in managing specific lake levels and residual water, it can produce energy and pump water at any time from Lake Zurich regardless of consequences for water-bound biodiversity at Lake Zurich and downstream along the River Limmat. The second highest prioritization is water-bound biodiversity (AS 8, 9). Both regulating authorities of Lake Sihl and Lake Zurich must fulfil requirements

for water-bound biodiversity in managing specific lake levels and amounts of residual water. In addition, water extractions from rivers for irrigation could be limited or prohibited in times of low runoff to protect water-bound biodiversity. Consequently, irrigation for food production (AS 10) has the lowest prioritization in this WEF nexus case.

The root causes for this outcome are a focus to mitigate climate change and an awareness of biodiversity threats but less awareness of impacts of climate change on Swiss water bodies such as water scarcity and climate change adaptation measures. This is described in the following:

1. An increasing awareness of biodiversity threats in Switzerland since 1900 but little awareness for water scarcity, which is a newer phenomenon in the last 20 years. This resulted in various laws on the protection of the environment but not on managing water scarcity at the constitutional choice level (AS 2, 3): a mandatory environmental impact assessment (AS 2) and regulations for residual water (AS 2) for granting water concessions (AS 5) or lake regulations (AS 6), and the right to appeal by locally affected actors and NGOs (AS 3) against rulings of the national or cantonal authorities, for example on water rights (AS 5–7). As a result, directly affected actors and NGOs became entitled to participate in the decision-making procedures, influencing water rights at the collective choice level (AS 5–7).

   However, actors are not aware of low runoff at the River Limmat in times of droughts with consequences for water extraction and irrigation. The farmers do not even know that restrictions are mentioned in their concession (see S1 in the electronic supplementary material). In consequence, the actors do not realize the prioritization between the water, energy, and food sectors. This led to regulations for residual water for water-bound-biodiversity (AS 2, 5, 6) but not for runoff management ensuring the extraction of the licensed amount of irrigation water (AS 7) from the river for food production (AS 10) in times of low runoff.
2. An increasing consideration to mitigate climate change through renewable energy, in particular, hydropower production, but fewer considerations to adapt to climate change resulted in decisions in action situations at the collective choice level considering mitigation more than adaptation: the Swiss Energy Strategy 2050 (AS 1) includes goals to increase renewable energy, in particular hydropower production, and subsidies for hydropower projects to support renewable energy (AS 2). In addition, some measures of the Swiss Energy Strategy 2050 have been made legally binding through recording in the Swiss Energy Act (AS 2). This resulted in a draft hydropower concession (AS 5) without requirements regarding coordination with Lake Zurich and downstream water extractions.

However, national and cantonal adaptation strategies including measures for multiple uses of reservoirs and lakes and for coordination between sectors were not considered in the negotiations about the draft hydropower concession (AS 5), and only partly considered in the lake regulation (AS 6). The lake regulations consider residual water for biodiversity but not water extractions for irrigation (AS 10).

Identifying leverage points for shifting the WEF nexus case towards sustainability

The diagnosis of the dynamics in the current WEF nexus served for the elaboration of leverage points for shifting the WEF nexus towards a coordination between different sectors and for creating a shared systemic problem understanding regarding impacts of climate change on Swiss water bodies. The leverage points are expected to target the root causes of the outcome described above so that they destabilize the interactions between action situations that maintain the situation and create new interactions. The process to identify the leverage points included an iterative expert deliberation process as described in the methods section. In this process, we identified eight leverage points (LP) with different strengths of leverage for shifting the WEF nexus case (Table 1). All experts agreed on the expected impacts of the leverage points to shift the WEF nexus case.

Based on the expected impacts to shift the WEF nexus case described in Table 1, the eight leverage points are categorized into shallow, middle-range, and deep leverage points (Fig. 4). LP1 is a shallow leverage point with limited potential for system change. LP2–3 are middle-range leverage points. LP2 is expected to increase the adaptive capacity of the system and LP3 to ensure downstream water needs for water-bound biodiversity and water extraction for irrigation. However, both LPs have limitations to ensure these changes (Table 1). LP4–8 are deep leverage points, which are expected to have a high potential to shift the current system towards sustainability.

