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Key Points:
- Governance processes of upstream reservoirs need to anticipate multiple upstream and downstream water demands
- Coordination gaps are caused by a lack of water shortage awareness and reservoir-management studies and by trade-offs between mitigation and adaptation measures
- There is a need for integrative governance processes with state and non-state actors at the spatial scale of affected catchments

Supporting Information:
- Supporting Information S1

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Reservoir Governance in World's Water Towers Needs to Anticipate Multi-purpose Use

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Abstract Mountains, said to be the world's water towers, are central for the provision of downstream water demands. This provision service is strongly challenged by climate change associated with changes in runoff amount and seasonality caused by the retreat of glaciers, rising snow lines, and changes in precipitation. One potential adaptation strategy is the construction of new water reservoirs or the adjustment of current reservoir management strategies. These strategies need to account for various water uses originating from sectors and governments with different economic interests. Here, we investigate governance processes leading to reservoir management strategies ignoring downstream water needs in one of the most important water towers of the world, the European Alps. We assess why governance processes can lead to a coordination gap between an upstream reservoir and downstream water needs. We show that downstream water deficits could potentially be covered through an upstream reservoir under mean and partially under extremely low inflow conditions. However, these hydrological conditions were neglected in the governance processes. The decision-making when issuing the new reservoir concession was influenced by (a) a lack of knowledge and of an appropriate reservoir-management study, (b) an interest to increase renewable energy production, (c) a focus on environmental agreements in the participatory process, and (d) economic interests. Our analyses provide factors, which need to be considered when designing governance processes for the management of reservoirs in world's important and vulnerable water towers. We conclude that immediate action is required toward balancing upstream and downstream water needs in governance processes.

Plain Language Summary Mountains are central for the provision of water demands and are therefore commonly referred to as "water towers." This provision service is strongly challenged by climate change associated with changes in the water cycle caused by the retreat of glaciers, rising snow lines, and changes in precipitation. One potential strategy to cope with these challenges is the construction of water reservoirs or the adjustment of current reservoir management strategies. These strategies need to account for various water uses. Here, we focus on governance processes leading to the (suboptimal) management of a reservoir in one of the most important water towers of the world, the European Alps. We assess why negotiation processes can lead to a coordination gap between an upstream reservoir and downstream water needs. We show that downstream water deficits could potentially be covered through an upstream reservoir, which was neglected when negotiating the concession for the reservoir. The decision-making was influenced by (a) a lack of knowledge and data, (b) an interest to increase renewable energy production, (c) a focus on environmental agreements in the participatory process, and (d) economic interests. We conclude that immediate action is required toward balancing upstream and downstream water needs in negotiation processes.

1. Introduction

Mountains play an essential role in storing water and providing it to downstream regions and are therefore commonly referred to as "water towers of the world" (Immerzeel et al., 2020; Viviroli et al., 2020). In particular, they provide runoff in the lowlands' low flow season by contributing snow- and glacier-melt (Jenicek et al., 2018). Globally, 1.9 billion people depend on these runoff contributions from mountains (Immerzeel et al., 2020), which are currently and in future impacted by climate change through the retreat and volume loss of glaciers (Dussaillant et al., 2019; Huss & Hock, 2018; Zekollari et al., 2019), rising snow lines, changes in precipitation amount and seasonality, and changes in evapotranspiration (Arnell, 2003; IPCC, 2014).

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The expected changes in runoff seasonality and variability can have socioeconomic impacts including a seasonal reduction in water availability for irrigation (Biemans et al., 2019), municipal and industrial needs (Flörke et al., 2018; Pritchard, 2019), environmental flow requirements (Best, 2019; Körner et al., 2017), or hydropower production (Beniston et al., 2018). These impacts can lead to losses of income and livelihoods (Huggel et al., 2019), increased anthropogenic stress on rivers (Best, 2019), social instability or conflicts, and sudden migrations triggered by water shortages (Pritchard, 2019).

Conserving the essential role of water towers in providing water, food, and energy security requires both mitigation of and adaptation to changes in the water cycle. Mitigation and adaptation actions should include local efforts to preserve or increase the buffer capacity of mountain ranges in case of water shortage, for example by establishing protected areas, building sustainable reservoirs, or increasing water use efficiencies (Huss et al., 2017; Immerzeel et al., 2020). Among potential adaptation measures, reservoirs have been shown to be increasingly important in ensuring water security and facilitating drought management (Ehsani et al., 2017). Reservoirs can potentially cover or reduce water deficits during the dry and high-demand season by releasing water stored in the wet season (Wanders & Wada, 2015). For the Alps, this would mean that spring melt and winter precipitation not stored in the snowpack are stored in a reservoir and used for downstream water supply in summer and fall. Furthermore, reservoirs can be used for the production of renewable energy through hydropower, which helps to mitigate climate change.

Potential locations for new reservoirs that are expected to become ice-free during the 21st century have been assessed worldwide (Farinotti et al., 2016, 2019) because of the importance of reservoirs in reducing the vulnerability of water towers. Previous studies have focused on the hydrological potential for reservoirs or general assessments of government effectiveness and governance risks (Best, 2019; Immerzeel et al., 2020). Governance processes, however, strongly vary from case to case, which necessitates a case study approach rather than approaches based on general governance indicators. Still, there exists limited systematic evidence on the functioning of governance processes related to the planning, construction, and management of multi-purpose reservoirs in newly deglaciated areas provided through case study approaches. The lack of case study approaches to analyze the actual governance processes is astonishing since many studies come to the conclusion that the vulnerability of water towers is driven by ineffective governance (Immerzeel et al., 2020), that governance is the most critical barrier for dealing with changes in river basins effectively (Best, 2019; Biemans et al., 2019), and that the water crisis is mainly a crisis of governance (Gupta et al., 2013; GWP, 2000; Mirzaei et al., 2017). In general, integrated water governance is challenging due to the potentially competing water uses related to different sectors active at different geographic and governmental scales with different economic interests, and power relations (Pahl-Wostl et al., 2020; Sayles & Baggio, 2017; Weitz et al., 2017). This challenge becomes particularly apparent in the case of multi-purpose reservoirs.

Water governance needs to be adapted to changes in the water cycle expected due to climate change (Aguiar et al., 2018; Herrfahrdt-Pähle, 2013; Knieper & Pahl-Wostl, 2016; Porter & Birdi, 2018). However, adapting water governance is challenging because of incoherent policies and institutions (Hill, 2013; Hurlbert & Montana, 2015; Oberlack & Eisenack, 2018; Sosa et al., 2018). Incoherence could exist between different sectors, between climate change mitigation and adaptation strategies, and across administrative borders (Gupta et al., 2013; Shrestha & Dhakal, 2019; Sosa et al., 2018). Such incoherencies can lead to contradictory incentives, responsibilities, and use rights (Kellner et al., 2019). Other obstacles to coordination reside in sectoral planning and implementation procedures (Pahl-Wostl, 2019a, 2019b); the levels and spatial scales of governance not being adapted to the affected catchment (Newig & Fritsch, 2009; Udall & Overpeck, 2017); the absence of non-state actors in decision-making (Benson et al., 2012; McNeill, 2016; Parés et al., 2015); power imbalances between upstream and downstream water users (Anghileri et al., 2013; Cody, 2018; Denaro et al., 2018) as well as between influential, powerful elites and the rural poor (Kuenzer et al., 2013); a lack of or disputed data records (Dombrowsky & Hensengerth, 2018; Never & Stepping, 2018); and a lack of institutional capacity to govern across sectoral boundaries (Benson et al., 2015; OECD, 2011).

