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Key Points:

- Growth and Underinvestment (G&U) system archetype characterizes unsustainability
- Biotic homogenization driven by water resources development exemplifies G&U
- Policy levers are identified to avoid the G&U trajectory

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Water resources management in a homogenizing world: Averting the Growth and Underinvestment trajectory

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Abstract Biotic homogenization, a de facto symptom of a global biodiversity crisis, underscores the urgency of reforming water resources management to focus on the health and viability of ecosystems. Global population and economic growth, coupled with inadequate investment in maintenance of ecological systems, threaten to degrade environmental integrity and ecosystem services that support the global socioeconomic system, indicative of a system governed by the Growth and Underinvestment (G&U) archetype. Water resources management is linked to biotic homogenization and degradation of system integrity through alteration of water systems, ecosystem dynamics, and composition of the biota. Consistent with the G&U archetype, water resources planning primarily treats ecological considerations as exogenous constraints rather than integral, dynamic, and responsive parts of the system. It is essential that the ecological considerations be made objectives of water resources development plans to facilitate the analysis of feedbacks and potential trade-offs between socioeconomic gains and ecological losses. We call for expediting a shift to ecosystem-based management of water resources, which requires a better understanding of the dynamics and links between water resources management actions, ecological side-effects, and associated long-term ramifications for sustainability. To address existing knowledge gaps, models that include dynamics and estimated thresholds for regime shifts or ecosystem degradation need to be developed. Policy levers for implementation of ecosystem-based water resources management include shifting away from growth-oriented supply management, better demand management, increased public awareness, and institutional reform that promotes adaptive and transdisciplinary management approaches.

1. Introduction

Biotic homogenization influences the genetic, taxonomic, or functional similarity of biodiversity over specified spatial and temporal scales through anthropogenic reshuffling of biota from different regions [*Olden et al.*, 2004]. This process is occurring at an alarming rate, causing a loss of ecological resistance and resilience, threatening ecological integrity, and reducing capacity of the environment to provide essential life-sustaining functions [*Olden et al.*, 2004]. In turn, global sustainability is being challenged [*McKinney and Lockwood*, 1999] with potential deleterious impacts on well-being and health of humans [*Millennium Ecosystem Assessment*, 2005]. To reverse this trend, it is imperative to examine the human use and alteration of water resources and aquatic ecosystems from a holistic approach, better understand the feedbacks between various drivers and implications of this process [*Hjorth and Madani*, 2014], and develop effective ecosystem-based natural resource management that addresses the problem.

This commentary illustrates the interconnections between the global homogenization process and natural resource management. We emphasize the need for water resources management to expedite a shift to ecosystem-based planning and management [*Christensen el al.*, 1996; *Slocombe*, 1998] by embracing these linkages and enforcing necessary checks and balances for promoting sustainability. The ecosystem-based management approach requires vigorous research by water resources scholars, who have often adopted technocratic approaches to water resources planning and management [*Gleick*, 2000a; *van der Brugge et al.*, 2005; *Mirchi et al.*, 2010]. The objectives of the engineering approach to sustainable water resources planning and management are frequently curtailed to sustain human socioeconomic well-being at the expense of ecological integrity. This is because conventional approaches fail to bring together "environment," i.e., where we live, and "development," what we do to improve living condition, although these two are inseparable and form our "common future" [*Hjorth and Madani*, 2013]. Thus, it is essential for contemporary water resources experts, policy makers, and stakeholders to recognize ecological integrity as a paramount management mission alongside human water security [*Vörösmarty et al*., 2010].

Water resources management decisions of the past were made using the "predict-and-control" paradigm based on era-dependent values and information about the natural environment, a paradigm that is challenged by continuing global socioeconomic and hydro-environmental change [*Pahl-Wostl*, 2007]. By analogy, humans have been managing water resources as a corporation with absolute monopoly, treating the environment as an exogenous constraint rather than a critical dynamic and responsive component of the system. This practice is rooted in nonsystemic application of decision theory to human-centered and supply-oriented water resources management [*Hjorth and Madani*, 2013]. We must realize, however, that making individual subsystems (e.g., economy, water resources, and environment) sustainable does not necessarily render the whole system sustainable [*Hjorth and Madani*, 2014]. The accelerating increase in the number of threatened species is an indication that past warnings about the urgency of the paradigm shift [e.g., *Falkenmark*, 1986; *Gleick*, 1998] have failed to trigger effective action. There is a need for a continuous and systematic learning process, informed by interdisciplinary knowledge, to update and improve prevailing management approaches [*Pahl-Wostl et al*., 2007].

