Highlights:

1. Managing water equitably should be a main goal of any water management approach.
2. Quantifying change is critical to water security and adaptive management, yet very difficult to do, and usually costly in the long-term.
3. Social learning is a key factor for adaptive management and requires additional research and refinement.

# Adaptive management and water security in a global context: Definitions, concepts, and examples

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**Abstract**
Conventional water governance that centralizes decision-making and focuses on increasing supply has sometimes led to ecological degradation and inequitable outcomes. As a corrective, Integrated Water Resources Management (IWRM) incorporates sustainability principles that integrate social, ecological, and infrastructural systems. However, this governance mode still does not address complex issues for an uncertain future, and fails to offer a clear goal. Adaptive management, another approach, relies on public participation and active knowledge exchange between scientists and policy-makers; it also incorporates uncertainty into decision-making. The concept of water security emerged subsequently to address the lack of a clear goal for water management. In this paper, we set into context the terms “adaptive management” and “water security” and review their evolution and their critiques. Both concepts require measurement and monitoring of outcomes in order to determine progress towards established goals so as to guide decision-making. We discuss the challenges and different ways of measuring water security and provide a representative list of potential indicators. The essay provides some examples of adaptive-management studies across the world and discusses adaptive management as it relates to the UN Sustainable Development Goals. Our concluding remarks reflect on present challenges, practical limitations, and promising ideas for a future type of water governance that is participatory, equitable, and adaptive.

## 1. Introduction

To set into context the terms *adaptive management* and *water security*, we review the evolution of concepts related to water governance and management (Figure 1). Arguably the most practical and tangible water management approach spawned by the principle of sustainability has been *integrated water resources management*, or IWRM [1]. This governance model aims to decentralize decision-making by including stakeholders in water management, while integrating social, ecological, and infrastructural systems [2].

Despite the widespread adoption of IWRM globally, however, some critics found the concept insufficiently comprehensive, noting that the "integrated" part of the term referred exclusively to the water sector. One response to that was the articulation of the notion of the *nexus*, which expanded "integrated" to include the inextricably linked energy and food-production sectors [3,4]. Other observers have focused on the kind of "management" IWRM promoted, in particular whether management would be "adaptive" [5]. According to this line of reasoning, a missing ingredient of IWRM was the capacity of a management regime to adapt to uncertain conditions—different landscapes, cultural conditions, economic resources, political systems, and changing climate.

While the concepts of nexus and adaptive management have rendered the IWRM paradigm more complete, another important ingredient remained absent: IWRM was intended to improve water management—to make it more responsive, effective, and efficient—but to what end? Thus, a new idiom, water security, built upon the elements of adaptive management to address this shortcoming [6,7].

## 1. Adaptive management

The introduction of "adaptive management" into the lexicon of the water sector addressed a perceived shortcoming of IWRM. Because many issues in water management are complex, the adaptive-management approach adds the potential of learning-by-experimenting in an iterative process that tests hypotheses and evaluates outcomes [2,5], in essence treating these management interventions as experiments in a continuous cycle [8].

### 1.1. Adaptive capacity

Adaptive management is distinguished from *adaptive capacity*. The former is a governance approach to the management of risk and uncertainty, often derived from the literature on resilience, whereas the latter is a property of vulnerability, related to the robustness of social, human, financial, governance, physical, and management capitals [5,9,10,11]. Adaptive capacity is seen as a link between vulnerability and resilience frameworks through common foundations in governance, institutions, and management mechanisms [12]. Governance approaches, such as adaptive management and IWRM, can increase adaptive capacity and lead to successful adaptation [13]. Such approaches assume that adaptive capacity will increase when scientific knowledge is adopted and this, in turn, will lead to increased resilience; however, little empirical evidence supports this assumption [2].

1.1. Science-policy dialogues

We emphasize that adaptive management is not trial-and-error experimentation, but rather systematic experimentation from hypothesis testing, and it serves as a conduit for learning and incorporating science into decision-making [14]. Often, the success of adaptive management is contingent on public participation and active knowledge exchange between scientists and policy-makers. Citing successful efforts in the arid Americas, Scott et al. [15,16] and Ocampo-Melgar et al. [17] advocate for *science-policy dialogues*, structured approaches toward adaptive management that involve knowledge-sharing, flexible planning, and capacity building. Time-intensive but effective approaches include the co-production of science and policy through interventions by organizations that span research and practice [18,19]. Such initiatives emphasize more active engagement in decision-maker perspectives for developing policy [20].