Linking the leverage points with the NAS approach (Fig. 4 and 5) allows a determination that the identified middle-range leverage points (LP2–3) change action situations at the collective choice level (AS 5–6) with consequences for the operational choice level. Deep leverage points (LP4–7) lead mainly to changes of action situations at the constitutional choice level with consequences for action situations at lower levels. The deep leverage point LP8 is a shift in a mental model, which could emerge at different levels, depending on the intervention (AS 11), and would have the potential to influence actions situations at each level in each direction. For example, after repeated drought seasons or

Table 1 Description of the identified eight leverage points and their expected impacts to shift the Water-Energy-Food (WEF) nexus case towards coordination between different sectors and a shared systemic problem understanding regarding impacts of climate change on Swiss water bodies

Leverage point	Description	Expected impacts to shift the WEF nexus case
1	Design principles for integrative participatory processes for the development of new water rights at the collective choice level	Appropriate design principles are expected to support the integration of all affected actors, building trust between participants, promoting a shared systemic problem understanding of the sustainability challenges in a WEF nexus case, and a more diverse comprehension of the issue at stake, which improves mutual knowledge between—potentially competing—resource users and therefore supports coordination of different water uses (Kellner et al. 2019). However, existing power imbalances between participants could inhibit sustainable outcomes despite design principles
2	Shorter duration of water concessions	Reducing the duration is expected to increase the adaptive capacity of the WEF nexus case because hydrological and socio-economic changes could be integrated into the renewal of concessions at more frequent intervals. However, due to sectoral interests combined with power plays, new concessions could still not integrate specific use interests
3	Extension of natural lake regulations for downstream water extractions	The extension is expected to ensure better coordination between water uses at the lake, residual water, and downstream extractions of the licensed amount of irrigation water (AS 7) for food production (AS 10). However, if the upstream Lake Sihl could still pump water at any time, the opportunities for regulation at Lake Zurich would be still limited
4	Mandatory drought management assessment for downstream catchments in the process of granting water rights	The legal provision on a mandatory drought management assessment (AS 2) in the process of granting water rights (AS 5–7) will provide data on the hydrological and socio-economic conditions in the affected catchment for current and future drought scenarios and reservoir management options. These data are expected to lead to knowledge-based decisions of water rights at the collective choice levels (AS 5–7) ensuring balanced coordination between different sectors at the collective and operational choice level (AS 5–10) and increasing awareness for impacts of climate change on Swiss water bodies (AS 11)
5	Subsidies for water reservoirs are only granted if multiple water uses and drought management are taken into account	The implementation of subsidies linked with drought management (AS 2) is expected to increase the willingness to consider multiple water uses and drought management in water rights (AS 5–7) ensuring balanced coordination between different sectors at the collective and operational choice level (AS 5–10) and increasing awareness for impacts of climate change on Swiss water bodies (AS 11)
6	Extension of the right to appeal to affected downstream actors such as farmers	The extension of the right to appeal (AS 3) will lead to more power for downstream affected actors and is therefore expected to ensure that the needs of downstream actors are considered in the negotiations about upstream water rights (AS 5, 6). This ensures balanced coordination between different sectors at the collective and operational choice level (AS 5–10) and increasing awareness for impacts of climate change on Swiss water bodies (AS 11)
7	Recording of national and cantonal adaptation strategy measures regarding coordination of water uses in legally binding laws	Making adaptation strategy measures legally binding (AS 2, 4) is expected to guarantee the consideration of multiple water uses in developing water rights (AS 5–7) ensuring balanced coordination between different sectors at the collective and operational choice level (AS 5–10) and increasing awareness for impacts of climate change on Swiss water bodies (AS 11)
8	Raising awareness for impacts of climate change on Swiss water bodies including water scarcity	Changing a mental model such as awareness for impacts of climate change on Swiss water bodies is expected to create a shared systemic problem understanding, which is crucial for system change and the implementation of leverage points

AS action situation

interventions such as broad information campaigns about the effects of climate change on Swiss water bodies, actors at different levels are expected to increase their awareness. After a drought season with restrictions to extract water from the river for irrigation, the farmers would be more aware of expected water scarcity. This could lead to bottom-up activities of the farmers influencing decision-making at upper levels. A shift in awareness—leading to shared perspectives and mental models—is a strong predictor of behaviour change. This is an "important prerequisite for collective action, and therefore fundamental to institutional innovation and making choices about shared resources" (Kimmich et al. 2019a, b). Therefore, we expect that raising awareness for impacts of climate change will create a shared systemic problem understanding, which is crucial for the implementation of the other leverage points.