The discussions and recommendations presented herein aim to improve the holistic understanding of the global homogenization process and its implications for sustainable water resources management. We argue that it is urgent to shift from the current supply-oriented practices to water resource management that includes the health and viability of ecosystems as a critical element for sustainability. Using a systems view of global socioeconomic growth, the anthropogenic pressures on natural resources, and degradation of environmental integrity due to loss of native biodiversity, we speculate that the global socioecological system is governed, and threatened, by the Growth and Underinvestment (G&U) system archetype. This system archetype simply states that any exponential growth process, if unattended to, will inevitably lead to resource scarcity and collapse [*Senge*, 1990]. We illustrate the need for modern water resources management to redefine objectives based on appropriate ecosystem-based performance and process indicators in order to have viable, long-term socioeconomic development. Finally, we discuss options for institutional and methodological reform in water resources management that could serve to mitigate biotic homogenization.

2. Global Homogenization Process

Loss of native biodiversity is an artifact of a multifaceted global homogenization process driven by human agricultural activities, economic and behavioral globalization, and degradation of natural systems (Figure 1). Human encroachment into natural ecosystems can spread non-native species or enhance their establishment, driving the homogenization process, which can trigger ecological regime shifts to which native flora and fauna are less tolerant. Modern agricultural practices create highly homogenized, disturbed, and productive ecosystems in which humans grow select species by providing abundant supply of water and nutrients, and deterring pests and competitors to maximize crop yields [*Tilman*, 1999]. Likewise, increased tourism and immigration drive ecocultural unification through introduction of exotic and often invasive species by human travelers and migrants who distribute biota over geographical barriers [*Gössling*, 2002]. Furthermore, symptoms of economic homogenization fueled by the globalization phenomenon are observed worldwide as small local businesses, with local connections and responsibilities, are replaced by multinational corporations [*Gilpin*, 2000].

Recent trends in the global population growth, number of threatened species, resource exploitation (e.g., water withdrawal and energy use), and agricultural production (Figure 2) reveal symptoms of an accelerating biotic homogenization process, which is facilitated by exploitive, supply-oriented natural resource management practices. Consequently, species that can thrive in human-altered environments are replacing and displacing a significantly larger number of native species, creating a homogenized biosphere [*McKinney and Lockwood*, 1999] with no robust biological or technological fix on the horizon.

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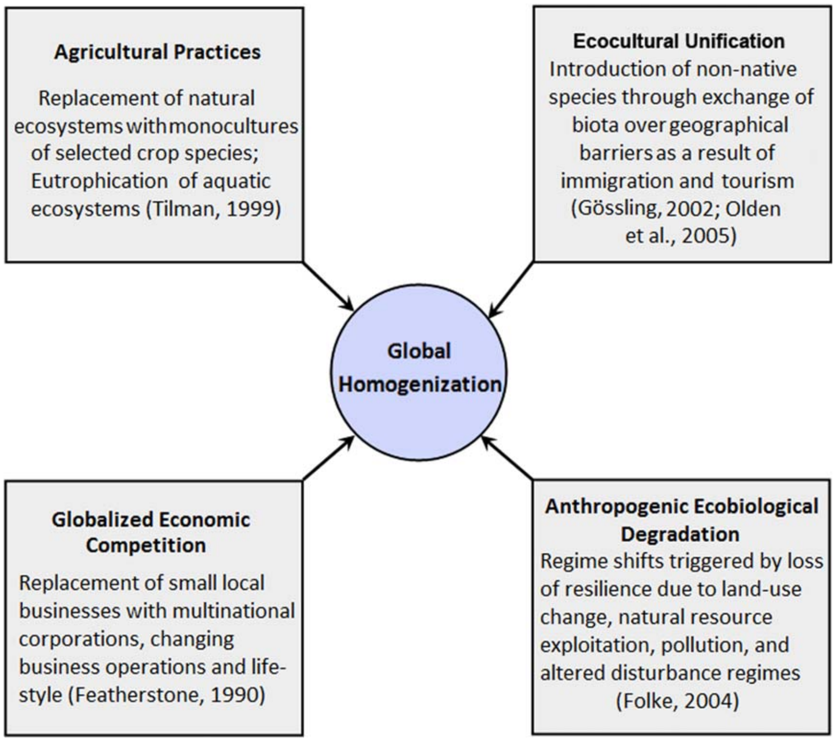

Figure 1. Examples of anthropogenic mechanisms driving global homogenization.

3. Systems View of the Homogenization Problem: The Growth and Underinvestment Archetype

The G&U system archetype, which builds on the well-known Limits to Growth [*Meadows et al.*, 1972], helps identify leverage points where human intervention can promote sustainable growth. As illustrated in Figure 3, the growth of a system governed by G&U will continue until constrained by a resource problem. Such curbing of the growth will lead to perception of a need for investment to address the limit, although the actual investment may occur with a delay. The perceived need to invest is often negatively affected by tolerance for loss. Sufficient and timely investment in expanding/maintaining capacity must be made in order to sustain growth by avoiding the growth limiter. However, in malfunctioning systems that are on the way to collapse, performance standards are often lowered and tolerance for loss is raised to legitimize underinvestment and lower expectations [*Senge*, 1990] (Figure 4).