This paper assesses the governance processes related to the planning of a future reservoir in one of the most important water towers of the world, the European Alps. We ask how governance processes lead to a coordination gap between an upstream reservoir and potential downstream water shortage. To answer this question, we look at a case study in the Swiss Alps, the region Trift. This region has recently been

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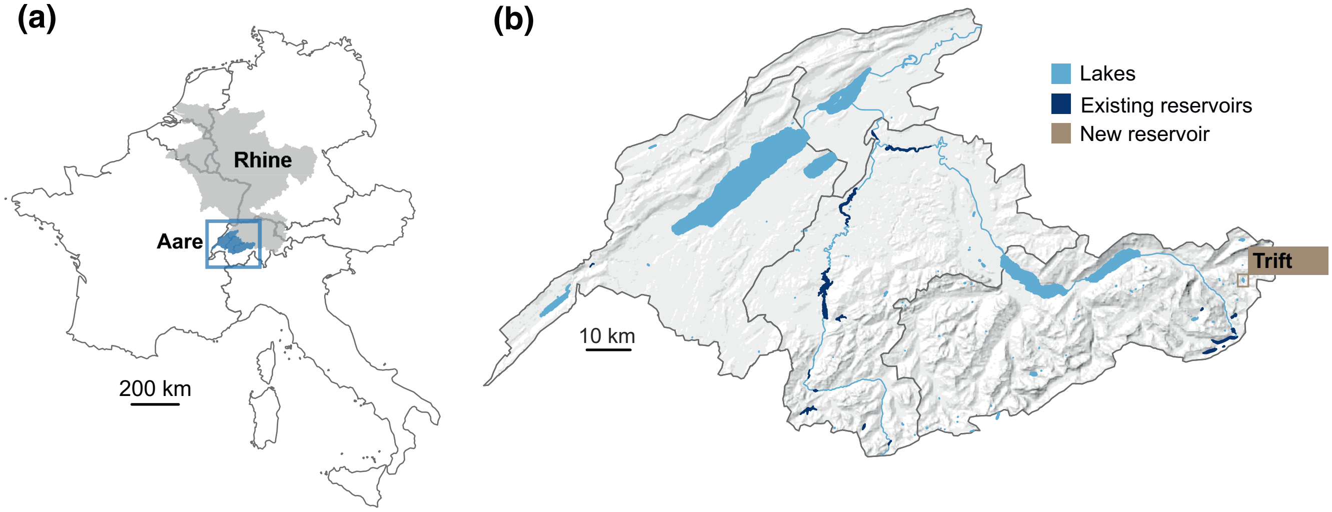

Figure 1. (a) Location of the Aare catchment in the upper Rhine basin in the European Alps and (b) location of the Trift reservoir in the upper part of the Aare catchment.

deglaciated and lies in the upper part of the Rhine basin, which is crucial in providing water to the middle and lower reaches of the Rhine basin especially during the summer low-flow season (Stahl et al., 2017) (Figure 1). We use the Institutional Analysis and Development (IAD) framework, which comprises an analysis of governance processes and their "contextual factors" such as "biophysical conditions," that is, "hydrological conditions"; "socioeconomic conditions"; and "rules-in-use." Compared to previous studies, which have focused either on the modeling of the hydrological conditions or on general governance assessments using global governance data, we combine both types of analyses using quantitative and qualitative approaches. This combination allows us to identify factors leading to the neglect of potential downstream water shortage in upstream reservoir planning. The factors identified provide deeper insights into challenges related to the planning of multi-purpose reservoirs than general indicators of governance and hydro-political tension (Kaufmann et al., 2010; Stefano et al., 2017; UNEP-DHI & UNEP, 2016) and can provide guidance for improving the design of future water governance processes for upstream reservoirs in other important water towers of the world.

This study first introduces the case study region in the European Alps and the project of the Trift reservoir in Switzerland (Section 2). Section 3 then introduces the networks of action situations (NAS) approach rooted in the IAD framework and describes the methods for the hydrological analyses focusing on a comparison of upstream reservoir capacity and inflow with current and future downstream water shortages. Section 4 presents key findings on the network of action situations identified and the role of different contextual factors with an emphasis on the biophysical conditions. In Section 5, we relate our results to previous studies and reflect on the limitations of our approach. Section 6 discusses the results' wider implications for future governance processes for water reservoirs in the world's water towers.

2. Case Study

The Swiss Trift region in the European Alps is an interesting case for investigating how governance processes related to an upstream reservoir inhibit multi-purpose water use because (1) it is part of the Rhine basin, one of the top five most important worldwide water towers (Immerzeel et al., 2020), (2) its cryosphere is strongly affected by climate change (Zekollari et al., 2019), (3) an 80 years concession for a new reservoir in a landscape with a receding glacier is about to be granted (Schweizer et al., 2019), (4) the indicators for good governance and hydro-political tension are ranked very high for Switzerland (Kaufmann et al., 2010; Stefano et al., 2017; UNEP-DHI & UNEP, 2016), (5) Switzerland has recently adopted a new energy strategy (Energy Act SR 730.0), (6) Switzerland has developed a climate adaptation strategy recommending the use of reservoirs for multiple services (BAFU, 2012a, 2014), and (7) Switzerland has elaborated guiding principles for integrated water management (BAFU, 2012b; Water Agenda 21, 2011).

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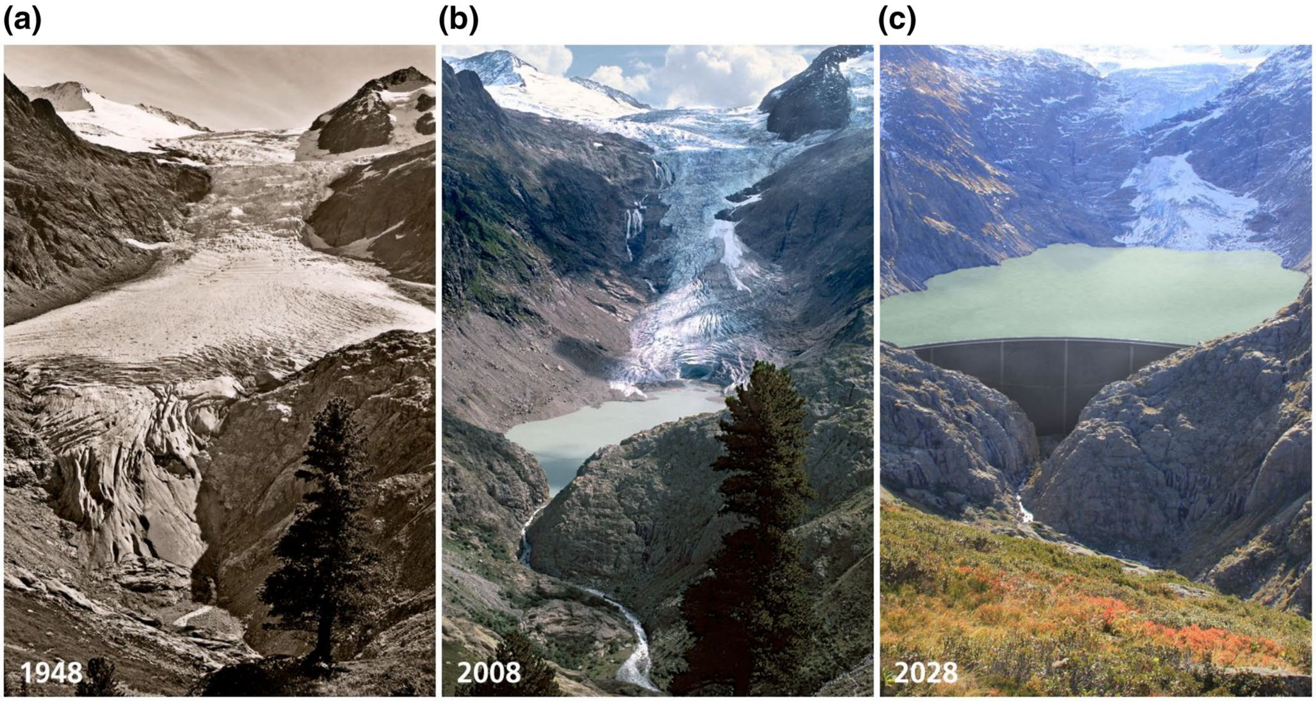

Figure 2. Temporal evolution of the landscape in the region of the Trift glacier where the new hydropower reservoir is planned: (a) Glacier cover in 1948, (b) lake formation in 2008, and (c) illustration of the planned dam retaining water in a reservoir (Source: Kraftwerke Oberhasli AG).

