

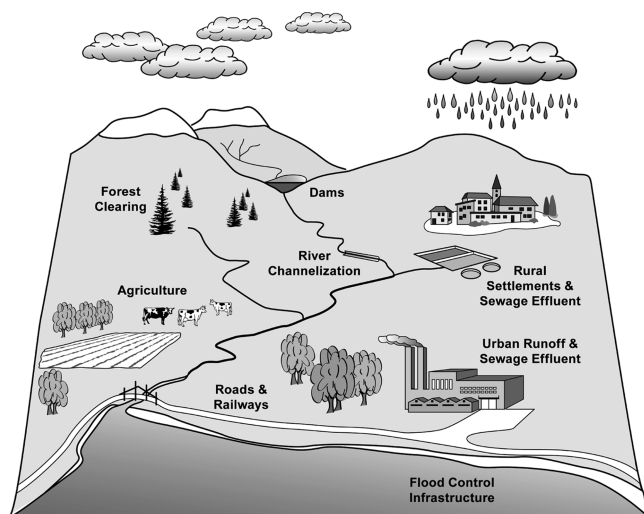
Moving Targets, Long-Lived Infrastructure, and Increasing Needs for Integration and Adaptation in Water Management: An Illustration from Switzerland

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■ INTRODUCTION

Basic needs for water (e.g., for drinking water supply, irrigated agriculture, transportation, and waste assimilation, etc.) have been recognized throughout human history. Societies have traditionally invested heavily in water infrastructure to the point that human activities, such as dam construction, can be considered as a major geomorphic force on the water environment. In contrast, indirect ecosystem services provided by the water environment are only beginning to be fully appreciated.¹ Pressures on available water resources have been increasing in many regions, and the need to maintain “environmental flows” (i.e., water that supports aquatic and terrestrial habitat) has been acknowledged if not always satisfied.²

Water infrastructure has been developed in response to societal needs and values under specific environmental and geographic conditions (e.g., climate, hydrology, geomorphology, and ecological, biological, and chemical conditions) and with the technological, economic, and socio-political resources available at the time of design and construction. During the long lifetime of water infrastructure, all of these factors may evolve. In addition, new challenges may arise that the infrastructure was not designed to meet and unintended consequences may become apparent over a time-span of decades. Thus the criteria by which the success of water infrastructure is defined can also change over time.

The development of water infrastructure is embedded in the broader context of the management of water resources and the

water environment. Thus deficiencies in technical performance that arise from unanticipated demands and/or unintended consequences may be addressed not only by modification of the infrastructure but also by alternative strategies that obviate the need for such modification. It is therefore of interest to consider how future decisions regarding the use, protection, and management of water resources as well as the replacement, upgrading, or redesign of infrastructure will be different from those of the past. Here we use examples from Switzerland, a country with a long history of intensive water infrastructure development, to illustrate the multiple and evolving challenges that must be addressed in the management of water resources and infrastructure.

■ WHY SWITZERLAND?

The designation of Switzerland as the “water tower of Europe” reflects the importance of water resources and their management to the Swiss national identity. Switzerland has a long history of water infrastructure development and of active management of its water resources at a very high level of technical competence. As a water-rich country, with 1.5 m of precipitation annually, Switzerland faces only local issues of water availability. It must nonetheless address a number of conflicting objectives in the management of water infrastructure and water resources in the context of highly altered rivers and floodplains. As an alpine country subject to severe flooding, Switzerland initiated the development of large-scale water infrastructure in the early 19th century. Today, in the Swiss midlands (i.e., at altitudes below 600 m), half of all water courses exhibit ecomorphological impairment.³

Switzerland is typical of many industrialized countries in that the management of water infrastructure and water resources has been highly professionalized. This has facilitated the incorporation of expert knowledge and technical information but has also promoted a bias toward large infrastructure and a narrow definition of problems and potential solutions.⁴ As is common in many industrialized countries, responsibility and authority on issues related to water resources, water supply, and the aquatic environment are fragmented among various agencies. The issue of fragmentation is compounded by Swiss federalism and the strong tradition of local authority. Although legal and regulatory requirements are established at the Federal level, the ownership