Conceptually, the involvement of scientists in the dialogue process ensures knowledge sharing and formulation of new, user-responsive (or *use-inspired*) research objectives, where a bottom-up approach enhances the impact of research to make it more meaningful to society [21,22]. Here, flexible planning—in which outcomes are monitored, evaluated, and revised to permit changes over the short term—can be very useful. Adaptive management, then, is an iterative process that allows for uncertainty over the long term by re-evaluating a plan during each iteration, leading to new objectives.

1.1. Critiques of adaptive management

There exist several critiques of adaptive management. Lemos [2] states that adaptive learning that integrates social and ecological systems is very difficult to accomplish because it requires a sufficient knowledge base, and even successful implementation of learning does not always lead to behavior change. In addition, while the term is used heavily in peer-reviewed literature, few adaptive-management projects actually have been implemented, and those that exist are characterized by a duration too short to evaluate their effectiveness [14,23]. Schoeman et al. [8] note that adaptive management is more "an ideal than a reality … (with) little evidence of success; ambiguity of definition; complexity; institutional barriers; risk; and cost" (382). Other critiques involve the high cost of monitoring a resource over the long-term and—due to the iterative nature of the adaptive-management process—the inability to provide the quick results needed to meet compliance deadlines [14].

## 1. Water security

The concept of "water security"—likely first used by the Global Water Partnership (GWP), the organization primarily responsible for defining, promoting, and helping to implement IWRM—framed water security as an overarching goal from the household to the global level, in which "every person has access to enough safe water at affordable cost to lead a clean, healthy and productive life while ensuring that the natural environment is protected and enhanced" [24:12]. Since then, the term has undergone numerous refinements and redefinitions [e.g., 15,25]. At its core, though, the notion of water security is intended to shift emphasis from a process (adaptive management) to a goal—that goal being secure access to good-quality water for populations and natural environments.

Having taken hold beyond academia to affect policy decisions, water security also is part of discourses including biodiversity and ecosystem health, food shortage, and national security [26**,27]. In a comprehensive review of the concept, Cook and Bakker [28] found that when water security is defined in a broad integrative manner, priorities can be established and governance decisions can be made at the policy level.

Water security integrates core elements of IWRM and considers the connections between hydrological systems and land-use change, between political and scientific features of water management, and between ecosystems and human health [29]. Water security emerges as a consequence of four concerns: (1) threats to drinking water supply systems—whose pollution or diminishment would directly imperil populations, (2) threats from water-related hazards to economic growth and livelihoods such as droughts, floods, and toxic contamination, (3) threats to ecosystem services—e.g., loss of wetlands or mangroves—that would reduce the socio-economic benefits of those services, and (4) variability in, and thus costly unpredictability of the water cycle, a likely consequence of an El Niño phenomenon or of climate change [29].

An ancillary principle is that the dynamic interactions between social, ecological, and hydrological systems affect water security [16]. When one system is pushed enough against resilience thresholds, a new state may emerge, which generates feedbacks that affect other systems, with uncertain magnitude, impact, and duration. An example is the Santa Cruz River in and around Tucson, Arizona. There, groundwater pumping for agricultural and urban-water supply has lowered the aquifer, dessicating extensive reaches of the river permanently or intermittently. An ecological feedback has been loss of the cottonwood-willow gallery forest and encroachment of mesquite bosque (that previously occupied only the higher, drier river terraces). A subsequent social feedback to both hydrological and ecological thresholds being crossed has been calls for water allocation to the river, leading to the use of effluent from the city's main wastewater treatment plants to reconstitute the river. Fragile interactions such as these may be intensified under climate changes, particularly in the hydrological system, which may lessen water security.