The case study region is located in the canton of Bern, which has a cantonal strategy of water following an integrated water management approach (BVE, 2010). This strategy includes measures to expand hydropower production and to integrate reservoirs in water management during extreme situations, such as floods or droughts. The upstream part of the case study region is mountainous and only sparsely populated, while the downstream part is used for industry and agricultural crop production thanks to its flat topography and fertile soils. The Trift reservoir is hydrologically connected to its downstream region and the Rhine catchment via the river Aare. The Aare provides significant ice melt contributions to the Rhine, which are particularly important in dry years (Stahl et al., 2017) (Figure 1a). The hydrological regimes of the catchments in the upper Aare basin (Figure 1b) are characterized by glacier- and snow-melt processes and therefore high flows in summer and low flows in winter. In contrast, the hydrological regimes of the downstream catchments are rainfall-dominated with generally wet winters and dry summers. In this dry season, the downstream catchments therefore rely on inflow from the runoff-rich upstream catchments.

Two natural lakes (Brienz and Thun) are located between the Trift reservoir and the downstream region (Figure 1b). The storage capacities of the lakes are large (5,170 Mio m^3; 6,500 Mio m^3) compared to the storage capacity of the Trift reservoir (85 Mio m^3). However, their usable storage capacities (70 Mio m^3; 78 Mio m^3), as defined through lake regulations, are comparable to the storage capacity of the Trift reservoir. The planned Trift reservoir is part of a complex system of power plants, which have been built over the years by the local hydropower company, Kraftwerke Oberhasli (KWO). In total, 195 Mio m^3 of water are stored in eight reservoirs. KWO is half owned by Berner Kraftwerke (BKW) Energie AG and the other half is shared in equal parts by the three Swiss cities Bern, Zurich and Basel. The canton of Bern holds 51% of the shares of BKW. Decisions on new KWO projects are taken by the management of BKW independently of the shareholders. In 2012, KWO proposed to build a new dam in front of the retreating Trift glacier at an altitude of 1767 m a.s.l. (Figure 2). The area where the new reservoir is planned is not (yet) protected. The dam would transform the newly formed lake in the proglacial area of the Trift glacier into an 85 Mio m^3 hydropower reservoir. The estimated mean annual inflow would be twice the volume of the reservoir (154 Mio m^3 under current conditions). The reservoir would not only capture the water from the direct catchment of the Trift glacier, but also the water from the indirectly contributing catchment around the Stein glacier, which would be transferred to the Trift catchment via pipes (KWO, 2019).

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From 2008 to 2011, scientists conducted feasibility studies for a new hydropower dam at lake Trift as part of the large Swiss National Research Programme 61 "Sustainable water management" (Haeberli et al., 2013). Based on the results of this study, KWO decided to further pursue the project. Later, the canton of Bern conducted a feasibility study to determine the possibilities and limits of the management of the Trift reservoir as a multi-purpose reservoir with regard to flood and drought management while imposing hydropower as a main purpose (geo7, 2017).

Hydropower projects across Switzerland have led to severe conflicts and stalemate situations in the past. Several Swiss non-governmental organizations (NGOs) and hydropower companies therefore drew on these earlier experiences to test new governance processes with a participatory approach. Learning from these successful processes, the canton of Bern together with KWO decided to develop a draft concession for the Trift project using a participatory process to prevent objections (Schweizer et al., 2019). The participants in the process, which lasted from 2012 to 2017, were actors from KWO, the cantonal administration, the mountain municipalities affected, and environmental NGOs who could potentially file an objection to a granted concession. However, the process did not include any downstream actors.

At the time of finalizing this study, spring 2020, various national and cantonal administrative bodies were examining the draft concession to ensure that it complies with applicable laws and regulations. Following this review, the Great Council of the canton of Bern will probably vote on granting the concession at the end of 2020. The concession will have a validity of 80 years. The drafted concession, however, only regulates hydropower production, the height of the dam, the retention volume for flood protection, the amount of residual water for ensuring ecological downstream water needs, and the ecological compensation measures to be taken, while the alleviation of downstream water shortage is excluded from this multi-purpose use.

3. Methods

To analyze the governance processes in developing the concession for the Trift reservoir, a framework focusing on institutional analysis within social-ecological systems (SES) is required. Therefore, we used the IAD framework (McGinnis, 2011a; Ostrom, 2005, 2011), which has been developed to analyze collective choice processes and social interactions within SES. The focal point of the IAD framework are action situations, which can be both physically and institutionally shaped. The contextual factors shaping action situations include biophysical conditions (in our case, hydrological conditions); socioeconomic conditions and rules-in-use, which include formal and informal rules. We combined qualitative and quantitative methods to analyze how decision-making emerged in the governance processes of the upstream Trift reservoir and to assess current and future hydrological conditions in the downstream region of the reservoir.

3.1. Qualitative Analysis

Action situations, socioeconomic conditions, and the rules-in-use were assessed by collecting empirical data. Field work was carried out between 2017 and spring 2020. The data collection included 31 semi-structured face-to-face interviews with the main actors representing the hydropower company, associations involved, public authorities on different levels, downstream farmers, agricultural representatives, and a scientist (Table S1). The expert interviews yielded in-depth information on specific resource use interests and political strategies and fostered the specific understanding of governance processes. Additional information sources included are as follows: participatory observations of meetings, document analyses of legal materials (laws, regulations, concessions, and national, cantonal and regional strategies), and reviews of gray literature on the case (including administrative and NGO reports and newspaper articles). The interviews were transcribed and data analyses followed the general principles of qualitative content analysis (Mayring, 2010).

We analyzed action situations to assess simultaneous and dynamic patterns of interactions in decision-making while developing the concession for the Trift reservoir. An action situation is a situation of social interaction where actors with specific preferences interact, leading to specific outcomes (Schlüter et al., 2010). Individual and collective action situations range from spontaneous to strongly institutionalized settings in organizations. Action situations are considered to be directly linked if the outcome of one action situation directly influences the actors in another action situation (McGinnis, 2011b). Furthermore, an action situation and its outcome is influenced by the knowledge of the participating actors and by formal and

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informal institutions such as public policies and local arrangements (Schlüter et al., 2010). The configuration of action situations and the linkages between them constitute NAS. These linkages can be social (e.g., networks and institutions), economic (e.g., shared resources and transactions), or ecological (e.g., material and resource flows) (Kimmich, 2013).

The analysis of NAS has gained growing interest in recent years (Kimmich & Villamayor Tomas, 2019; Kimmich et al., 2020; Lubell, 2013; McGinnis, 2011b; Oberlack et al., 2018; Pahl-Wostl et al., 2010; Villamayor-Tomas et al., 2015). We used the NAS approach rooted in the IAD framework to analyze action situations and the interactions between them, to find out why drought management was finally not considered in the decisions leading to the draft concession for the Trift reservoir. Therefore, we first delineated the boundaries of action situations along the situations of social interactions that influenced this outcome. Second, we identified the main actors involved and the ways in which these actors interact with each other to address their claims. Third, we identified the action situations with immediate relevance for decision-making and analyzed the action situations which shaped the decision in decisive manners preparing the ground for decision-making. Finally, we summarized the main factors explaining the coordination gap between upstream reservoir management and the alleviation of downstream water shortage.

3.2. Quantitative Analysis (Hydrological Conditions)

The biophysical conditions of main interest here were upstream water availability via reservoir inflow in comparison to downstream water shortage during the summer season. We quantified current (1981–2010) and future (2071–2100) summer water surplus/shortage for the downstream region by modeling water supply and water demand and compared these shortage estimates to potential upstream water availability. The water shortage estimates were derived on a local scale by comparing local supply with local demand, that is potential upstream influences and transfers are excluded. This procedure allows for an independent assessment of upstream supply and downstream demand and does not require the performance of a detailed water and reservoir management study.