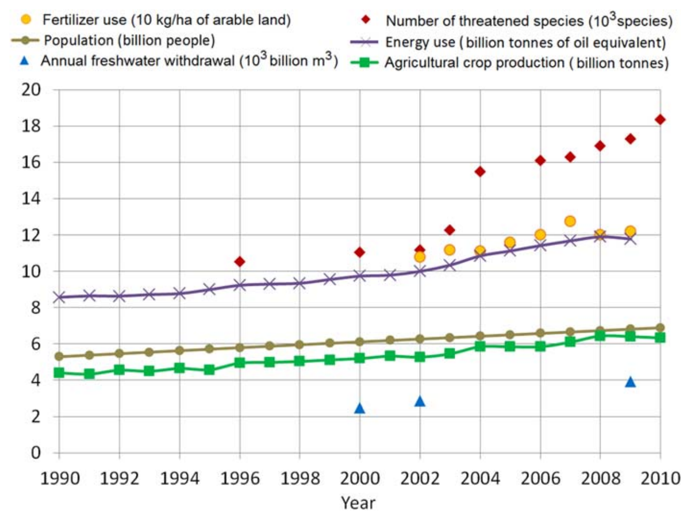

Figure 2. Recent global trends of annual freshwater withdrawal, agricultural crop production, population size, energy use, fertilizer use, and number of threatened species including vertebrates, invertebrates, and plants. Data are from the *World Bank* [2012], except for agricultural crop production and number of threatened species, which were obtained from *Food and Agriculture Organization of the United Nations* [2012] and *International Union for Conservation of Nature* [2011], respectively.

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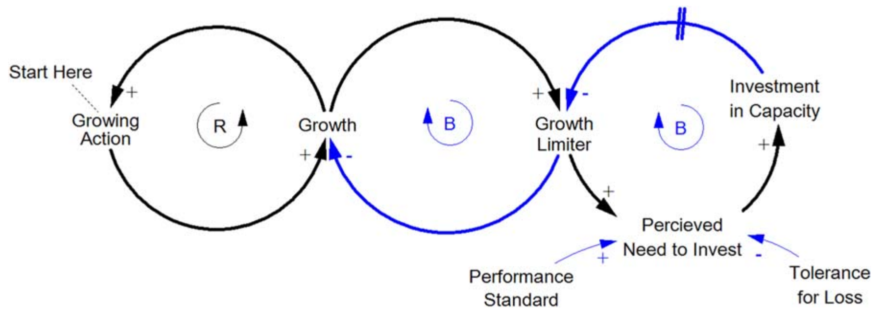

Figure 3. Generic causal loop diagram (CLD) of G&U archetype [adapted from *Senge*, 1990]. Growing action is suggested as the start point to navigate through this CLD. Polarized arrows denote the direction and type of causal relationships. R and B stand for reinforcing and balancing loop, respectively. Double bars indicate lag time.

3.1. Sustainability Implications of Growth and Underinvestment

The essential insight from the G&U archetype is that in the face of homogenizing impacts of unrestricted resource exploitation, dysfunction of the links between homogenization and ecological maintenance tends to reduce environmental integrity and carrying capacity in the long run, resulting in unsustainable development (Figure 5). In a sustainable socioecological system, symptoms of biotic homogenization and diminishing environmental integrity would reinforce the perception of the need for ecological maintenance and adaptive management [*Holling*, 1978]. As a result, sufficient and timely investment would be made to adjust the rate of resource exploitation with carrying capacity based on ecological responses.

Figure 6 illustrates potential long-term behavior of selected variables of the global system under hypothetical management shifts to (a) anthropocentric resource management (ARM); (b) ecosystem-based resource management (EBRM); and (c) ecocentric resource management (ERM). The ARM and ERM scenarios, respectively, characterize extremes of natural resources management approaches [*Purser et al*., 1995], whereas EBRM represents an integrated approach. The ARM scenario characterizes conditions in which the link representing the information flow between homogenization (e.g., biodiversity loss) and perceived need for ecological maintenance is dysfunctional and the public is either indifferent about biodiversity loss or unwilling to allocate any resources to negate it. The EBRM scenario hypothesizes that a functional link exists between homogenization and perceived need for ecological maintenance, even if some level of tolerance for biodiversity loss exists. In contrast to ARM, the ERM scenario assumes that the public is purely concerned with maintaining ecological diversity, and thus markedly intolerant of any biodiversity losses.