The deep leverage points LP4–8 were integrated into the NAS of the Swiss Water-Energy-Food (WEF) nexus case (Fig. 3) to envision how they could lead to a shift towards sustainability (Fig. 5). The implementation is expected to change various modes of coordination between action situations. It could introduce more hierarchical modes of coordination within and between action situations at the constitutional and the collective choice level (red arrows) and more cooperative modes of coordination between action situations at the collective and operational choice levels, which may appear as cooperation, coordination, or conflict resolution (blue arrows). The awareness of impacts of climate change on Swiss water bodies is expected to lead to a shared systemic problem understanding, which is crucial for system change and the implementation of leverage points. Overall, the increasing modes of coordination combined with a shared systemic problem understanding are expected to lead to a shift towards the sustainable and equitable provision and utilization of WEF resources.

Discussion

Given the need for transformative changes to reduce fossil energy use, food insecurity, and water scarcity, as well as protecting the environment (Liu et al. 2018), the WEF nexus concept seems highly relevant in the twenty-first century (Stein et al. 2018). However, deep analyses about the root causes of unsustainable WEF nexus cases and how to shift the system are still rare (Srigiri and Dombrowsky 2021; Weitz et al. 2017). This paper contributes to the debate by conceptualizing a WEF nexus case in Switzerland with the Networks of Action Situations (NAS) approach combined with systems thinking. The results provide new insights into how current dynamics in the WEF nexus case have been leading to a coordination gap between the different sectors and that not all sectors were considered equally. The identified leverage points are expected to ensure balanced coordination between different sectors and a shared systemic problem understanding regarding impacts of climate change on Swiss water bodies resulting in a shift towards a more sustainable and equitable provision and utilization of WEF resources.

Sustainability challenges in the WEF nexus case

The analysis of the current WEF nexus case demonstrated how decision-making is based on a focus to mitigate climate change and an awareness for biodiversity threats but less awareness of impacts of climate change on Swiss water bodies such as water scarcity and climate change adaptation measures.

The lack of awareness of impacts of climate change on Swiss water bodies was observed in action situations at each level resulting in no knowledge of the prioritization between the water, energy, and food sectors in times of water scarcity. Not even the farmers are aware of potential water scarcity in the River Limmat resulting in restrictions for extraction of irrigation water. This is in line with another WEF nexus case in the canton of Bern in Switzerland (Kellner and Brunner 2021). Due to the lack of awareness, no self-organizing governance processes emerged bottom-up in this WEF nexus case to overcome institutional fragmentation, tackle cross-sectoral problems, or deal with cross-system interactions in the absence of hierarchical steering mechanisms (Galaz et al. 2012). However, an awareness for biodiversity threats is present and considered in decision-making. Biodiversity loss is an increasing topic in Switzerland since 1900. This long-standing awareness resulted in the emergence of various NGOs that are primarily active in protecting and enhancing the environment (S1 in the electronic supplementary material) and various public policies protecting the environment such as environmental impact assessments, lake level regulations, specific amounts of residual water, and the right to appeal for NGOs. In contrast, climate change and its impact on Swiss water bodies is an emerging topic only in recent years and it is still very common to perceive Switzerland as the water tower of Europe (Kellner and Brunner 2021). This is also reflected in the fact that Switzerland considers its water management with the second in the latest self-reporting on the implementation of Integrated Water Resource Management (IWRM) (UNEP 2021). In this report, IWRM is defined as "an approach that helps to balance competing water demands from across society and the economy, without compromising the sustainability of vital ecosystems. This is achieved through coordinated policy and regulatory frameworks, management arrangements, and financing." (p. VII). If there is a lack of awareness for water scarcity among decision-makers, they cannot see the prioritization between sectors and instead rank themselves