3.2.1. Water Supply

We quantified current and future water supply for 11 catchments along the Aare river and the inflow of the Trift reservoir, using daily runoff time series simulated by Brunner et al. (2019a) for 307 medium-sized catchments with the hydrological model PREVAH (Viviroli et al., 2009). PREVAH is a conceptual process-based model which consists of several sub-routines representing interception storage, soil water storage, snow accumulation and melt, glacier melt, groundwater, runoff and baseflow generation, discharge concentration, and flow routing. The model has previously been adopted in climate impact studies (Köplin et al., 2010) because it reliably simulates the water balance in mountainous regions (Speich et al., 2015; Zappa & Pfaundler, 2009).

The calibrated and validated model was driven with daily meteorological data representing both reference and future climate conditions. The reference period comprised the years 1981–2010, while the future period lay at the end of the century (2071–2100). The transient forcing meteorology for current and future climate was derived from the CH2018 climate scenarios (NCCS, 2018) and included the variables precipitation, temperature, relative humidity, radiation, and wind speed. The CH2018 scenarios are based on the EURO-CORDEX initiative (Jacob et al., 2014; Kotlarski et al., 2014), which uses representative concentration pathways (Moss et al., 2010; van Vuuren et al., 2011) and a regional downscaling approach based on quantile mapping (Gudmundsson et al., 2012; Themeßl et al., 2012). The meteorological data were derived for the 39 model chains in the ensemble. For a full list of the model chains used and for further details on the modeling procedure, please refer to Table A1 in Brunner et al. (2019a).

3.2.2. Water Demand

Current and future water demand was estimated for drinking water supply (households and tourism), industry (second and third sector), ecology, hydropower, and agriculture (irrigation and livestock feeding). We here provide a short description of the estimation procedures and refer to Brunner et al. (2019a) for more details. Drinking water supply was estimated for households and the tourism sector by multiplying the water use rate of 142 l per person and day (Freiburghaus, 2015) with the number of inhabitants per

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catchment (FSO, 2017). Industrial water demand was estimated for the second and third sector by multiplying the water use rate per employee and year (148 m^3 for second sector, 85 m^3 for third sector) with the number of employees per catchment (FSO, 2018). Ecological flow requirements were considered by using a threshold flow value corresponding to the 5% quantile of daily discharges as prescribed by Swiss legislation (Aschwanden & Kan, 1999). The water demand for hydropower production was estimated for each storage reservoir within Switzerland and then aggregated to basin-wide water demand. The monthly water demand was estimated by multiplying the monthly percentage change in storage content with the storage capacity of the reservoir, and by subsequently adding the monthly natural inflow to the reservoir. The monthly inflows were computed based on the catchment runoff simulated with the hydrological model PREVAH (see previous section), which was adjusted proportionally to the catchment area contributing to reservoir inflow. For this study, we excluded upstream hydropower demand as we focused on the question of how much water would potentially be available for downstream use if it was not used for hydropower production. Agricultural water demand was derived from water demand for livestock feeding and irrigation. Livestock water demand was computed by multiplying the water use rate per unit of livestock (110 liters per day) (Freiburghaus, 2009) with the number of livestock per catchment (FSO, 2015). The irrigation water demand, which represents the difference between the crop water requirement and effective precipitation (Allen et al., 1998) was computed using time series derived by the hydrological model described in the previous section. Irrigation water demand is seasonally variable but withdrawal for irrigation was restricted to spring and summer (April to September). For calculating future water demand, we considered changes in the demand related to population growth and changes in the hydrological conditions. The hydrological model simulations and the demand estimates are available for download via the EnviDat repository (Brunner et al., 2019c).

3.2.3. Water Surplus/Shortage

Water surplus or shortage were estimated by subtracting total local water demand from local water supply estimates at monthly resolution at the scale of the sub catchments without considering water transfers from upstream to downstream catchments. Positive values indicated a water surplus while negative values indicated a water shortage. We focused on the summer season, which is the main season of drought occurrence in the downstream Aare region, to compute extreme water surplus/shortage situations. Summer water shortage was computed as the water shortage accumulating over the months June to September. Extreme summer water shortage was estimated using univariate frequency analysis on these cumulative shortages by fitting a Generalized Extreme Value (GEV) distribution (Coles, 2001). For future conditions, we used the water shortage estimates combined from all 39 climate model chains (i.e., 30 times 39 values). We used the fitted GEV distribution to derive water shortage estimates corresponding to return periods of 10 and 100 years. In order to show the changes in supply, demand, and shortage along the river network, we first provided estimates of these quantities for 11 river stretches along the main river Aare.

We finally compared the downstream water shortage for the eight river stretches downstream of the Trift region during the summer months to the storage capacity and the inflow volume of the Trift reservoir. This comparison of potential upstream water availability and downstream demand allows for the determination of the potential of the reservoir for alleviating downstream water shortage in case the stored water is not bound to hydropower production.

3.2.4. Reservoir Inflow

As years with a high water shortage could theoretically coincide with years of low reservoir inflow, for example in a year when a hot and dry summer is preceded by a winter with small snow accumulation, we compared the extreme shortage estimates (10 and 100 years) with extreme inflow estimates. Extreme reservoir inflow for current and future conditions was estimated using annual reservoir inflow time series derived from the PREVAH streamflow simulations. The estimates were derived by fitting a normal distribution to the simulated annual inflow time series, which was subsequently used to derive inflow estimates corresponding to return periods of 10 and 100 years. The normal distribution was neither rejected for current nor future conditions based on the Kolmogorov-Smirnov goodness-of-fit test ($a = 0.05$) (Smirnov, 1933).

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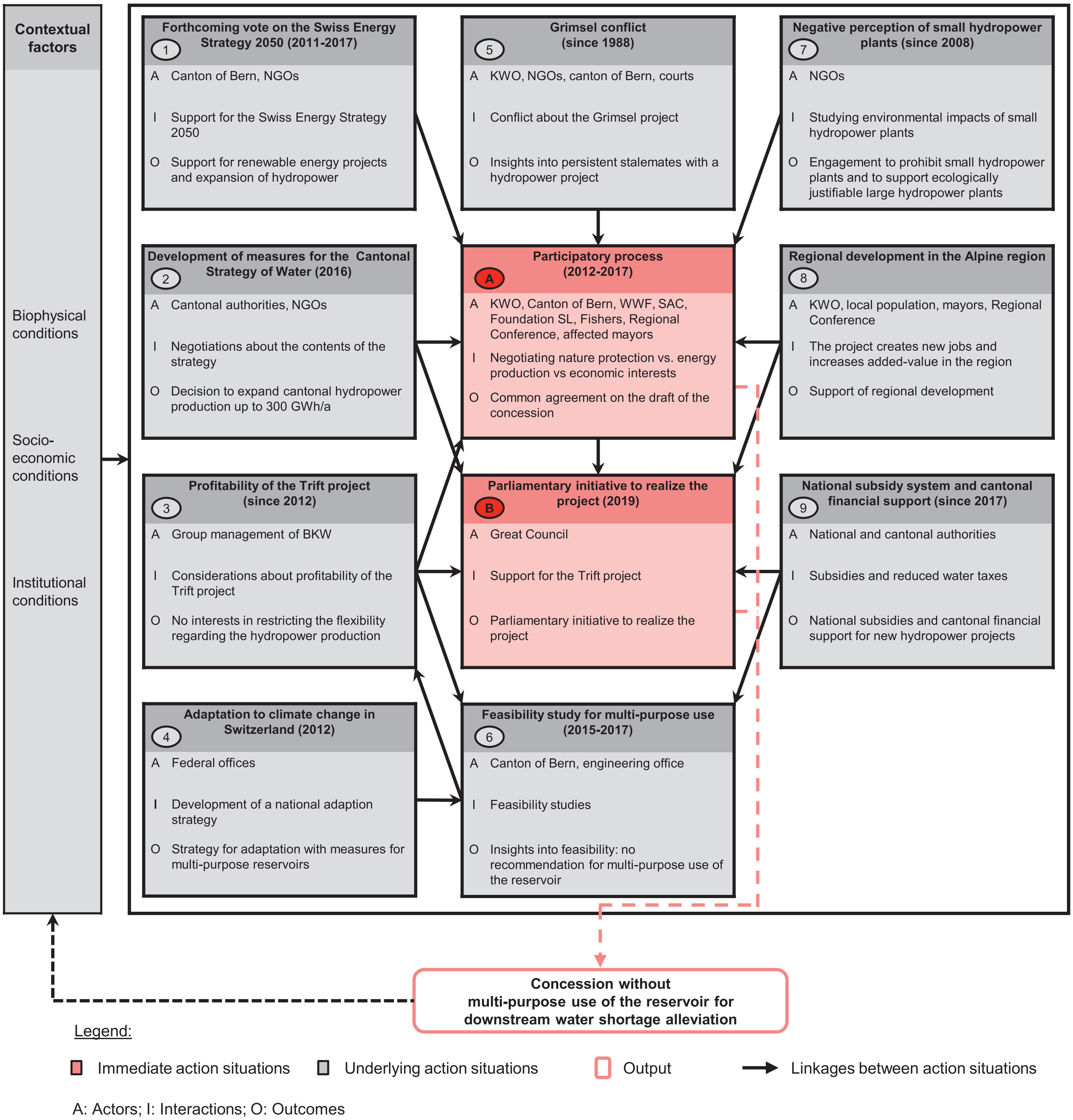