Under the assumption of a continually growing material economy, environmental integrity will inevitably decline (Figure 6). The symptoms of G&U are most noticeable under the ARM scenario, threatening the sustainable growth of the system due to an overshoot and collapse (Figure 6a). The socioeconomic growth under ERM will likely be slow, with maximal investments being made to maintain biodiversity, which may cause socioeconomic stagnation (Figure 6c). Similar to ERM, the EBRM scenario may cause socioeconomic growth to lose its momentum in the short run due to negative feedback from ecological maintenance cost. In the long run, however, the benefits of sustained global productivity supported by functional ecosystems and socioecological diversity will outweigh the short-term losses (Figure 6b). Given the reality of anthropogenic homogenizing forces, the EBRM approach appears to be more favorable in the long-term than the extreme approaches, at least at a conceptual level. Thus, policy makers should seek cost-effective ways of maintaining biodiversity by bearing the ecological maintenance costs that are

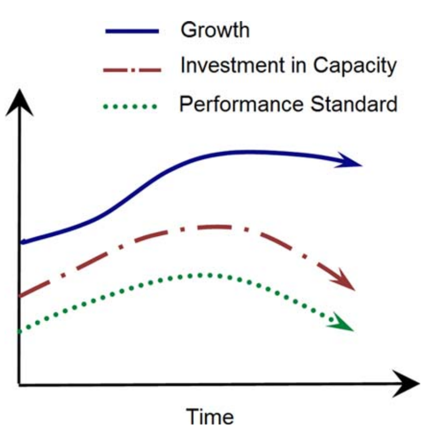

Figure 4. Common behavioral trend of growth, investment in capacity, and performance standard in the G&U archetype observed in malfunctioning systems [adapted from *Braun*, 2002].

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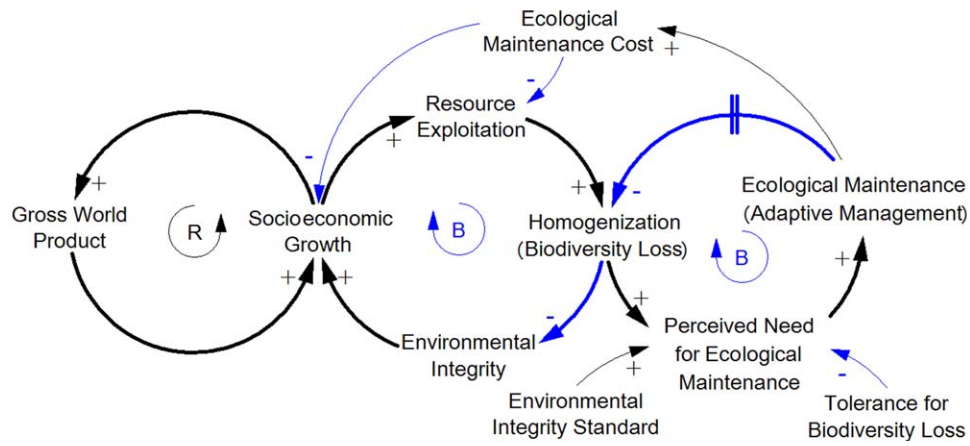

Figure 5. Causal loop diagram of G&U archetype for global homogenization, including feedback from ecological maintenance cost. R and B denote reinforcing and balancing loops, respectively. Double bars indicate lag time.

"merely substantial" as opposed to "intolerably large" [*Ciriacy-Wantrup*, 1952]. This denotes the importance of explicitly accounting for trade-offs between socioeconomic growth, biodiversity loss, and ecological maintenance cost for the sustainability of socioecological systems.

3.2. The Notion of Collapse

Ecological systems may have a delayed recovery from large perturbations, reducing system resilience to regime shifts [*van Nes and Scheffer*, 2007] which may lead to a terminal overshoot and collapse (Figure 6a). This is a natural dynamic process that controls the growth with reference to resource stock availability [*Meadows et al*., 1972; *Diamond*, 2005]. Collapse may also occur as an oscillating overshoot cycle around the carrying capacity (Figure 6b). Growth, loss of integrity, ecosystem maintenance, and carrying capacity are not spatially or temporally homogeneous across the planet, so neither will be the amplitude and periodicity of the oscillations. In the absence of a pragmatic action plan, however, the extent and consequences of partial and sectoral terminal collapses may become overwhelming [*Meadows et al*., 2004; *Randers*, 2008]. In this context, sustainability can be viewed as a framework for making sufficient and timely investments commensurate with socioeconomic growth in order to delay and dampen the peak of human resource consumption and associated ecological footprint.

While partial collapses of ecological resource stocks on local to regional scales [*Carpenter and Gunderson*, 2001; *Vörösmarty et al*., 2010] reinforce premonitions of impending global collapse [e.g., *Wackernagel et al*., 2002; *Meadows et al*., 2004], the connection between the G&U archetype and potential collapse of managed natural systems remains unrecognized. During the first decade of the third