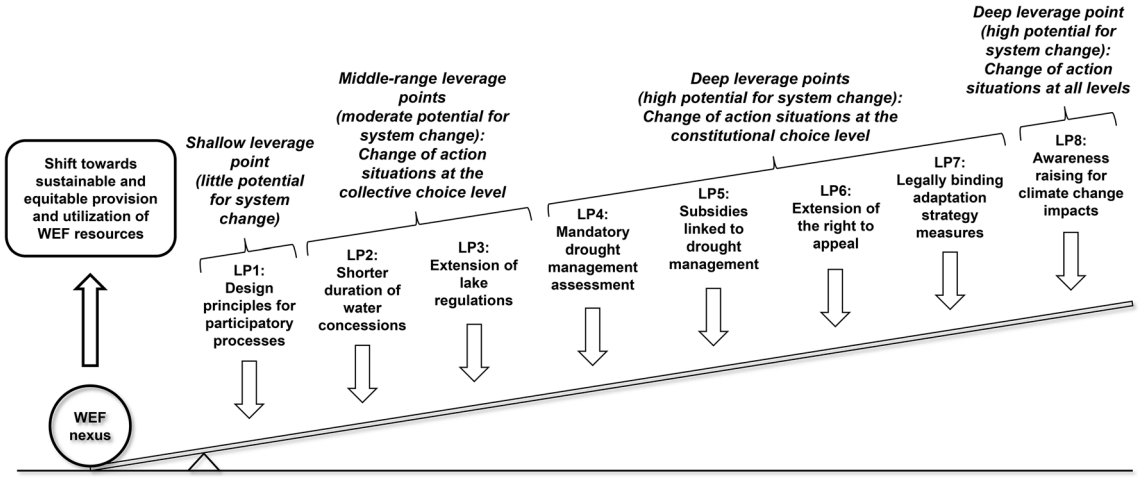

Fig. 4 Leverage points (LP) for shifting the Water-Energy-Food (WEF) nexus case towards the sustainable and equitable provision and utilization of WEF resources (adapted from Fischer and Riechers 2019). The leverage points LP2–8 are linked with different levels of the network of action situations

high in managing IWRM. This is one of the problems of self-reporting assessments. In addition, no NGOs are active on the issue of water scarcity, and it has not yet influenced public policies despite the presence of (non legally binding) adaptation strategies. This points out that changing environmental conditions need time to shift awareness and to lead to adaptations of public policies. It indicates also that a necessary condition to achieve shifts towards sustainability is to intervene at the deepest level of mental models where the way of human thinking and acting is anchored (Senge 2006).

However, the results also reflect the extensive development of largely uncoordinated sectoral use and protection policies e.g., for water, agriculture, and energy. They produce use regulations that are incompatible with each other (Buren 2015) and lead to contradictory incentives, mandates, responsibilities, use rights, and procedures in resource management (Kellner et al. 2019). The results show also that key actors are endowed with largely sectoral mandates for, e.g., water, energy, or agriculture (food) (Venghaus and Hake 2018). In contrast, the Swiss national and cantonal adaptation strategies address cross-sectoral effects, but they are not legally binding and are not taken sufficiently into account in decision-making. Currently, existing European Union policies give only a recent account of cross-sectoral effects among all three nexus resources and, if at all, then predominantly in the form of non-formalized statements of intent (Venghaus and Hake 2018). In European Union policies, cross-sectoral thinking is most advanced between the agricultural and water sectors, which seems to be rooted in their respective and historically grown roles within the nexus system. Switzerland is not part of the European Union and in the Swiss case, cross-sectoral thinking is more advanced between the sectors of energy (hydropower production) and water-bound biodiversity, mainly due to long-standing awareness for biodiversity and conflicts about hydropower projects and the adoption of the right to appeal for environmental NGOs (Kellner and Brunner 2021).