Figure 3. Social interactions explaining the decision-making process for the Trift concession: (A) Participatory process, (B) Parliamentary initiative, (1) Forthcoming vote on the Swiss Energy Strategy 2050, (2) Development of measures for the Cantonal Strategy of Water, (3) Profitability of the Trift project, (4) Adaptation to climate change in Switzerland, (5) Grimsel conflict, (6) Feasibility study for multi-purpose use, (7) Negative perception of small hydropower plants, (8) Regional development in the Alpine region, and (9) National subsidy system and cantonal financial support. Abbreviations: BKW = BKW Energie AG (Bernische Kraftwerke AG); Foundation SL = Swiss Foundation for Landscape Conservation; KWO = Kraftwerke Oberhasli AG; NGO = non-governmental organization; SAC = Swiss Alpine Club; WWF = World Wide Fund for Nature.

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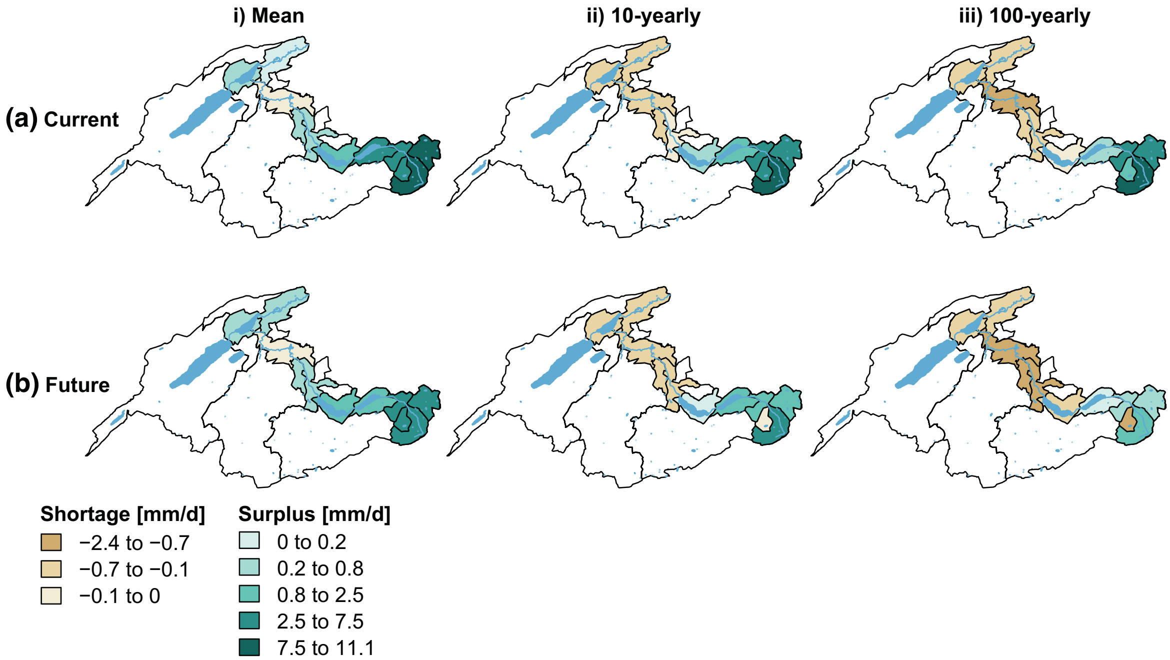

Figure 4. Summer water surplus/shortage (unit: mm/d) along the river network for (a) current and (b) future—i) mean and ii), iii) extreme (10- and 100-year estimates) conditions. Current hydropower demand is included as a water demand in the upstream catchments.

4. Results

A range of biophysical, socioeconomic, and institutional conditions provided important contextual factors, under which decisions on the Trift concession were made. The comparison of reservoir capacity and mean annual inflow with estimated downstream water shortages shows that water transfers from highland to lowland catchments could potentially alleviate current and future regional water shortage situations. Such transfers would require a multi-purpose management of the Trift reservoir including water shortage alleviation, which would have to be formalized in its concession. However, water shortage alleviation was not specified as a reservoir purpose in the draft of the concession. Our results show that the decision not to integrate drought management in the concession emerged as a result of 11 interdependent processes of social interaction within the Trift area and in adjacent action situations (Figure 3).

In the following paragraphs, we first describe the contextual factors including biophysical, socioeconomic, and institutional conditions. Second, we discuss the social interactions within two action situations with immediate relevance for decision-making, (1) the participatory process (AS A) and (2) the parliamentary initiative (AS B).

4.1. Contextual Factors

4.1.1. Biophysical Conditions

The biophysical conditions are summarized in terms of current and future summer water surplus/shortage for 11 stretches along the river Aare (Figure 4) in order to show the changes in surplus/shortage while moving from the upstream to the lowland region. The gradients in surplus/shortage estimates under mean conditions ranged from a water surplus of 10 mm/d in the upstream region to a water shortage represented by slightly negative values in the downstream part of the catchment. The slight shortage under normal conditions became more severe when focusing on extreme conditions. In the case of a 10-yearly shortage event, the greatest part of the downstream region was found to be affected by water shortage both under current and future conditions (−0.1 to −0.7 mm/d). This shortage was projected to become even more severe in the case of a 100-yearly event (−0.7 to −2.4 mm/d).