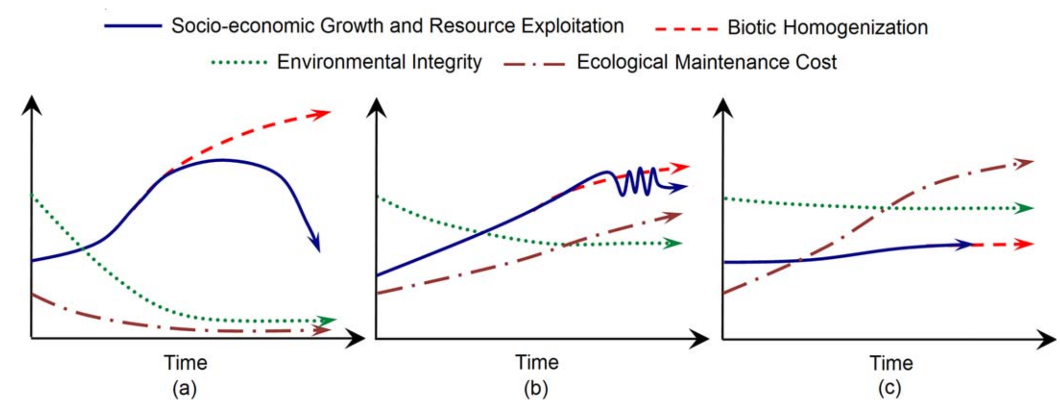

Figure 6. Long-term qualitative behavior of the global system under hypothetical natural resource management paradigm shifts to (a) anthropocentric resource management (ARM); (b) ecosystem-based resource management (EBRM); and (c) ecocentric resource management (ERM). Note that these graphs are not necessarily drawn to the same relative scale within or across panels.

Table 1. Common Water Resources Management Activities That Drive Homogenization Through Ecological Integrity Loss

Activities	Ecological Impacts	Examples
Regulation, containment, and extraction[a]	Elimination, modification, and creation of terrestrial and/or aquatic habitats (e.g., inundation, blocking access, changing soil moisture content, and wet-dry cycles) which reshuffle species, facilitating invasion of exotics and extinction of natives; Disruption of life cycle, reproduction, and biotic interaction through spatial and temporal alteration of natural hydrogeologic regimes (e.g., magnitude, frequency, timing, duration, and flashiness) and geomorphology (erosion, sediment wash-out, and siltation); Changes in energy sources and food web[b]	Increased biotic homogenization due to dams, levees, and interbasin water transfers in Portugal [*Collares-Pereira et al.*, 2000], Australia [*Arthington and Pusey*, 2003], continental U.S. [*Poff et al.*, 2007], and North America [*Williams et al.*, 1993]; Extinction and endangerment of native biodiversity due channelization of the Kissimmee River, Florida, U.S. [*Toth et al.*, 1998]; Native biodiversity loss around the world due to groundwater overdraft [*Danielopol et al.*, 2003]
Recycling and disposal[a]	Alteration of ecosystem dynamics (production, respiration, and uptake) due to toxicity, oxygen content reduction, and nutrient-enrichment, degrading trophic state, and food web in a disrupted primary production process[c]	Aquifer contamination and recharge with low-quality water [*Danielopol et al.*, 2003]; Disrupted reproduction of fish communities and altered species assemblages due to effluent discharge in Alberta, Canada [*Schindler*, 2000], and Colorado, U.S. [*Vajda et al.*, 2008]

[a]See *Gleick* [2000b] for a review of water resources management practices.
[b]See *Poff et al.* [1997] for synthesis of ecological components and responses due to alteration of flow regimes.
[c]See *Dudgeon et al.* [2006] for synthesis of the impacts of water quality on aquatic systems.

millennium, total environmental expenditures of the 27 European Union (EU) member states and candidate states increased from 2% to 2.25% of GDP [*Szirony and Steurer*, 2012]. The U.S.' environmental expenditures during the same period fluctuated around 2.7% of GDP, increasing to 2.8% by 2010 [*Bezdek et al.*, 2008]. Environmental expenditure data are not readily accessible for many other regions of the world. Nonetheless, the current trend of biotic homogenization associated with various anthropogenic environmental footprints underscores the need for additional investments in ecological sustainability [*Pearce*, 2007].

4. Water Resources Development Drives Homogenization

Managing water resources systems for socioeconomic benefits is a substantial driver of native biodiversity loss [*Poff et al.*, 1997; *Dudgeon et al.*, 2006]. Most water resources systems affect critical environmental functions, including the capacity to supply resources (source function), the capacity to assimilate pollutants (sink function), the capacity to sustain (life-support function), as well as other functions such as enhancing well-being and welfare of humans [*Christensen et al.*, 1996]. Currently, the amount of annual fresh water withdrawal is nearly twice the amount of water available in the global river network without man-made reservoirs [*Oki and Kanae*, 2006]. Total capacity of the global man-made surface water storage is roughly twice the amount of annual withdrawal, which helps humans to cope with high spatial and temporal variation of water availability [*Oki and Kanae*, 2006]. About 20% of the annual water withdrawal is supplied from groundwater resource stocks [*Shah et al.*, 2000], which are exploited beyond their recharge capacity in vast areas of the world [*Wada et al.*, 2010]. These withdrawals, along with biogeochemical and geomorphic alterations of water resources, are driving ecological homogenization by causing sharp declines in native species that cannot survive in the modified and/or degraded conditions [*Vörösmarty and Sahagian*, 2000].