The idea of water security suggests a dual nature of water—as a resource and as a hazard. Accepting this duality can enhance stakeholder engagement by attracting different perspectives to the table [17]. Threats related to *water insecurity* bring the concept of risk to the fore, which calls for a need to measure water security with *indicators* or indices, particularly in terms of hazards (e.g., toxic contaminants), exposure (to natural disasters such as floods), and vulnerability (e.g., by disadvantaged or poorly-situated communities) [7].

### 1.1. Critiques of water security

Water security, too, has its critics. In a comprehensive literature review, Gerlak et al. [30] found multiple critiques of: indicators and metrics [31**]; the inability to measure water security reliably [32**]; the common absence of multi-scale and small-scale approaches [33**,34**]; a lack of inclusion of poor populations, a difficulty of translating goals to policy [32**]; and too great a focus on demand side and not enough on supply [35].

Because it is difficult to analyze linkages between risk, vulnerability, and resilience under uncertainty and across multiple sectors, disciplines and scales, water security research faces challenges. These include lack of unity among different approaches, absence of commonly-accepted measurement techniques, and ambient skepticism by engineers and technocrats [29]. Additionally, competing definitions further reduce the applicability of water security. Bakker [29] identifies three main challenges to water security research: (1) multiple, sometimes discordant definitions, which can lead to contending approaches to redress insecurity (e.g., definitions vary across different regions—arid regions may stress quantity, poor regions may emphasize quality, and unstable regions may accentuate emergencies), (2) scalar mismatch of water-security research (e.g., difficulty to operationalize water security at a national level because it requires fine-grained analysis), and (3) need to work with experienced practitioners, not just other academics. However, water-security research can contribute significantly if funding, incentives, graduate education, and research design are tested, refined, and replicated systematically [29].

## 1. Measuring adaptive management and water security

The word "adaptive" in adaptive management suggests explicitly that to succeed, a management approach or regime must respond to its surroundings, in the broadest sense. Climate, physical environment, natural-resources availability, sociocultural conditions, economic health, legal and administrative frameworks, level of infrastructure, and geopolitical considerations—all are among the variables shaping the adaptive capacity of management systems.

Water security, too, is a relative construct, subject to analogous influences. One cannot speak of a universal state of water security—one that is similar or even comparable in diverse physical settings (e.g., Andean deserts vs. Polynesian coastal plains) and disparate social contexts (the German Saar basin vs. U.S. Southwest rangelands).

Necessarily, then, discourses about adaptive management and water security must remain relative, reflecting, for example: an inquiry's political or practical motivation, a narrator's academic and/or theoretical orientation, actual conditions on the ground, and various stakeholders' expectations [36]. Consequently, while relativity offers flexibility, the term is burdened by a cloudiness that complicates comparisons and eludes quantification.

### 1.1. Non-quantitative methods

Applying a given definition of water security [e.g., 16] to a particular setting, after observation and study, might allow an assertion—perhaps intuitive—that the setting *is* or *is not* water secure. Going further, sufficient data over time could support a conclusion that an area has become more, or less, water secure. A similar—and most likely, as subjective—approach could attempt to ascertain the adaptive capacity of a particular management strategy.

These sorts of assessments—relying heavily on an observer's experience and astuteness—have an appeal. They avoid the pitfalls of depending on hard-to-obtain, unreliable data. They also tend to eschew the use of and reliance on arcane and frequently inappropriate algorithms, models, statistical instruments, and quasi-mathematical analyses. And, at a time when institutional performance—in schools, hospitals, and the workplace, e.g.—is increasingly expressed in standardized measures of success, observation-reliant (non-quantitative) methods avert reductionist tendencies to express outcomes numerically.

### 1.1. The need to compare and quantify

But despite the allure of qualitative assessments, observational modes can seem inconclusive. How can we determine, for instance, whether a community is or is not water-secure, or whether an intervention strategy is or is not effective? Such knowledge can be required to diagnose a given local situation in terms of participatory policy-making, or to design a new financing platform to achieve water security. Given existing tools, it remains difficult to assess local conditions or to effect intra-regional or cross-regional comparisons.

This has led to calls for relevant benchmarks, place-based metrics, suitable models, and reliable monitoring to account for and overcome contextual diversity. For example, indicators can be useful metrics that simplify complex situations in multiple dimensions, tracking progress and communicating trends, thus bridging gaps between society and science (see Table 1) [37]. But Zeitoun et al. [38] warn that such measurement tools can also be reductionist. Dickson et al. [37] consolidated a list of 176 indicators—both quantitative and qualitative—and categorized them according to six dimensions: water resources, environment, water-delivery systems, community capacity and capital, access and equity, health and wellbeing (Table 1).