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Table 1. Evolving Focus of Water Resources Management As Evidenced by Federal Legislation and Regulations^a

period	principal goal	key legislation and regulation
1870–1908	flood protection	1877 Federal Law on Hydraulic Engineering (SR 710.10) 1878 Federal Law on Forests (revised 1902, 1991 – SR 921.0)
1908–1953	hydropower	1916 Federal Law on the Exploitation of Hydroelectric Power (SR 721.80)
1953–1991	water quality protection	1955 Federal Law on Water Protection (revised 1971, 1991, 2010 – SR 814.20) 1991 Federal Law on Fisheries (SR 923.0) 1991 Federal Law on Flood Protection (SR 721.100)
post-1991	integrated water resources management	1992 Ordinance on Protection of Flood Plains (SR 451.31) 1998 Water Protection Ordinance (SR 814.201) 2001 Ordinance on Environmental Quality (SR 914.14)

^a Source: Vermont.⁴³

of public waters and responsibility for enforcement rests mainly with the Cantons (i.e., the 26 Swiss states), and implementation and operation and maintenance of infrastructure are generally performed at the municipal or community level.

Despite this decentralization of authority and responsibility, the Swiss Federal legislation provides a useful overview for the evolution of societal goals over time (Table 1). Expanded flood protection effectively increased the availability of land for settlement and agricultural use, and hydropower development supported rapid industrialization. Thus legislation in these domains may be considered as increasing the direct benefits gained by Swiss society from the environment. In contrast, the focus of later legislation and regulations (corresponding to the goals “water quality protection” and “integrated water resources management” in Table 1) shifted toward environmental protection as the detrimental impacts of human activities on the environment and the need for their amelioration became apparent.

MOVING TARGETS: UNINTENDED CONSEQUENCES AND UNANTICIPATED DEMANDS

It is clear from Table 1 that some of the activities conducted under the auspices of earlier Federal legislation (particularly related to flood protection and hydropower development) led to conditions that were later considered unacceptable to society. Although some of the environmental impacts of these early measures (e.g., the loss of fluvial habitat) were not the intended consequences of river channelization and dam construction, they were mostly anticipated and were considered as an acceptable consequence at the time. During the long lifetime of water infrastructure, an increasing value has been placed by society on the conservation of landscapes, biodiversity, and native species (particularly fish populations) with a consequent emphasis on preserving and restoring aquatic habitat. These values can be considered as an unanticipated demand on the infrastructure that compromises its perceived success in the long term. Similarly, various types of measures that have been employed by society can be evaluated not only in terms of their intended goals but also in terms of their unintended consequences on the water environment and the unanticipated demands that they must accommodate (Table 2).

CONTEXT FOR PRESENT AND FUTURE MANAGEMENT OF WATER INFRASTRUCTURE AND WATER RESOURCES

Past decisions on the management of water infrastructure and water resources (as illustrated by Federal legislation and regulation

corresponding to the goal “integrated water resources management” in Table 1) have incorporated an increasing recognition of the complexity and interrelatedness of the systems being managed. Although existing infrastructure and long-term agreements (such as hydropower concessions) constrain present-day and future decisions, a pragmatic strategy of adaptation can, in many cases, accommodate evolving scientific understanding and societal expectations. Thus, for example, the problem of eutrophication of lakes in the Swiss midlands was addressed through a combination of advanced wastewater treatment, the elimination of phosphates from detergents, and improved agricultural practices (see Box). Cooperation across political boundaries, for example the formation of voluntary associations of communities to collect and treat wastewater,⁵ has been motivated by the need to overcome limited capacities or to achieve economies of scale.

REVERSAL OF EUTROPHICATION IN LAKES OF THE SWISS MIDLAND:

After World War II, eutrophication was observed in Lake Zürich, a large lake (volume 3.9 km³, surface area 88.66 km², average depth 49 m) in the Swiss midland. Algal blooms were first observed in 1949 (Figure 1, left panel) and were accompanied by a steep rise in phosphate concentrations.³⁹ In smaller lakes, maximum phosphate concentrations were observed around 1970 (Figure 1, right panel) despite implementation of iron-based phosphate removal in wastewater treatment plants as early as 1960. Expanded wastewater treatment resulting from infrastructure subsidies in the 1970s combined with a ban on phosphate-containing detergents^{40,41} was successful in controlling phosphorus concentrations in many Swiss lakes that had become eutrophic⁴² and restoring them to mesotrophic or even oligotrophic status.