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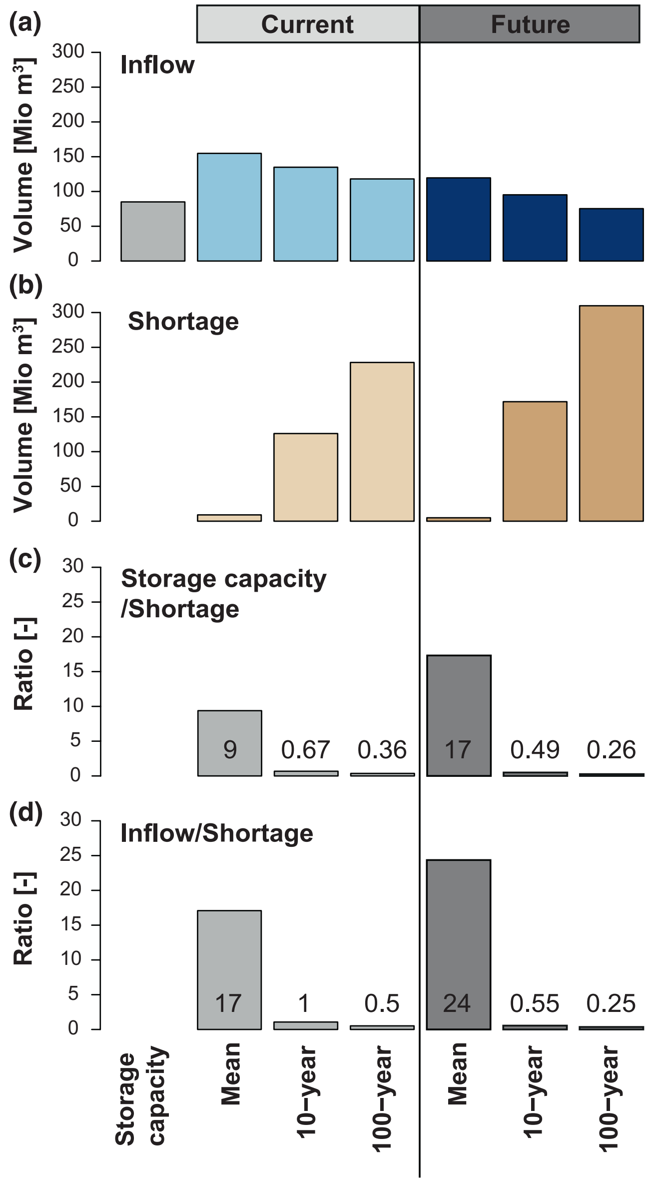

Figure 5. Storage capacity, reservoir inflow, and downstream shortage estimates and their relationship. (a) Storage and estimated mean and extremely low annual inflow volumes of the Trift reservoir, (b) estimated summer shortage for the downstream region under current and future mean and extreme (10- and 100-yearly) shortage conditions. (c) Storage capacity/shortage ratios for current and future mean and extreme shortage conditions. (d) Inflow/shortage ratios for mean and extreme conditions if extreme shortage co-occurs with extremely low inflow (e.g., 10-yearly inflow is compared to 10-yearly shortage).

To assess whether the capacity and inflow of the Trift reservoir are potentially sufficient to cover downstream summer shortage, the storage capacity of the Trift reservoir and its estimated current and future mean and extreme inflow volumes were compared to the regional downstream shortage volumes (eight river stretches below the three upstream stretches; Figure 5). Mean reservoir inflow was found slightly higher for current (c) than future conditions (119 Mio m^3) and estimated to decrease to 134 (10-yearly) and 118 Mio m^3 (100-yearly) under current extreme conditions and to 95 (10-yearly) and 75 (100-yearly) Mio m^3 under future extreme conditions (Figure 5a). The future extreme inflow estimates are similar to the storage capacity of the reservoir (85 Mio m^3), indicating that the reservoir might still be filled under extreme conditions.

The estimated downstream shortage under current and future mean conditions was with ~9 Mio m^3 found to be much smaller than the storage capacity of the Trift reservoir (Figure 5b). The 10-yearly downstream water shortage was with roughly 126 Mio m^3 under current conditions and 171 Mio m^3 under future conditions found to be twice the storage capacity of the Trift reservoir (85 Mio m^3) but equal to the mean annual inflow to the reservoir (154 Mio m^3). In contrast, the 100-yearly downstream shortage was with 228 Mio m^3 under current conditions and 309 Mio m^3 under future conditions estimated to be three times as high as this storage capacity and twice the total expected mean inflow volume of the reservoir (154 Mio m^3). While the storage capacity of the Trift reservoir is a multiple of the volume of mean downstream shortage, the storage capacity could only partially cover extreme shortage volumes (Figure 5c). In the case of a 10-yearly shortage, the storage capacity could cover up to 70% and 50% of the shortage under current and future conditions, respectively, while it would cover roughly 35% to 25% in the case of a 100-yearly shortage. If we assume that the whole inflow volume instead of just the storage capacity can be used to cover downstream water shortage, a slightly bigger part of the shortage can be covered by reservoir releases (Figure 5d). Under current conditions, extreme inflow (100-yearly) was estimated to cover roughly 50% of extreme shortage. This percentage was further reduced to 25% under future extreme conditions (100-yearly).

These findings indicate that the water available in the Trift reservoir would be sufficient to cover a large part of current and future regional downstream water shortage under mean reservoir inflow conditions and if the whole reservoir capacity was made available, while only 25%–50% could be covered if the storage capacity can only be used once (i.e., when the reservoir does not refill fast enough) or when extreme inflow conditions coincide with extreme regional water shortage. The results presented in this study were not available for decision-makers and did therefore not influence their decision-making.

4.1.2. Socioeconomic Conditions

In the decision process, socioeconomic conditions in the upstream region were weighted more than those in the downstream region. On the one hand, a new hydropower dam would support the socioeconomic development of the upstream, rural region if its profitability was ensured by operating the reservoir with hydropower production as a main target. On the other hand, including further target water uses could prevent economic losses in industrial and agricultural production downstream. These latter economic conditions did not influence decision-making because of the absence of downstream representatives in

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the decision-making process and the lack of knowledge on how multi-purpose water use including downstream water needs would affect hydropower revenues. As a result, downstream drought management was excluded as an explicit purpose of the reservoir. However, water releases from the reservoir related to hydropower production could indirectly still contribute to the alleviation of downstream summer water shortage, also under future socioeconomic conditions. Future electricity demand may potentially shift from winter more to summer due to an increase in air conditioning (Wenz et al., 2017) which would result in a better overlap with high downstream water demand in summer.

4.1.3. Institutional Conditions

Various institutional conditions including national and cantonal laws and regulations are relevant for the construction and operation of water reservoirs (Tables S2 and S3). In the case of the Trift reservoir, these regulations led to contradictory incentives, responsibilities, and procedures in the decision-making process because of their low coherence introduced during their evolution following a sectoral logic (Kellner et al., 2019).

4.2. Networks of Action Situations

We identified two action situations with immediate relevance for decision-making: the participatory process (AS A) and the parliamentary initiative to realize the Trift project (AS B) which are discussed in detail here. These two processes took place under the influence of additional nine action situations (AS 1–9, Table S4).

4.2.1. AS A: Participatory Process

The canton of Bern and KWO established a broad participatory process to prevent conflicts and stalemates that could arise because of concerns regarding the environmental impacts of the project. They wanted to reach a common agreement on the draft of the concession with actors who might object to the concession and therefore exercise their veto-power. The main group of the participatory process was thus composed of a variety of representatives from environmental NGOs with veto-power, KWO, cantonal authorities, and the Regional Conference.

All actors in the participatory process shared the overarching goal of phasing out nuclear energy and of increasing renewable energy through an ecologically justifiable expansion of hydropower production (AS 1 and 2). By supporting the Trift project as a reservoir for hydropower production, the actors also promoted the Swiss Energy Strategy 2050 before it was voted on and contributed to fulfilling the target of the Cantonal Strategy of Water to expand cantonal renewable energy through hydropower production. The NGOs, who support the Trift project, see the project as a chance to prevent the construction of a number of new, small hydropower plants, which would have greater negative environmental impacts than a large plant as envisioned in the Trift project (AS 7). In contrast, the participating actors were not as concerned about the national adaptation strategy, which proposes the use of reservoirs for additional purposes than hydropower production (AS 4). The focus of the participatory process was on finding a consensus on how to minimize the environmental impacts of the dam project and on ecological compensation measures (AS 5 and 7). All actors except the environmental NGOs promoted economic interests such as ensuring the profitability of the dam project (AS 3) and regional development (AS 8).