With a perspective for mitigation versus adaptation and sustainable development, the WEF nexus case study shows trade-offs between global goals and local resource systems as well as within the spatial and temporal dimensions. Global goals such as climate change mitigation—resulting in national strategies—to increase renewable energy could negatively impact local resource systems like water-bound biodiversity and food production, e.g., in the case of upstream hydropower reservoirs. The challenge of the spatial dimension appears because achieving SDGs in one location (e.g., SDG 7 Clean energy through upstream hydropower production) should not put at risk the achievement of SDGs elsewhere (e.g., SDG 14 Life below water, SDG 15 Life on land through water-bound biodiversity along downstream lakes and rivers, and SDG 12 Ensure sustainable consumption and production patterns through downstream food production). The case study also emphasises the challenges regarding the temporal dimension as achieving SDGs in the present should not put at risk the achievement of SDGs for future generations under different climate and socio-economic conditions. Here, the challenge is the duration of the draft hydropower concession of 80-years without considering downstream water extractions.

The current nexus dynamics show that a rapid and effective shift leading to more awareness of the impacts of climate change on Swiss water bodies is necessary and that long-term water rights without considering the impacts of climate change should no longer be granted.

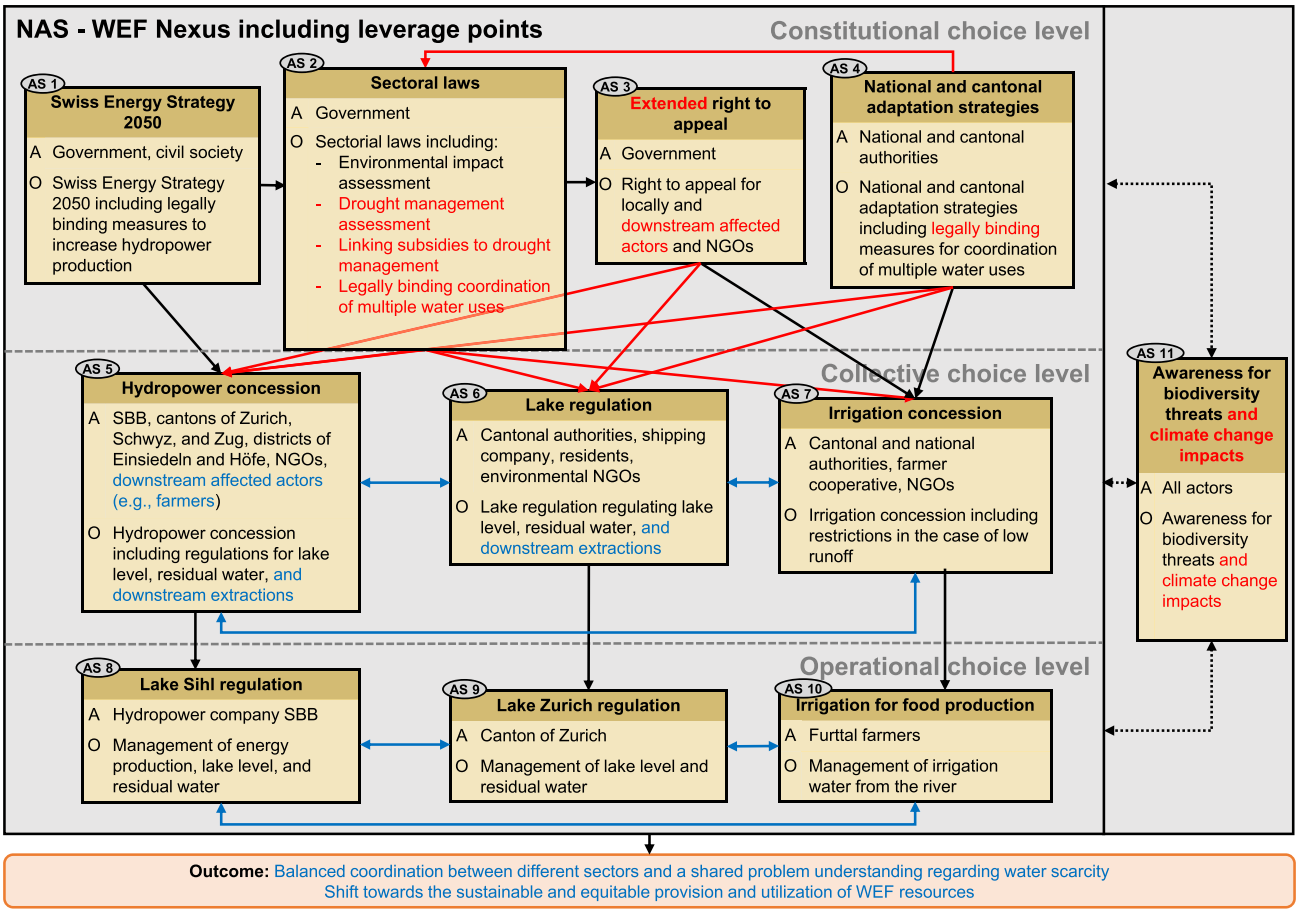

Fig. 5 Network of Action Situations (NAS) of the Swiss Water-Energy-Food (WEF) nexus case including the five identified deep leverage points (LP4–8) for system change (red writing). The figure shows how the implementation of the deep leverage points is expected to change action situations and their interactions (red, blue, and dotted arrows; blue writing). The changes are expected to lead to more balanced coordination between different sectors and a shared systemic problem understanding regarding impacts of climate change on Swiss water bodies resulting in a shift towards the sustainable and equitable provision and utilization of WEF resources. *AS* action situations, *A* actors, *O* outcome

Leverage points for shifting the WEF nexus case towards sustainability

The second step of this study was to identify leverage points for interventions to shift the WEF nexus case towards coordination between different sectors and a shared systemic problem understanding regarding the impacts of climate change on Swiss water bodies. In an iterative expert deliberation process, we identified eight leverage points ranging from shallow to deep leverage points. Linking the leverage points with the NAS approach showed that the two middle-range leverage points are located within action situations at the collective choice level and four of five deep leverage points at the constitutional choice level. Action situations at the constitutional