It is likely that future management of water infrastructure and water resources will demand a more systematic approach to integration across sectors and adaptation to evolving boundary conditions than has been followed in the past. This is partly the consequence of demographic and historical developments that have resulted in highly altered rivers and floodplains, a dense distribution of existing infrastructure, and spatial overlap of different impacts on aquatic ecosystems in many locations. Furthermore, an increasing awareness of the importance of ecosystem services and biodiversity has been accompanied by the recognition that aquatic systems should be considered as

Table 2. Characterization of Measures Related to Water Infrastructure and Water Resources Management

measure	goal	unintended consequences	unanticipated demands
river channelization	flood protection land reclamation	loss of habitat	conservation of biodiversity
		loss of biodiversity	conservation of native species
		loss of native species	
dam construction	hydropower	loss of habitat	conservation of biodiversity
		loss of biodiversity	conservation of native species
		loss of native species	
construction of sewers and wastewater treatment plants	sanitation	waste of resources (energy and nutrients)	refractory constituents of wastewater (e.g., micropollutants)
<i>increased transport and artificial waterways^a</i>	<i>transportation of goods</i>	colonization by invasive species	conservation of biodiversity
river restoration	improvement of ecological status	conflicts with groundwater protection	conservation of native species climate change

^a italics indicate that the goal and measures were not primarily related to water resources management.

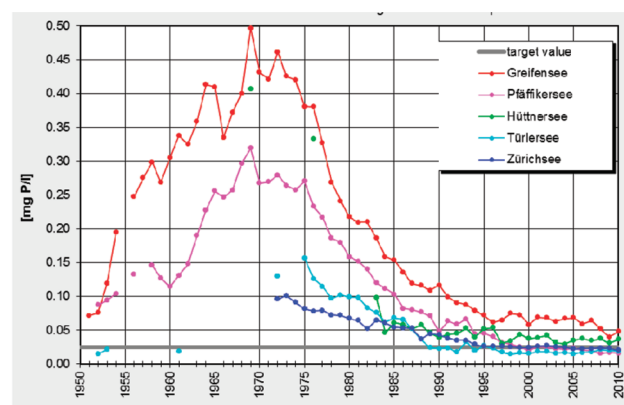


Figure 1. (left) Blooms of filamentous green algae in Lake Zürich ca. 1955 (Source: <http://www.limnology.ch/station/history.php>). Used by permission of the University of Zürich. (right) Annual average concentrations of total phosphorus based on volume-weighted depth profiles. Source: http://www.awel.zh.ch/internet/baudirektion/awel/de/wasserwirtschaft/gewaesserqualitaet/seen_kenngrößen.html. Used by permission of the Office of Water, Energy and Air of Canton Zürich.

dynamically linked spatial networks that do not necessarily correspond to administrative boundaries and that surpass our current understanding and predictive capabilities. Changing societal expectations require that decisions previously addressed in a sectoral manner (e.g., location, design, and management of hydropower operations) must now incorporate broader objectives such as ecological impact and societal acceptance.

The integrated management of water resources at the catchment scale is also being actively promoted by Swiss Federal Office for the Environment (FOEN) as the preferred approach for managing water resources and supply, the protection of surface water and groundwater, and water infrastructure.⁶ In addition, the Swiss traditions of direct democracy and local control provide a strong basis for stakeholder participation, which is important for the acceptance and implementation of cross-sectoral measures.

CURRENT AND EMERGING CHALLENGES

Here we examine three topics that are rapidly developing within the Swiss (and European) framework and would be likely to benefit from an integrated and adaptive approach. The issue of hydropower expansion and river restoration addresses difficult

conflicts between direct benefits to society and ecological protection. The issue of micropollutants illustrates the potential for engagement of different sectors in protecting the quality of surface water and groundwater. And the issue of biodiversity and the impact of invasive species illustrate the need for societal measures in the absence of effective technical controls. The diversity of these topics reflects the variety of pressures that human activities exert (often simultaneously) on the water environment.