Mechanistic links between water resources management and reduced biotic integrity, including homogenization, are well established (Table 1). Groundwater overdraft affects ecosystems by lowering water tables, stream flows, and lake levels [*Danielopol et al.*, 2003]. Large-scale storage development and diversion of surface water through extensive dam building modifies fluvial processes and flow dynamics [*Poff et al.*, 2007]. Interbasin water transfer projects across the world cause biodiversity loss due to removal of

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Table 2. Example Problem Areas Indicated by the G&U Archetype and Policy Levers to Mitigate Water Resources-Related Biotic Homogenization

Link	Problem	Policy Lever
Resource Exploitation —(+)→ Homogenization (Biodiversity Loss)	Exceedence of natural supply capacity; Poor qualitative and quantitative understanding of the impact of water resource exploitation on native biodiversity loss due to lack of representative biodiversity metrics and regular monitoring campaigns	Reduce resource exploitation by shifting away from supply-oriented management and focusing on efficient pricing; Develop reliable metrics of native biodiversity and include them in the objective of water resources plans; Monitor system trajectory and ecological responses to management actions to guzide adaptive management
Homogenization (Biodiversity Loss) —(+)→ Perceived Need for Ecological Maintenance	Lack of public concern about water resources-related native biodiversity loss	Implement regular outreach programs about the connection and trade-offs between water resources management and biodiversity and acuteness of underinvestment in ecological maintenance to raise public awareness and lower the tolerance for biodiversity loss
Perceived Need for Ecological Maintenance —(+)→ Ecological Maintenance (Adaptive Management)	Underinvestment in mitigation and actual implementation; Inaction or delayed action due to lack of funds and unwillingness of decision makers to accept uncertainty in their management plans	Design robust institutions and incentives for maintaining native biodiversity as a global common pool resource; Promote a reform in social preference orderings to prioritize the maintenance of biodiversity
Ecological Maintenance (Adaptive Management) —‖(-)→ Homogenization (Biodiversity Loss)	Long natural delay (double bars) in the recovery of ecological processes and belated or inadequate restoration which may result in regime shift and increased homogenization	Invest in adaptive management based on well-defined ecosystem-based goals; Continually evaluate the effectiveness of ecological maintenance and restoration in the adaptive management process

biogeographical barriers between donor and recipient watersheds, as well as alteration of natural hydrology and biogeochemistry of aquatic and terrestrial ecosystems [*Davies et al.*, 1992]. The interbasin transfer of biota can also result from water navigation that transports stowaway invasive species on ship hulls or in ballast water [*Hulme et al.*, 2008].

There are good reasons to suspect that the homogenizing impact of anthropocentric water resources management will increase in the future. Global water demands relative to river flows will rise significantly by 2025 due to population growth alone [*Vörösmarty et al.*, 2000]. Likewise, the water footprint of the energy sector is expected to increase by 37–66% within the next two decades [*Hadian and Madani*, 2013] to meet the energy demand of the developing world, which also requires more water for food production. Furthermore, climate change will exacerbate the complexity of water resources management [*Jackson et al.*, 2001; *Mirchi et al.*, 2013] by increasing the severity of water stress [*Arnell*, 2004] due to increased spatial and temporal variability of natural replenishment. With additional storage needed to accommodate shifting seasonal flow patterns, it is anticipated that conflicts between flood mitigation and water supply functions of water resources systems will intensify. These trends may trigger additional manipulation of water resources through infrastructure development, leading to further homogenization of biodiversity and ecohydrology and altering dynamic feedbacks between ecological and hydrological processes such as evapotranspirative patterns [*Newman et al.*, 2006]. While regional flexibility in the supply-oriented management practices could mitigate risks of reduced water supply to humans [e.g., *Rajagopalan et al.*, 2009; *Connell-Buck et al.*, 2011; *Munoz-Hernandez et al.*, 2011], it is difficult to envision how environmental flows will be maintained to support nonmarket ecosystem functions and services (e.g., sustainable food webs, wildlife habitat, and nutrient cycling), unless they are given regulatory priority [*Yin et al.*, 2011].

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5. Insights for Ecosystem-Based Water Resources Management

A paradigm shift in water resources management approaches is urgently needed in order to mitigate biotic homogenization. The G&U system archetype (Figure 5) illustrates the weak links where systematic underinvestment in the protection of native biodiversity may occur (Table 2). Herein, we highlight a number of policy levers to slow or shift this trajectory, including water supply and demand management, public awareness and institutional reform, ecosystem-based planning, and transdisciplinary vision.