choice level guide and constrain action at the collective choice level (Kiser and Ostrom 1982; Ostrom et al. 2014) and have, consequently, high potential to shift complex social-ecological systems such as WEF nexus cases. They structure activities in multilevel and interconnected systems, coordinate governance in multiple areas, and structure direct drivers such as rule-making directly affecting resource uses (Chan et al. 2020; Galaz et al. 2012). This is also in line with Abson et al. (2017) who identified 'restructuring institutions' as one of three key realms of leverage for sustainability transformation, which are transformations of SES from unsustainable development pathways towards more sustainable ones. The fifth deep leverage point—raising awareness for impacts of climate change on Swiss water bodies—cannot be located at a specific level of action situations but at the level of mental models in the iceberg model (Fig. 1). This leverage point has the potential to shape all actions situations, including bottom-up processes, because

mental models underpin human action and shape the emergent direction to which the WEF nexus case is oriented (Jones et al. 2011; Abson et al. 2017). Further, as mentioned before, awareness of climate change impacts is expected to shape shared perspectives and mental models leading to collective action about shared resources (Kimmich et al. 2019a, b).

The identified deep leverage points are expected to enable more knowledge-based decisions in the process of granting water rights, to take more account of drought management through economic incentives, to shift the existing power balance more to downstream affected actors such as farmers, to increase policy coherence through legally binding cross-sectoral measures in adaptation strategies, and to create a shared systemic problem understanding. This mix of interventions is expected to ensure balanced coordination between different sectors and a shared systemic problem understanding regarding the impacts of climate change on Swiss water bodies. This allows the Swiss WEF nexus to overcome the unintended consequences of uncoordinated policies between different sectors (Weitz et al. 2017) and to destabilize the processes that maintain the situation. Moreover, the interventions create change at multiple levels, which is usually more powerful than interventions that just target one specific level of a system (The Wayfinder 2018).

However, because institutions tend to be self-reinforcing and resistant to change, institutional change such as the extension of the right to appeal can be difficult despite significant and dedicated processes of co-production of knowledge among stakeholders (Rudberg and Smits 2018). Therefore, the fifth deep leverage point—raising awareness of the impacts of climate change on Swiss water bodies—is essential to create a shared systemic problem understanding, which is crucial for system change and the implementation of the other leverage points (Kellner et al. 2019; Enfors-Kautsky et al. 2021).