Hydropower Expansion and River Restoration The pressure for climate change mitigation through expansion of renewable energy with low carbon intensity and the political decision to phase out nuclear power are driving an increasing interest in hydropower generation. Renewable energy technologies, particularly wind and solar power, often require equalization to offset periods of decreased production or to supplement production to meet peak demands. Alpine hydropower operations offer an opportunity to meet these needs, but careful design is needed to minimize environmental harm. New projects can be evaluated based on the adequate management of issues such as minimal flow and hydropowering.⁷ Prior experience in Switzerland has demonstrated that stakeholder dialogue can be a mechanism to incorporate ecological concerns;

in the case of the 1000 MW pumped storage plant of Lago Bianco this led to the public acceptance of an improved technical design.⁸

An increase in small hydropower operations is occurring in Switzerland, partly in response to available or anticipated subsidies. Future environmental harm could be minimized by prioritizing catchments when locating such new operations. In one Swiss prioritization project, catchments have been characterized based on their current ecological value and level of environmental pressure (not only from existing hydropower operations but also from infrastructure for flood control, wastewater treatment, etc.).⁹ Such prioritization is intended to optimize the benefit of protecting some catchments and allowing hydropower development in others.

Environmental harm associated with existing hydropower operations, specifically with hydropeaking, could also be mitigated through the use of buffer zones or reservoirs.¹⁰ The establishment of such buffers as well as the allocation of additional space for rivers would need to be incorporated into the design of future river restoration projects. A substantial increase in such projects is expected as a result of the 2010 revision of the Federal Water Protection law that explicitly requires and funds both river restoration and technical measures to offset the ecological impacts of hydropower.

Guidance for these future efforts is provided by recent past experiences, such as the pilot river-widening projects conducted on the Thur River that integrated flood protection and river restoration and also incorporated scientific assessment and stakeholder engagement.^{11,12} Key components of this project were preproject baseline monitoring, the direct involvement of stakeholders in the planning process, and postproject success evaluation.¹² The need for baseline data is even more urgent in the context of climate change, which calls into question the assumption that historical conditions can provide adequate boundary conditions for the future.¹³ Future river restoration projects will, however, be constrained by the prohibition on river restoration in groundwater protection zones near losing rivers.¹⁴ The examples of hydropower development and river restoration illustrate the broad set of constraints for today's decision making compared to the simple guidelines of economic and technical feasibility five decades ago.

Micropollutants. Pending Federal regulation in Switzerland will require wastewater treatment plants (WWTPs) that discharge effluent to streams with insufficient dilution capacity or to lakes close to drinking water intakes to reduce their discharge of micropollutants. This regulation is strongly driven by the precautionary principle, which dictates avoidance of possible (unknown) harm. Reduction of micropollutant emissions can be accomplished through advanced treatment processes, such as ozonation or activated carbon.^{15,16} Although WWTPs are an important point source of micropollutants, diffuse sources are also significant. Urban diffuse sources include sewer exfiltration,¹⁷ outdoor urban use of lawn and garden products, and leaching of biocides from facades and construction materials.¹⁸ The primary nonurban diffuse source is the use of pesticides in agriculture.

The variety of sources offers multiple options for reducing the loading of micropollutants to the environment. In addition to reducing the discharge from WWTPs, it could also be feasible to put greater emphasis on keeping pharmaceuticals and personal care products (PPCPs) out of sewage (and also landfills) through measures such as required "take-back" of unused material at pharmacies and better control of pesticide use. A "green chemistry" approach would incorporate considerations of environmental fate

and effects in product formulation, though this may be complicated by possible incompatibility between desirable criteria for intended product use and environmental protection. Consumer pressure could be engaged through "eco-labeling" (e.g., providing information on the biodegradability of products in WWTPs).

These multiple options also present the risk that the various actors (i.e., regulators in various sectors, WWTP operators, chemical industry, consumers, etc.) may shift the responsibility for protection of the aquatic environment among themselves. It is also difficult to make a strong case for control or substitution in the absence of direct causal evidence of ecotoxicological harm. An informed decision as to which set of options would best serve the goal of minimizing pollution risks should be based on quantitative predictions of the environmental fate and effects of chemicals on aquatic organisms as well as the preferences of societal actors.

Biodiversity and the Impacts of Invasive Species. The long, recorded history of human alteration of the European landscape has tended to blur the distinction between native and introduced species. Some species have been deliberately introduced; in Switzerland, 15 species of introduced fishes represent 25% of the fish fauna.¹⁹ There is, however, an increasing concern for the conservation of biodiversity and the pressures that invasive species exert on native species. The increase in invasive species in Europe has paralleled the proliferation of interbasin (and intercontinental) water transfers through the construction of navigation and transport canals between basins.²⁰ In the future, increased connectivity in restored rivers, which is often an explicit goal of restoration, could facilitate the spread of invasive species. Hence, there is a risk of unintentional, negative ecological effects of measures taken to improve the ecological status of streams.