The actors in the participatory process—except for the canton and the hydropower company—were not aware of the existing feasibility study on multi-purpose water use (AS 6). This is surprising given that Switzerland follows the principle of public access for reports and studies funded by public agencies. One potential reason for the suboptimal communication of crucial information may be the fact that the canton, who commissioned the study, may have had a conflict of interest because of their role as a shareholder of the hydropower company and their responsibility to fulfill the target of the Cantonal Strategy of Water to expand cantonal hydropower production. However, the canton had already limited the scope of the study by agreeing to KWO's main objective of producing electricity with the Trift reservoir (geo7, 2017). The study results showed that affected downstream areas are located too far away from alpine reservoirs and that the

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influence of its retention would be small due to dampening effects of lakes which the water passes on its way from the reservoir to the downstream region. Accordingly, the study concluded that a multi-purpose use of the Trift reservoir is inappropriate for drought management (geo7, 2017). Our results, in contrast, show that the water available in the Trift reservoir would be sufficient to cover a large part of current and future regional downstream water shortage under mean reservoir inflow conditions and could even partially alleviate water shortage under extreme inflow conditions (Figure 5). The different conclusions of our and the geo7 study may stem from different definitions of "water deficits." The geo7 study defined deficits based on water supply as volume differences between mean and extremely low flow conditions while our study derived explicit downstream water demand estimates for different types of water uses. However, the conclusions of the geo7 study about the dampening effects of lakes are in line with the general narrative brought forward by many actors in Switzerland despite the fact that the usable lake volumes lie in the same order of magnitude as the storage capacity of the Trift reservoir (Section 2). Downstream water uses were not considered and potentially affected downstream actors were not included in the participatory process as a result of the national goal to promote the Swiss Energy Strategy 2050 and to increase renewable energy production, the cantonal interests to contribute to these goals, and the results of the geo7 study. Moreover, most of the decision-makers and downstream farmers were neither aware of the fact that downstream water shortage is likely under future extreme conditions nor that the Trift reservoir could potentially alleviate a substantial part of this shortage. This lack of awareness may result from the widespread perception of Switzerland as "the water tower of Europe" (Agenda, 1998; Viviroli et al., 2007). The multi-purpose use of the reservoir for downstream water shortage alleviation was therefore not discussed in the decision-making process. The outcome of the participatory process was a common agreement on the draft of the concession, which was submitted to the canton of Bern in 2017. This draft only considers hydropower production, and neglects downstream water shortage alleviation.

4.2.2. AS B: Parliamentary Initiative to Realize the Project

Since 2017, the state's authorities have been assessing whether the proposed concession is legally acceptable. Once this assessment is completed, the Great Council of the canton of Bern will vote on granting the concession. In 2019, the members of the Great Council adopted a parliamentary initiative to support the Trift project (Mentha et al., 2019). The main request is that the canton of Bern, which represents the majority shareholder of BKW, should ensure that BKW, as the main shareholder of KWO, supports and promotes the implementation of the Trift project as quickly as possible. At the time of the initiative, the Swiss Energy Strategy 2050 had already been adopted and decisions to introduce subsidies for hydropower production and a discount of cantonal water taxes had been made (AS 9). The initiative argued that the hydropower company could benefit from these national subsidies of up to 40% and the reduced cantonal water taxes. This financial support makes the project more profitable (AS 3). Moreover, the project was seen to support regional development by creating jobs and increasing value in the region (AS 8). The Great Council was also very pleased with the performance and the outcome of the participatory process (AS A). In addition, the Canton's feasibility study on multi-purpose use did not recommend a multi-purpose use of the Trift reservoir (AS 6). The Great Council argued that the decommissioning of the cantonal nuclear power plant should be compensated with cantonal renewable energy instead of nonrenewable foreign energy. Using the Trift reservoir only for hydropower production would also help the canton in meeting its obligation to contribute to both the Swiss Energy Strategy 2050 and the Cantonal Strategy of Water (AS 1, 2). This and other arguments elaborated on above convinced the Great Council to adopt the parliamentary initiative. This initiative was a further step toward granting the concession without the consideration of drought management.

5. Discussion

5.1. Coordination Gap

The analyses of this study uncovered a coordination gap between a planned upstream reservoir in a recently deglaciated area and potential downstream water shortage and provide insights on factors, which led to this coordination gap. The results of the water resources analysis show that the water available in the Trift reser-

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voir would be sufficient to cover a substantial part of current and future downstream water shortages, partly, even under extreme conditions. Still, the actors involved in the participatory process leading to the draft concession did not consider downstream water needs in their decision-making even though the concession constitutes a property right und could not be adapted before its expiration in 80 years (Kellner, 2019).

Four main factors influenced the decision in favor of hydropower production—instead of a multi-purpose use including downstream water shortage alleviation: (1) a lack of knowledge, awareness and available data about future downstream water shortages and potential reservoir-management options for multi-purpose use, (2) a strong interest in phasing-out nuclear energy and increasing renewable energy production, (3) a focus on reaching consensus on environmental issues with the NGOs in the participatory process, and (4) strong economic interests in hydropower production. Our results demonstrate that governance processes for new hydropower reservoirs are well established in Switzerland, whereas the multi-purpose use of such reservoirs is a nascent topic based on little experience, both procedurally and legally. While environmental concerns regarding reservoirs were taken more seriously than in the past, decision-makers neglected potential downstream water shortages enhanced by climate change. This is also evident from the fact that authorities did not invest in an extensive study on how to manage and operate a multi-purpose, multi-reservoir system as common in evaluating reservoir projects (Tu et al., 2003; Wheeler et al., 2018; Wu et al., 2016; You & Cai, 2008) (see Section 5.2). Such a detailed hydrological and socioeconomic analysis including their systemic interactions could indicate the potential impact of multi-purpose use on downstream water shortage alleviation and drought risk, hydropower production, and costs and benefits for all sectors. Such information could lead to more awareness about the socioeconomic consequences of neglecting downstream water uses, could offer unexpected solutions for seemingly insuperable obstacles, and could shift the focus in the participatory process from mitigation goals (hydropower production) to the incorporation of adaptation goals (alleviate water shortage). However, even the availability of such a study may not have changed the outcome of the decision process because of the current political situation (forthcoming vote on the Swiss Energy Strategy 2050), path dependencies (conflicts with former projects), power imbalances between the hydropower company and downstream actors, and economic interests (i.e., significant subsidies for hydropower projects).

Our findings are in line with previous findings focusing on water governance as a multi-level challenge under climate change (Gupta et al., 2013; Pahl-Wostl, 2019a, 2019b). Although many water uses can jointly contribute to climate change mitigation and adaptation, climate policies have generally addressed both challenges in separate strategies (Berry et al., 2015; Locatelli et al., 2015). Mitigation and adaptation strategies differ regarding knowledge generation; analytical approaches (Biesbroek et al., 2009); spatial, temporal, institutional, and administrative scales (Hennessey et al., 2017; Shrestha & Dhakal, 2019); and their relevance for different economic sectors, so that the distribution of costs and benefits is uneven (Swart & Raes, 2007). There is a critical need to clarify priorities and responsibilities on a national as well as on an international level. To date, the two goals have been often perceived as trade-offs and more effort is needed to maximize synergies between the different goals. Dealing with such complex trade-offs and synergies poses a challenge for decision-makers (Breuer et al., 2019). As a result, national climate goals usually ignore mitigation-adaptation interlinkages (Berry et al., 2015; Leonard et al., 2016; Shrestha & Dhakal, 2019).

The present paper contributes to the mitigation-adaptation debate by showing that Switzerland has two different national strategies, one for mitigation, and one for adaptation. The mitigation strategy represented by the energy strategy includes clearly defined quantifiable targets and measures for financial support such as national market premiums and subsidies. In contrast, the national adaptation strategy generally recommends using water reservoirs for multiple services but does not envisage the provision of financial support. This unavailability of financial support is common for adaptation strategies (Swart & Raes, 2007) because the responsibilities and financial obligations related to adaptive measures are unclear. These diverging implementation approaches for the mitigation and adaptation strategies were reflected in the governance processes of the Trift project and influenced decision-making.