In general, the leverage points aim to maximize synergies in the WEF nexus, which are mutually beneficial outcomes for the WEF resources, and to minimize trade-offs, which include non-optimal outcomes for each WEF resource. More concretely, the 'shifted' Swiss WEF nexus is expected to have similar protection for biodiversity but more food security at the expense of energy production. This is expected to lead to conflicts between the two sectors, which is why balancing national interests is embodied in Swiss spatial planning laws. This is particularly important because plans exist (Ehrbar et al. 2018; Farinotti et al. 2016) and processes are started for new hydropower projects in the Swiss Alps (UVEK 2021; Kellner 2019; Kellner and Brunner 2021; Kellner et al. 2019) with similar challenges for downstream water scarcity. Further, various 80-year hydropower concessions in the Swiss Alps expire in the next 20 years (Kellner 2020), which would be a window of opportunity to integrate downstream water uses in the renewal of the concessions. However, without awareness of potential downstream water scarcity, no trade-offs will be recognized, and no competing interests need to be balanced. This is also shown by the fact that national representatives for hydropower and environmental NGOs signed in 2021 a commitment to build 15 new hydropower projects in the Swiss Alps without consideration of downstream water scarcity (UVEK 2021).

However, as mentioned in the methods section, the implementation of the leverage points was not part of this study. After finishing the study, I was repeatedly invited to present the results in front of state and non-state actors in Switzerland. This kind of information sharing has been leading to spontaneous activities of a cantonal politician in another Swiss canton with a similar WEF nexus case. The politician has been writing a successful proposal to integrate downstream drought management in a hydropower concession of an upstream Alpine reservoir in 2021. The concession is planned to be granted soon by the cantonal Grand Council he is part of. This process shows how the implementation of leverage points is not directly steerable and that information sharing with various state and non-state actors could be an important process to increase the probability for implementation.

Methodological reflection

This study is the first contribution combining the NAS approach with systems thinking and the results demonstrate the reciprocal benefits. The study links and operationalizes the analysis of a WEF nexus case with this approach. The Swiss case illustrates how the combined approach enables the identification of actions at different levels, and linkages across energy, water, and food-related situations, and how outcomes of action situations limit or facilitate synergies and trade-offs along the WEF nexus affecting provision and utilization of WEF resources. Further, the iterative expert deliberation process with representatives from the Federal Offices for Energy, Environment, and Agriculture and scientists showed that the visualization of the WEF nexus case with this approach facilitates a shared systemic problem understanding of the dynamics within the network and discussions about the root causes for the outcome of the WEF nexus case. This encourages a perception of the WEF nexus as a complex social-ecological system, which supports the understanding of its interconnectedness, and serves as the first step in a transformation process (Sanneh 2018).

The combined approach links leverage points with the different levels of the network of action situations. This helps to identify leverage points at the effective level of intervention for shifting the WEF nexus towards sustainability. In addition, it adds the influence of mental models on action situations, which is until now not a prominent aspect

in NAS studies. Action situations with mental models as outcomes could emerge at each level and influence adjacent action situations at each level. Whereas systems thinking postulates clearly that mental models influence the creation of regulations (Davelaar 2021), the NAS approach has not yet addressed such kinds of action situations. After identifying leverage points, the combined approach allows envisioning the impact of potential interventions on the network of action situations. However, complex systems such as WEF nexus cases are inherently unpredictable (Biggs et al. 2021) since they are characterized by feedback loops, non-linear effects, learning, and novelty (Preiser et al. 2018). Further, our understanding of the systems that we are part of and intend to intervene in could not be more than partial (Enfors-Kautsky et al. 2021). Therefore, any envisioned network of action situations should not be considered as a prediction but rather as one of many ways that would result in a more sustainable outcome.