From this comprehensive list, we identify two distinct kinds of indicators: (1) those that focus on outcomes (i.e., water resources, environment, access and equity, and health and wellbeing), and (2) those that measure processes (i.e., community capacity and capital). As shown in Table 1, some dimension—i.e., water delivery systems—may contain indicators that measure outcomes and indicators that measure processes.

An adaptive-management approach to water governance would monitor a selected set of indicators over the long-term to identify emerging trends and act accordingly. In a transparent participatory process, it is essential to achieve consensus on appropriate indicators so as to avoid equity issues and social conflicts.

## 1. Studies of adaptive management and water security

Global water problems are increasingly turning to the water security concept to frame debates, and here we have learned that the problem is not so much lack of availability of water, but inability to manage water equitably [26**]. Therefore, in order to increase water security, it becomes important to examine what we have learned about adaptive management. Although adaptive-management projects are rare [23], there have been important learning experiences that value (a) stakeholder participation [17,39,40], (b) embracing uncertainty [41], and (c) learning from other projects to save time and resources [14].

### 1.1. Examples of adaptive management

*Thailand*: The adaptive-management approach emphasizes the role of stakeholders in water management, and a study in Thailand provides interesting results. Cookey et al. [39] examined water-governance perceptions by residents of Thailand's Songkhla Lake Basin. They found it useful to factor local peoples' input in governance policies, because involvement rendered them more likely to cooperate and comply with policies.

*Spain*: The conclusions of Cookey et al. [39] are consistent with recent research from Spain, which found that open data-sharing policies and citizen participation through information and communication technologies (i.e., the Internet, social media, or email) can increase participation in water governance [42,43].

*United States*: A long-term adaptive-management effort in the United States has revealed interesting results regarding uncertainty. A study by Melis et al. [41] shows how an array of management treatments implemented since 1996 for the operation of the Colorado River basin's Glen Canyon Dam (e.g., releases from the dam, fishing regulations, recreational raft-trip regulations, removal of non-native fish) have not necessarily led to clear management prescriptions. Instead, these measures have gained from adaptive learning via such unexpected responses to the treatments as (a) spread of invasive aquatic and terrestrial species, (b) growing awareness of natural-disaster threats such as earthquakes, and (c) the energizing of environmental activism. Through long-term monitoring, these findings have spawned valuable opportunities for learning not envisioned by ecosystem models. A key lesson is the need to "embrace uncertainty,"— i.e., to expect the unexpected and learn from it. In complex systems, surprise learning provides valuable opportunities to develop better hypotheses that can eventually lead to better policy [41].

*England*: Learning through adaptive management can be lengthy, but it can be shared from one project to another. Summers et al. [14] describe an example in England, in which the adaptive-management framework effectively transfers data and knowledge generated by one project to projects elsewhere. This framework was employed to study river flows in England and the authors found that this approach allowed learning to be transferred to similar projects in other regions, rendering the monitoring process cheaper, and the learning faster. Sharing datasets from one project to another can help improve understanding of outcomes resulting from particular management actions.

## 1. Application to UN Sustainable Development Goals (SDGs)

The UN defines water security as the ‘capacity of a population to safeguard sustainable access to adequate quantities of acceptable quality water for sustaining livelihoods, human well-being, and socio-economic development,” among other desired goals[44].

Building on the 2000 Millennium Development Goals (MDGs) that had been adopted by 189 countries, in 2015, many nations agreed to a new sustainable-development agenda as part of the UN effort “to end poverty, protect the planet, and ensure prosperity for all” [45]. The resulting Sustainable Development Goals (SDGs) feature 17 goals for the next 15 years, with the sixth goal aiming to “ensure access to water and sanitation for all” by 2030 (http://www.un.org/sustainabledevelopment/water-and-sanitatio/). The sixth SDG, which relates directly to water security, contains eight clearly-defined targets and recognize that water is essential for human well-being and for increasing urban resilience.