5.1. Water Supply and Demand Management

On the water supply side, it is necessary to shift away from growth-oriented management by focusing on increasing local infrastructural flexibility and internalizing ecological externalities. While growth-oriented management is losing favor, and purely structural solutions are facing greater opposition, engineering solutions continue to dominate water resources planning [*Gleick*, 2000a], especially in developing countries. The widely applied management scheme of relaxing resource constraints by short-sighted increases in supplies (e.g., interbasin water transfer projects) must give way to sustainable water management in which maintaining regional ecosystem integrity and biodiversity is an element of strategic decision making. Flexible management of existing water infrastructure can help improve ecological conditions by mimicking natural variability such as seasonal hydrologic patterns (e.g., "run of the river" reservoir management). Furthermore, internalizing the ecological maintenance costs of water resources development (e.g., taxation of effluent and groundwater extraction [*Rogers et al*., 2002]) can provide opportunities for funding restoration plans.

On the demand side, emphasis should be placed on efficient water pricing—that internalizes environmental costs—and on educating the stakeholders about the biophysical limits of water resources to meet demand. The public must be constantly reminded that the simplistic view of securing more resources to address the problem of Limits to Growth often overlooks the likelihood that water stress will reappear, perhaps in an exacerbated form, should the unbridled growth continue [*Gleick*, 2000a; *Madani and Mariño*, 2009; *Gohari et al*., 2013]. Although the common practice of providing water to the consumers almost free of charge has been changing [*Rogers et al*., 2002], consumers often do not realize that water is a scarce resource for which they are typically undercharged [e.g., *Gaudin*, 2006]. When socioeconomic conditions permit (i.e., water is used for purposes other than subsistence food production and basic hygiene), water markets may be warranted to increase flexibility and augment environmental flows [*Griffin and Hsu*, 1993].

5.2. Public Awareness and Institutional Reform

Public understanding of interdependencies of ecosystem services and human welfare is critical for generating support for ecosystem-based management campaigns [*Palmer et al*., 2004]. Water resources management bodies are "boundary organizations" [*Guston*, 2001] that are in position to communicate to policy makers and stakeholders the dire need for ecosystem-based approaches. Appropriate water resources outreach programs must be designed and implemented to raise public awareness about the connection and potential trade-offs between water resources management and biodiversity, lowering the communities' tolerance for the water resources-related biodiversity loss.

Furthermore, lack of robust institutions and incentives for maintaining native biodiversity as a global common pool resource is a principal obstacle to ecosystem-based management. Maintenance of native biodiversity often requires cooperation among multiple institutions that range in cultural diversity and scale from international to local [*Ostrom et al*., 1999]. Due to complex dynamic links between water resources systems, land management, and ecosystems, designing integrated land and water management frameworks will be important for mitigating biotic degradation. The effectiveness of maintaining ecological integrity through water-related statutory and institutional means (e.g., the U.S.' Clean Water Act [*FWPCA*, 2002] and the European Union's Water Framework Directive [*WFD*, 2000]) can be improved through complementary land management policies.

Generating support for implementation of ecosystem-based water resources management is challenging because individual and group interests may be at odds with public interest [*Larson et al*., 2009]. The shift to ecosystem-based planning will require a radical reform in social preference orderings of human societies to prioritize the maintenance of biodiversity as a global common pool resource over private gain. Such radical reform is hindered by anthropocentric neoclassical economics' axiom of technological abundance, i.e., emerging backstop technologies will address resource scarcity problems [*McMahon and Mrozek*, 1997]. Designing robust institutions and strong commons incentives for ecosystem-based decision making is a critical research frontier.

5.3. Ecosystem-Based Planning and Management

Perhaps the most challenging steps in finding sustainable solutions to water resources management problems are to break existing mental frames and the legacy of the reductionist view of sustainable resources management [*Hjorth and Madani*, 2013, 2014] and to define clear objectives accordingly [*Sheer*, 2010]. Improving environmental flow management will be critical [*Brisbane Declaration*, 2007] because "the environment as a legitimate user of water requires the same level of respect, advocacy, and protection allocated to societal needs if resource management is to achieve success" [*Naiman et al*., 2002]. The alarming rate of global biotic degradation [*Dudgeon et al*., 2006] should create a sense of urgency within the water resources community to translate dynamic metrics of native biodiversity into practical water resources management activities that proactively reduce the loss of native biodiversity. To do this, it will be essential to elevate ecological considerations from exogenous constraints to important internal properties included in the objectives of water resources management plans [*Richter et al*., 2003].

Advances in biophysical and hydroeconomic models of water resources systems that aid in watershed management [*Mirchi et al*., 2010] have occurred independently of models of ecological dynamics [*Petts*, 2009], particularly in relation to ecological responses to stream flow alteration [*Arthington et al*., 2006; *Poff et al*., 2010]. A persistent lack of quantifiable functional relationships for representing the complex mechanistic feedbacks between water resources management actions and ecosystem responses (e.g., sensitivity of the composition and spatial distribution of biotic communities to hydrologic alteration, and feedbacks on system resilience and integrity) complicates the development of ecosystem-based water resources systems models.