Numerous studies have shown that there is little chance of eradication once an invasive species is established; thus controls are currently focused on limiting transmission using models to support risk analysis.²¹ A rapid response to limit transfer and colonization of aquatic ecosystems by invasive species requires an early warning system based on cooperation among authorities and a means of predicting the probability of invasive pathways.^{20,22} In cases where the introduction of invasives can be linked with societal practices and human behavior, appropriate interventions can be directly targeted by regulations. Stocking of non-native fishes is currently prohibited in Switzerland with only a few exceptions in closed water bodies. In Norway, very stringent measures against the spread of crayfish plague have been adopted, including regulation of the transport of aquaria animals and recreational boats and equipment not only into the country but also between watersheds.²³

The need for early intervention or even pre-emptive measures and the lack of well-established measures for the effective control of invasive species demand management approaches that can integrate across sectors, incorporate outreach to commerce and consumers, and be adapted to improve their effectiveness.²²

■ INTEGRATION AND ADAPTIVE MANAGEMENT

The underlying rationale for strengthening integration in the management of water infrastructure and water resources is the possibility that innovative and/or cost-effective solutions, which might be excluded in traditional, sectoral approaches, could be identified and adopted. In addition, conflicting interests in different sectors or among various actors can be identified, addressed, and eventually resolved. An integrative approach must

then be sufficiently robust to justify a significant redirection of efforts from one sector to another. Key aspects of an effective integrative approach include identification of reference (or target) conditions, adequate predictive capability, appropriate treatment and communication of uncertainty, inclusive processes for decision-making that promote acceptance, and institutional capacities for implementation. Nonetheless, unintended consequences and unanticipated demands will often arise; these can be partly accommodated through adaptive management.

Near-Natural Aquatic Ecosystems As a Reference Condition. The current and emerging challenges to water resources management in Switzerland must also be considered in the context of the objective of achieving “good ecological status” under the Water Framework Directive (WFD) of the European Union (EU). Although “good ecological status” should be defined by comparison with reference sites subject to only minor anthropogenic impacts,²⁴ many aquatic systems are modified to such a degree that their natural state cannot be easily described. It is thus necessary to identify the characteristics of near-natural ecosystems with respect to their hydrology, geomorphology, biogeochemistry, and ecology.²⁵ The analysis of riverine invertebrates has also been used to establish a site-specific, biological reference condition.²⁶ Historical data, analogies to similar systems, and knowledge of ecosystem function can help in characterizing the near-natural state of an ecosystem. The goal of conservation or reestablishment of near-natural ecosystems is to maintain natural biodiversity and ecosystem function and services.

Predictive Capacity and Uncertainty. Environmental management relies on the expectation that the effects of interventions can be predicted, but such predictions are uncertain due to the limited scientific understanding of complex and dynamic systems. For decision-making, it is important to identify the sources of uncertainty and to quantify uncertainty in a robust and defensible manner, for example by probabilistic predictions.^{27,28} This approach was followed in a study that analyzed the causes of the declining catch of brown trout in Swiss rivers.²⁹ The effects of removing the two most important stressors on predicted adult fish density was examined. Particularly at a site affected by intensive agriculture and wastewater inputs, the predicted 2-fold increase in adult fish density was still within the bounds of uncertainty. In contrast, the predicted effects of improving habitat and reducing clogging of the streambed were significant even considering the uncertainty.

Decision Support. Water resources management involves difficult decisions that are subject to significant uncertainty, affect many stakeholders over long timeframes, and are constrained by governing legislation and regulation. It is therefore important that authorities take a well-structured and transparent approach that can easily be communicated.

Techniques of decision sciences³⁰ can be applied to water resources management.^{31,32} These techniques can guide stakeholder involvement processes and help in communicating decisions in a transparent manner. As part of such procedures, the elicitation of values from stakeholders can support the identification of societal objectives. In one study related to river restoration,³³ stakeholder values were elicited from eight constituency groups. Four management options were ranked by applying these preferences to the predicted outcomes of the options. It was observed that one alternative (the “administration” option) had the best ranking by five stakeholder groups but was ranked poorly by two others. The analysis of the basis for these low rankings led to the identification of a fifth “negotiation”

alternative. The fifth option had an overall ranking similar to the “administration” option but was not ranked poorly by any group, indicating less potential for future conflict.