It could be argued, then, that in transitioning from the MDGs to the SDGs, the UN applied an adaptive-management framework—by monitoring and evaluating the progress of the MDGs, revising outcomes to formulate the SDGs, and promoting stakeholder participation, including from local communities—all with a spotlight on capacity building. The water-security concept also can be identified in the SDGs; they attempt to measure different states, with two extremes: on one end water scarcity and lack of sanitation, and at the other end, total water security. This quantification of change is helpful for monitoring and evaluating outcomes: *it is easier to evaluate water security change if there are numbers to compare.*

The attainment of the ambitious sixth SDG will have to rely on state-of-the-art science to manage water resources at the global scale. Combining and applying IWRM, adaptive-management, and water-security approaches seems a likely path forward.

## 1. Conclusion: Challenges, practical limitations, and promising ideas

A new paradigm for water management is essential in an era of strong human influences over conditions once considered to be stable, such as climate and land cover. Conventional, top-down, engineering-reliant approaches that assume stationarity (i.e., that future conditions will be similar to past ones) and aim to maximize resource exploitation have proven insufficient to achieve water security; they have failed to manage water sustainably and equitably [8,46,47]. Alternatively, the IWRM, adaptive-management, and water-security paradigms attempt to improve water governance fairly and lastingly for future generations.

Within this mix of approaches, science-policy dialogues encourage managers and water professionals to acquire new, user-attuned knowledge, thus enhancing water security. But stakeholder engagement when there is substantial contested knowledge requires significant transaction costs and needs to be matched by adaptive behavior by researchers [48,49].

Many analyses point to lack of knowledge dissemination and transfer between scientists and stakeholders and to incomplete understanding of information trajectories and their influences on specific policies or practices. But these problems cannot simply be understood in terms of failures in information flows [50,51]. Rather, types of knowledge and practices that are isolated from other applications and disciplines actively shape institutions, particularly in the water-governance sector. This sort of "stovepipe" approach that inhibits interaction between engineers, scientists, policy-makers, and other members of agencies, organizations, and institutions, impedes communication between information-providers and decision-makers [52].

Adaptive-management approaches imply learning by systematic experimentation and by doing. S*ocial learning* is thus a critical element of adaptive water management. Iterative social learning, through robust partnerships between private, public, and civil society actors, is increasingly considered an essential ingredient of sustainable water-management decision-making [53,54]. However, the lack of clear learning goals, approaches, and outcomes—combined with insufficient or inappropriate strategies to deal with uncertainty—create a paradox for learning [55]. Medema et al. [56**] suggest that social learning is crucial in theory, but allow that it remains unclear how to achieve this in practice. One prospect for social learning that explicitly addresses uncertainty is scenario planning, which has been successfully implemented in various environmental-management contexts, including water-resources decision-making [17,57,58,59].

The present paper aims to clarify concepts used in water-management research and thereby enhance communication between academics and water professionals. Water security as a framework, provides broad enough goals and the ability to measure progress toward achieving these goals, considering connections between systems and sectors. Adaptive management encourages continually reviewing and improving the status of these goals by learning and participatory processes.

The integration of social and ecological systems in water management—along with empirical evidence (as verified by relevant and useful quantitative and qualitative indicators of status and outcome) is a key ingredient for assuring access to water. Undergirding this principle is the application of adaptive-management and water-security paradigms. Accompanied by rigorously participatory processes that include science-policy dialogues and emphasize equity, such an approach shows considerable promise for the future.