Developing economic-based yet ecologically relevant flow metrics in a process that involves stakeholder participation can be a preliminary means for objective ecosystem-based management. We deliberately call this a preliminary means because of inherent limitation of economic valuation in capturing the "full value" of ecosystems due to extreme uncertainty and complexity of ecological processes and their dynamic feedbacks with socioeconomic systems [*Wilson and Carpenter*, 1999; *Limburg et al*., 2002; *Chee*, 2004; *Norgaard*, 2010]. Furthermore, the outcome of ecosystem valuation depends on how much society cares about ecosystems (i.e., tolerance for biodiversity loss), indicated by the willingness-to-pay for ecological maintenance, as opposed to the "required" level of investment which may exceed willingness-to-pay. As a first step, comparison of actual expenditures with willingness-to-pay estimates, or stated "degree of care" for biodiversity [*Pearce*, 2007], can help quantify the acuteness of underinvestment in ecological maintenance. This information should be used along with findings of ecological integrity assessments to warn society about the implications of ecological underinvestment (i.e., destabilizing or irreversibly altering the life-support mechanisms) in order to lower tolerance for loss of native biodiversity.

Modern water resources management should invest more in adaptive management [*Pahl-Wostl*, 2007], basing it on well-defined ecosystem-based goals and process-based sustainability indicators [e.g., *Hellström et al*., 2000; *Bagheri and Hjorth*, 2007] for monitoring of system trajectory in order to maintain resilience and prevent catastrophic ecosystem state shifts. The simulated floods in the Grand Canyon in the U.S. are an example of such investment where some immediate socioeconomic benefits were lost (e.g., hydroelectric power generation) when water was released from the Glen Canyon Dam. The long-term benefits gained from such "scientific management action" were a better understanding of the geomorphological and ecological response of the riverine and riparian systems [*Meretsky et al*., 2000; *Cross et al*., 2011]. Similarly designed experiments in other regions can facilitate the learning process that is an essential element of adaptive water resources management.

5.4. Transdisciplinary Vision

Finally, integration of the noted components of ecosystem-based water resources management and their feedbacks with socioeconomic and biotic subsystems will require a transition from fragmentation to holism [*Hjorth and Bagheri*, 2006; *Ostrom*, 2009; *Wagener et al*., 2010]. As the dynamic between socioeconomic growth, natural resource consumption, and ecological degradation progresses, it is clear that major system shifts will occur; however, we lack the theories and models to predict the critical thresholds for regime shifts or ecosystem collapse [*Gunderson*, 2000; *Millennium Ecosystem Assessment*, 2005]. Adopting a systems thinking approach, water management bodies should initiate a transdisciplinary dialogue among experts in related and disparate fields, stakeholders, and policy makers to collaboratively address the knowledge gaps preventing the development of biodiversity-enhancing water management plans. The progress toward reaching the objectives, as well as potential remaining lack of knowledge, should be clearly communicated to policy makers and stakeholders to facilitate timely action and adaptive management plans that account for environmental uncertainty.

6. Conclusions

Global homogenization, manifested by a significant increase in the number of threatened terrestrial and aquatic species, is occurring at an alarming rate, which is an important indication of unsustainable development. Humans act as significant homogenizing agents, driving the global homogenization process through such mechanisms as agricultural expansion, natural resource exploitation, global economic competition, and ecocultural unification. The linkages between the homogenization process and resource management, especially water resources, are many and varied. A systems approach illustrates that socioecological systems may be threatened by ecological damages according to the Growth and Underinvestment archetype, including overshoot of natural supply capacity of resource stocks that could end in catastrophic collapse. To avert this trajectory, socioeconomic growth must be accompanied with adequate and timely investments in maintenance of ecological integrity in order for ecosystems to persist and continue providing sustainable life-supporting services. Ecosystem-based natural resources management, a middle ground between anthropocentric and ecocentric approaches, offers a promising framework for enforcing necessary checks and balances on overexploitation and unsustainable growth.

Concerning the water sector, ecological investments within an ecosystem-based water management paradigm are deemed necessary for maintaining environmental integrity and, ultimately, socioeconomic stability. The long-term benefits obtained from sustained global productivity supported by healthy and resilient ecosystems will outweigh the cost of ecological maintenance, making it a worthy investment. The absence of a social preference ordering to prioritize maintenance of native biodiversity and lack of robust institutions are among principle obstacles to ecosystem-based water resources management. Nonetheless, it is critical for water resources management to elevate ecological considerations from exogenous constraints to endogenous decision criteria that are represented explicitly in the objectives of water resources plans. Developing relevant biodiversity metrics in a participatory decision making process can provide a preliminary means for adding an ecological dimension to water resources management with the *caveat* that capturing the full value of ecosystems is complicated by uncertainty and complexity of ecological processes and their dynamic feedbacks with socioeconomic systems. Shifting away from supply-oriented water management, internalizing ecological externalities of water resources development, raising public awareness about the connection between water resources management and biodiversity, and advancing transdisciplinary research to develop ecosystem-based management actions can all contribute to sustainability.

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