Conclusion and outlook

The Water-Energy-Food (WEF) nexus has gained growing interest in recent years as a promising concept to overcome governance failures in dealing with complex resource management challenges. However, deep analysis about the root causes for effective coordination and how they can be shifted is still lacking. This paper contributes to filling this gap by conceptualising a WEF nexus case in Switzerland with the Networks of Action Situations (NAS) approach combined with systems thinking. The analysis of the current dynamics in the WEF nexus case showed a coordination gap between the different sectors and that not all sectors were considered equally. This leads to a prioritization of energy production over water-bound biodiversity and food production. The root causes for this outcome are a focus to mitigate climate change and an awareness for biodiversity threats but less awareness for impacts of climate change on Swiss water bodies such as water scarcity and climate change adaptation measures. Based on these insights, an iterative expert deliberation process to identify leverage points for interventions was performed. We identified five deep leverage points for shifting the WEF nexus case towards sustainability. They are expected to increase awareness of the impacts of climate change on Swiss water bodies, enable more knowledge-based decisions in the process of granting water rights, to take more account of drought management through economic incentives, to give more power to downstream affected actors such as farmers, and to create more policy coherence through legally binding cross-sectoral measures in adaptation strategies. This mix of interventions is expected to ensure a shared systemic problem understanding regarding impacts of climate change on Swiss water bodies and balanced coordination between different sectors resulting in the more sustainable and equitable provision and utilization of WEF resources. However, the implementation of deep leverage points in constellations of competing resource interests and within complex social and political contexts is challenging and needs more research.

This study shows that decision-making is embedded in hierarchical structures, where decisions at the constitutional choice level influence decisions at the collective and operational choice level. However, the study also highlights the influence of mental models—beliefs, values, and assumptions—on decision-making such as the awareness of biodiversity and impacts of climate change, which is underestimated in studies with the NAS approach. Awareness of specific topics at the local level could also lead to bottom-up activities influencing upper levels. Future research should consider the potential effects of mental models on the dynamics in networks of action situations more carefully. These initial findings should be further developed and concepts on how to integrate mental models in the network are needed.

The results show the reciprocal benefits of combining the NAS approach with systems thinking. The combination allows a deep analysis about the root causes of an outcome of a system, facilitates a joint understanding of the system dynamics to identify and rank shallow to deep leverage points for shifting the system towards sustainability, and to envision the impact of potential interventions on the system and its outcome. This approach can also be applied to other complex social-ecological systems.

Further, future research can combine WEF nexus studies focussing on the biophysical interlinkages with governance studies. The NAS approach could be expanded through the integration of ecological action situations, as Schlüter et al. (2019) already started, to capture intertwined social-ecological dynamics (Leach et al. 2018) and to overcome the current human–environment dichotomy in the NAS. This would allow conceptualising WEF nexus cases by interactions between the social and the ecological, which are not just bi-directional feedbacks between separately conceptualized natural and social domains (Brelsford et al. 2020) but intertwined (Folke et al. 2016) and continuously coevolving (Levin et al. 2013). Adopting a coevolutionary perspective could encourage a radical rethinking of how decision-making is conceptualised and practiced and could enable an understanding of their coevolutionary dynamics and emergent outcomes in WEF nexus cases with strong implications for sustainability (Haider et al. 2021; Schlüter et al. 2019). This perspective would allow the use of existing social-ecological dynamics as entry points, recognizing that current and new dynamics will coevolve with each other to create entirely novel pathways, and to identify deep leverage points for sustainable WEF nexus outcomes.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11625-022-01170-7.

Acknowledgements I would like to thank the interviewees for their participation in this study. I would also like to thank all experts from the Swiss Federal Offices for Energy, Environment, and Agriculture and Manfred Stähli, Roland Olschewski, Christian Unterberger, and Astrid Björnsen Gurung for the constructive discussions and feedback. This article greatly benefitted from the debate at the NAS panel at the ECPR conference, 24–28 August 2020, led by Christian Kimmich and Melf-Hinrich Ehlers. I would also like to thank Dominik A. Martin and Peter Rudberg for their very constructive and valuable comments on earlier versions of the article. I thank two anonymous reviewers and the guest editor for their constructive comments and suggestions to this article. This research was made possible through financial support from the Swiss Federal Office for the Environment (FOEN) within the Hydro-CH2018 project granted to the author via 15.0003.PJ/S122-0639.

Funding Open Access funding provided by Lib4RI – Library for the Research Institutes within the ETH Domain: Eawag, Empa, PSI & WSL.

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