Adaptive Management. Adaptive management entails a dynamic process of continuous learning from experience as a basis for adapting measures that fall short of achieving their objectives or that must respond to evolving societal preferences and/or boundary conditions. In the former case, monitoring of the effects of implemented measures and assessment of their success are clearly required.¹² Institutional structures must also be able to accommodate and respond appropriately to new information,³⁴ and financial means must be reserved for necessary adaptations.

a process which promotes the coordination of water, land, and related resources in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems.

The Integrated Water Resources Management (IWRM) Framework. The international planning community has been the driving force behind the development of the concept of integrated water resources management (IWRM),^{35,36} which is most commonly defined as follows:³⁶

a process which promotes the coordination of water, land, and related resources in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems.

Developing countries have been a principal focus of IWRM, which has consequently emphasized governance, poverty-alleviation, and gender-related issues. There is, however, also an agreement in the international planning community to apply IWRM in industrialized as well as developing countries; this goal is incorporated in the Implementation Plan from the 2002 World Summit on Sustainable Development.³⁶

The IWRM concept has undergone considerable evolution and is presented by one of its major advocates, the Global Water Partnership (GWP), as “a process of change”.³⁷ Although IWRM has been criticized quite harshly—mainly on the grounds that it is ill-defined and that there is little or no evidence for its benefits³⁵—it has also been taken up seriously within many national planning processes, including that of Switzerland.³⁸

Two Examples from Switzerland. In 2008, the platform Water Agenda 21 (<http://www.wa21.ch>) was established to promote dialogue among actors in Swiss water management. This voluntary organization advocates the cross-sectoral management of water resources and infrastructures in a long-term planning, implementation, and monitoring process, in which the boundaries of political decision making would become more aligned with natural watersheds or technological networks such as sewer systems and hydropower schemes. An adaptive process is recommended in which the progress toward long-term goals is monitored and measures are modified accordingly.⁶ The network includes federal and regional government agencies, NGOs, and

professional and academic institutions. It has identified needs related to the planning, validation, and implementation of new solutions for water-related problems. These activities will be particularly relevant in the context of the measures for river restoration and offsetting the ecological consequences of hydro-power production that will be required to comply with the 2010 revision of the Federal Law on Water Protection.

Several more formal agreements, among authorities with the direct responsibility for water resource management in specific areas, have also been recently established. For example, a commission with membership from five Cantons is developing a strategic plan for the River Birs that explicitly includes consideration of surface water quality, groundwater recharge and protection, nature protection, wastewater treatment, agriculture, flood protection, and regional planning (<http://www.labirse.ch/index.htm>).

OUTLOOK

Increasing the level of integration in the management of water infrastructure and water resources offers the potential to broaden the portfolio of measures that can be employed to meet societal objectives and to find more cost-effective solutions. This can be a pragmatic response to the recognition of the complexity and interrelatedness of the systems being managed and the difficulty in identifying the causes of ecological deficits, which are illustrated by the examples from Switzerland. Increased integration also introduces costs related both to the demands for data-intensive descriptions of systems and to the involvement of greater numbers of actors and a wider range of interests in the decision-making process. The benefits realized through integration should be greater than the costs of increased complexity.

These considerations suggest that the optimum extent of integration could be quite broad at higher policy levels and become narrower for specific issues, particularly at the stage of selecting and implementing possible measures. At this level, the benefits will depend on whether knowledge of the system and predictions of its response to alternative measures are sufficient to set priorities among sectors and whether the legal and institutional setting would allow a redirection of resources among them. The mainly voluntary arrangements within Switzerland are limited in the extent to which novel, integrated solutions can, in fact, be implemented. This situation is quite different in countries where serious water scarcity issues provide a strong driver for nonvoluntary, binding management structures. In any event, integration should not introduce transactional costs that exceed the benefits gained. Improving the understanding of the system and its dynamics may be necessary to quantify and reduce uncertainty. The adaptability of measures can also be important in coping with incorrect predictions and changes in societal values. Assessment of the performance of implemented measures is needed to improve system understanding and predictions as the basis for re-evaluation and modification of management plans. This will require the active engagement of scientists and engineers with various actors in the water sector on an ongoing basis.

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