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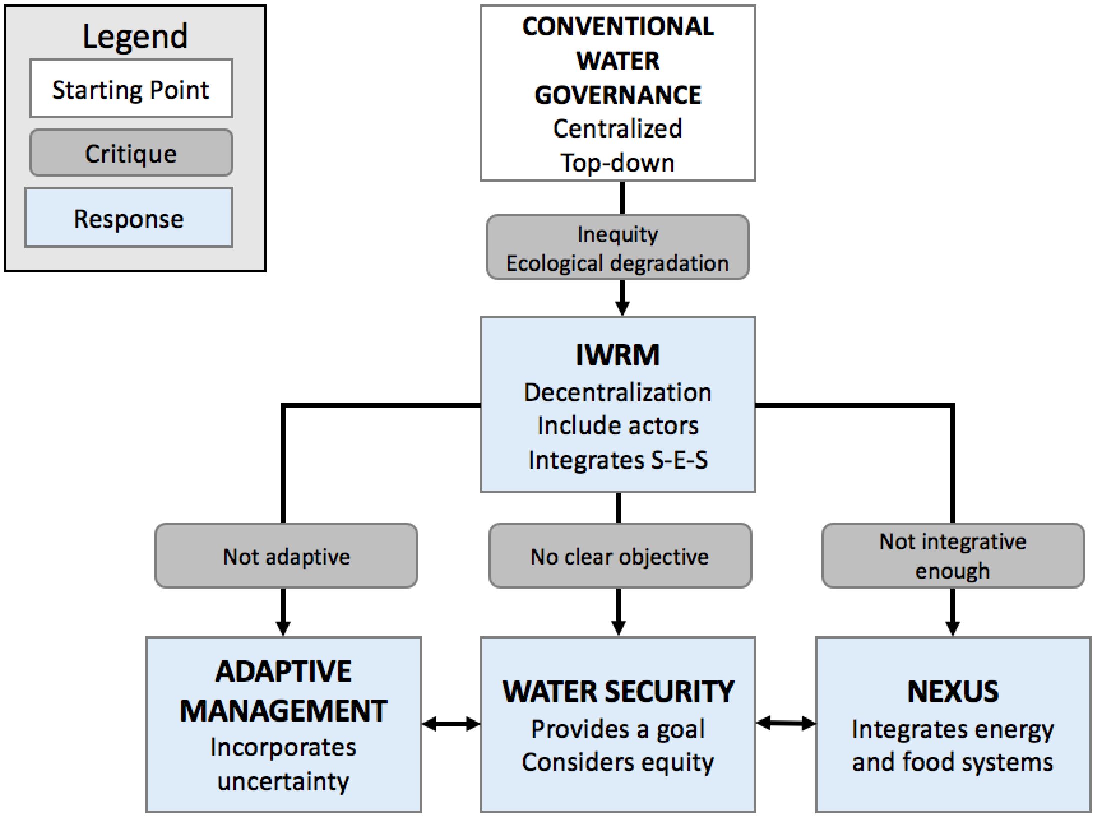


Figure 1. Evolution of water governance concepts (figure by authors)

Table 1 Examples of water-security indicators; adapted from [37]

| Kind of indicator | Dimension | Category | Type | Indicator | Metric | Q | q |
|---|---|---|---|---|---|---|---|
| OUTCOMES | Water resources | Water quantity | Multiple sources | Combined renewable surface- & groundwater | $m^3$/capita/yr | X | |
| | | Water quality | Contaminants | Turbidity | <1 NTU ideal; <5 NTU acceptable | X | |
| | Environment | Aquatic | Fish | Subsistence fish | Rated from <0.05 to >0.5 recruiting streams/km | X | |
| | | Stressors | Terrestrial | Soil erosion | Prorated (% of surface with severe erosion) | X | |
| | Access & equity | Community | Access to water | Is there a law that recognizes right to water? | Rated "no", "yes" | | X |
| | | Social access | Affordability | Ability & willingness to pay | Water costs should be ≤ 5% income | X | |
| | Health & wellbeing | Health | Illness | Water-related disease incidence | Prorated (from 0 to 0.001) | X | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | Behavior | Water practices | Home practices to improve water quality | Boiling, heating, chemical treatment, sedimentation, filtration | | X |
| | Water delivery systems | System capacity | Service levels | Yield/supply | Rated from <10 to >500 L/capita/day | X | |
| **PROCESSES** | Water delivery systems | Human resources & management | Personnel | Water operators training level | Rated no training, other training, industry certified | | X |
| | | | Management | Community engagement | % local popul. involved | X | |
| | Community capacity & capital | Social capital | Women | Women's participation | Rated from "very low" to "very high" | | X |
| | | Government policy & institutions | IWRM | Consensus betw. admin. & watershed boundaries | Rated from "bad" to "good" | | X |

Note: "Q" refers to quantitative indicators; "q" to qualitative indicators