In addition to these mitigation-adaptation trade-offs, an imbalance in power between hydropower and other sectors (Weitz et al., 2017) and between upstream and downstream water users (Anghileri et al., 2013; Cody, 2018; Denaro et al., 2018) could inhibit a good coordination. Previous studies indicated that the economic interests associated with hydropower development tend to outweigh environmental issues (Pahl-Wostl et al., 2013; Zarfl et al., 2015). Our case study shows that environmental considerations were tak-

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en seriously, as shown by the involvement of environmental NGOs, because of previous major conflicts and stalemates resulting from the ignorance of environmental issues. In contrast to environmental issues, drought management was considered less important even though effective drought management can have important socioeconomic implications for downstream industries and agriculture by avoiding production gaps and losses in crop yield. This result contributes empirical evidence that confirms prior research showing that power distribution becomes pivotal in negotiating water policies when the resource is scarce or its use is competitive among different actors (Denaro et al., 2018).

The Trift example underlines that Integrated Water Resource Management (IWRM) is difficult to implement on a broad scale despite its promotion in national and international policy arenas (Biswas, 2004, 2008; Medema et al., 2008; Petit, 2016). Similar to the majority of countries (UNEP, 2012), Switzerland has adopted IWRM principles in its national and cantonal policies. However, the principles include guidelines for watershed management procedures and consider interests of various sectors while they neglect downstream drought management. In the absence of such recommendations, IWRM principles do not overcome the lack of integrated governance processes (Pahl-Wostl et al., 2012) and the lack of institutional capacity to govern across sectoral boundaries (Benson et al., 2015).

Our results support findings of previous studies which conclude that the challenge of the water crisis is first and foremost a crisis of governance (Gupta et al., 2013). However, they also show that it is a crisis of incoherent regulations (Kellner et al., 2019). Even in a country like Switzerland, with one of the best governance indicators of the world (Kaufmann et al., 2010; Stefano et al., 2017; UNEP-DHI & UNEP, 2016), governance processes do not manage to compensate incoherent regulations and incentives.

5.2. Limitations

5.2.1. Limitations of the Quantitative Analysis

The assessment of the hydrological conditions consisted of a volumetric comparison of reservoir capacity and inflow to aggregated downstream water needs under current and future mean and extreme conditions. In order to directly compare upstream surplus to downstream shortages, each region was treated individually without considering water transfers between regions. This precluded a detailed water and reservoir management study. While such a study is not necessary to show the relationship between upstream supply and potential shortage arising downstream, it would be detrimental to identify suitable reservoir management strategies if the fulfillment of downstream water needs had been part of the concession. Such an analysis could be conducted by comparing different management schemes within a multi-objective optimization framework where upstream and downstream demands and the different reservoirs in the system are considered simultaneously (Anghileri et al., 2013; Wu et al., 2016). Such a management analysis may besides trade-offs between different uses also reveal potential synergies. One potential synergy could arise if the seasonality of future electricity demand shifts from winter toward summer, which is one among potential but uncertain future scenarios for the development of electricity demand (Gaudard et al., 2014; Ranzani et al., 2018; Wenz et al., 2017). Such a shift in demand would imply a shift in water releases to summer as well, which would coincide with the downstream demand from the agricultural sector. Ideally, such a study would have been done before the participatory process to inform the actors who organized the process and the actors who participated in the process and decided on the draft concession.

5.2.2. Limitations of the Qualitative Analysis

The used NAS approach is one tool to facilitate the application of IAD to complex policy settings (McGinnis, 2011b). While promising, the approach faces some methodological challenges. First, the system structure is only weakly defined. The identification of action situations and their system boundaries are delineated along situations of social interactions that influence the outcome. Social interactions "are distinct patterns of cooperation, coordination, and conflict among particular actors on particular governance issues generating particular outcomes" (Oberlack et al., 2018). Defining and bounding the study systems therefore depends to some degree on the researcher's perspective. Second, the NAS approach currently lacks sufficient detail

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to be directly empirically applicable. As a result, current applications rely on different research protocols that, while referring to the same NAS approach, produce empirical data hardly suitable for comparative and replicable analyses. Our case study approach provided insights into processes and considerations, which are not reflected in global indices and assessments. It enables establishing causal relationships in the complex setting considered. However, case studies do not necessarily allow for the generalization of results to similar regions because of their dependence on current political aspects and the relevance of history and path dependencies in decision-making (Epstein et al., 2020). Case studies can point out limitations of global studies and complement them by highlighting local features that need to be represented on larger spatial scales.

6. Conclusions

The findings of this study improve our understanding of governance processes related to the planning of reservoirs considering upstream and downstream water needs. We show for a case in the upper Rhine basin that artificial reservoirs can help cover downstream water shortage, partly even under extreme conditions. Despite the potential of reservoirs to alleviate water shortage, drought management is in the Alps often not considered as an additional water use besides hydropower. This study highlights the challenges inherent in governance processes related to the management of eventually competing water uses. Our case study in the Trift region shows that even in a country like Switzerland with one of the best governance indicators of the world, downstream water shortage is not necessarily considered in the planning process of a new reservoir. Not considering downstream water needs in decision-making seems striking particularly because of its long-term implications under climate change, that is the concession, as a water property right, cannot be adapted before its expiration in 80 years. We show that four main factors influenced the actors not to consider downstream water needs in their decision-making on the reservoir concession: (a) a lack of knowledge about future downstream water shortage and of an appropriate reservoir-management study, (b) an interest to increase renewable energy production, (c) a focus on environmental agreements, and (d) economic interests. These institutional conditions and governance processes as existent in the Trift case may also apply in other cases.

We conclude that governance processes for reservoirs in world's water towers need to address institutions which lack adaptive capacity and systemic interlinkages with positive synergies, but also negative interactions and externalities that imply difficult trade-offs between upstream and downstream water uses. Governance processes need to include all affected actors and ensure food and energy security as well as limited environmental impact. Such inclusion could be supported by providing sufficient data on the biophysical conditions at a relevant scale for current and future downstream drought scenarios, evaluating management options for multi-purpose reservoirs, and analyzing costs and benefits of a multi-purpose reservoir use. Providing comprehensive information to involved actors is critical to understand complex challenges and capitalize on synergies and co-benefits, while minimizing trade-offs. This knowledge enables refinement of governance processes by adapting their level and spatial scale to the one of the affected catchment, whose water shortage could be potentially alleviated with an optimal reservoir management. In addition, processes could be improved by involving downstream actors of the affected catchment and by fostering cross-sector dialogs that diffuse through different hierarchical levels of decision-making. The governance processes need to carefully consider impacts of financial instruments, such as national subsidies, on decision-making. Further, they could examine synergies and trade-offs, for example between mitigation and adaptation strategies, when addressing the potential contributions of a reservoir in a long-term perspective and when valuating economic impacts of providing water to downstream regions during water shortage situations on the hydropower sector. It is essential that future sustainable management of reservoirs for the world's important and vulnerable water towers, considers both upstream and downstream water needs.

Future research needs to focus on the problem of assigning responsibility for tackling trade-offs and identifying synergies between climate change mitigation and adaptation. Scholars need to reflect even more on specific aspects allowing for the improvement of governance processes and address questions such as: Which actors have the accountability and legitimacy to promote adequate governance processes considering both upstream and downstream interests when establishing regulations for reservoirs in the world's important and vulnerable water towers? Which competences and personalities are needed to lead complex

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processes with actors from different governments and sectors with diverging cultural and socioeconomic backgrounds and financial capacities? What are appropriate design principles of governance processes to address trade-offs as well as synergies between competing water uses leading to sustainable water uses?

As the global water crisis is expected to become more critical in the near future, it is crucial to promote both research and political progress to design and implement governance processes that can anticipate and deal with changes to satisfy various water needs of people sharing a common river basin.

Data Availability Statement

The hydrological model simulations and the water demand estimates for the different demand categories for current and future conditions can be downloaded via the EnviDat data repository (https://www.envidat.ch/dataset/hydro-ch2018-reservoirs).

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

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