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Review

Artificial Aquatic Ecosystems

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Abstract: As humans increasingly alter the surface geomorphology of the Earth, a multitude of artificial aquatic systems have appeared, both deliberately and accidentally. Human modifications to the hydroscape range from alteration of existing waterbodies to construction of new ones. The extent of these systems makes them important and dynamic components of modern landscapes, but their condition and provisioning of ecosystem services by these systems are underexplored, and likely underestimated. Instead of accepting that artificial ecosystems have intrinsically low values, environmental scientists should determine what combination of factors, including setting, planning and construction, subsequent management and policy, and time, impact the condition of these systems. Scientists, social scientists, and policymakers should more thoroughly evaluate whether current study and management of artificial aquatic systems is based on the actual ecological condition of these systems, or judged differently, due to artificiality, and consider resultant possible changes in goals for these systems. The emerging recognition and study of artificial aquatic systems presents an exciting and important opportunity for science and society.

Keywords: artificiality; reconciliation ecology; drainage; irrigation; ditches; ponds

1. Introduction

Humans alter geomorphology on an ever-increasing scale [1], one comparable with [2], and in some ways exceeding [3], rates of natural processes. Every change people make to the Earth's surface has the potential to affect the flow and accumulation of water. People have dug ditches, impounded streams and rivers, and otherwise shifted Earth's surface to direct and store water for human use, especially agriculture, for over 5000 years [1]. Today, land use matrices that entail human-engineered waterbodies, such as urban settlements, rice villages, and irrigated cropland, cover significant fractions of terrestrial Earth [4]. Patterns of surface water modification and extent are tightly linked to these land uses [5]. Man-made and -modified aquatic systems have become ubiquitous landscape features [6].

In spite of their commonness, artificial aquatic systems remain poorly understood. Indeed, it is often unclear which waterbodies even belong in the category of "artificial" or "anthropogenic". To date, the limited study of different artificial aquatic systems has been fragmented among various domains of ecology and other environmental sciences, and more often discussed on the margins of natural ecosystems than in conjunction with them, as part of a complete hydroscape [7]. Because science and management does not often focus on artificial aquatic ecosystems, their abundance and extent are poorly quantified, and their ecological statuses and causes thereof poorly understood. As a result, we lack a scientific basis for assessing the ecological value of artificial aquatic systems, or determining how management and policy might improve that value. The ubiquity of artificial aquatic systems, the potential commonalities among them and with natural aquatic ecosystems, and our limited understanding of their central and evolving role in the modern hydroscape all argue for more integrated study of the waterbodies created and transformed by human activity.

In this paper, we propose a framework for aquatic ecosystem artificiality that includes both the intent and magnitude of modification, and argue that policy and management often implicitly use these characteristics to differentiate in their treatment of aquatic systems. We assemble current estimates of the extent of some types of artificial waterbodies in the U.S., and review established knowledge of their ecological condition, including the ecosystem services and disservices that they provide. We argue that the condition of artificial aquatic systems, as for their natural counterparts, likely reflects ecological processes and human decisions both in place and within their watersheds, and that the often poor condition of these systems [8] is not necessarily inherent to their anthropogenic origin. Finally, we posit that scientific undervaluation of artificial aquatic systems may lead scientists, managers, and policymakers to treat artificial waterbodies in ways that perpetuate poor ecological conditions. To manage the rapidly changing and increasingly anthropogenic hydroscape, aquatic scientists need to better inventory its myriad artificial components, evaluate their current structure and function, and link these findings to drivers. Future assessment of artificial aquatic systems that clarifies what their real and perceived values are, and how to purposefully change those values, will require more deliberate, intensive, systematic and mechanistic study, and, perhaps, a shift in our perspective regarding what counts as nature.

2. Degrees and Axes of Artificiality

What does it mean to identify aquatic ecosystems as "artificial"? Designer ecosystems, like rain gardens and ponds, swales, and wetlands conceived and built for water treatment [9], are obviously deliberately constructed for human purposes, often where no waterbody existed before, and thus undisputedly artificial [10]. A stream or lake in a protected watershed far removed from intensive human land use might serve, in a traditional ecological study, as a "completely natural" or "pristine" reference site. However, many, or likely most, ecosystems fall between these extremes. For example, scientists and policymakers often differentiate between a channelized stream and a wholly man-made trench, but either may be colloquially called a "ditch" or "artificial", and the two may look and even function quite similarly, particularly within a highly modified agricultural landscape. All natural waterbodies do not necessarily maintain better structure and function than all artificial ones [11]. Restoration projects similarly blur the bounds of "natural" and "artificial" [10,12]. While restoration typically has the goal of returning an ecosystem to some more natural state [13], the process of restoration necessitates human intervention, which is often sustained through maintenance [14], an implicit acknowledgement that many ecosystems cannot withstand human disturbance without purposeful human assistance. Meanwhile, undirected human actions, like stormwater efflux, can accidentally "restore" natural systems [15–17]. Even mostly or wholly man-made systems, like retention ponds, can "naturalize", or become more biotic and ecosystem-like, in time, without deliberate human effort [18]. Both current character and driving forces behind it are often a combination of human and wild, artificial and natural.

These examples suggest that artificial aquatic ecosystems can be usefully organized along two axes: the degree to which their existence and characteristics depend on human activity, and the degree to which that activity is specifically intended to produce those changes (Figure 1). The first axis spans from moderate alteration of systems with initially geologic origins, to the wholesale creation of waterbodies on formerly dry land, sometimes away from topographic lows. The latter axis ranges from aquatic systems that came to exist as inadvertent or accidental by-products of other human activities on the Earth's surface to deliberate and intentional products of such activity [19]. These two artificiality axes are gradients, not discrete categories, and can be difficult to parse, especially for the many waterbodies with complex, multi-layered histories of modification [20–22]. Depending on the purpose, it may be appropriate to define "artificial" waterbodies broadly or narrowly within this space.

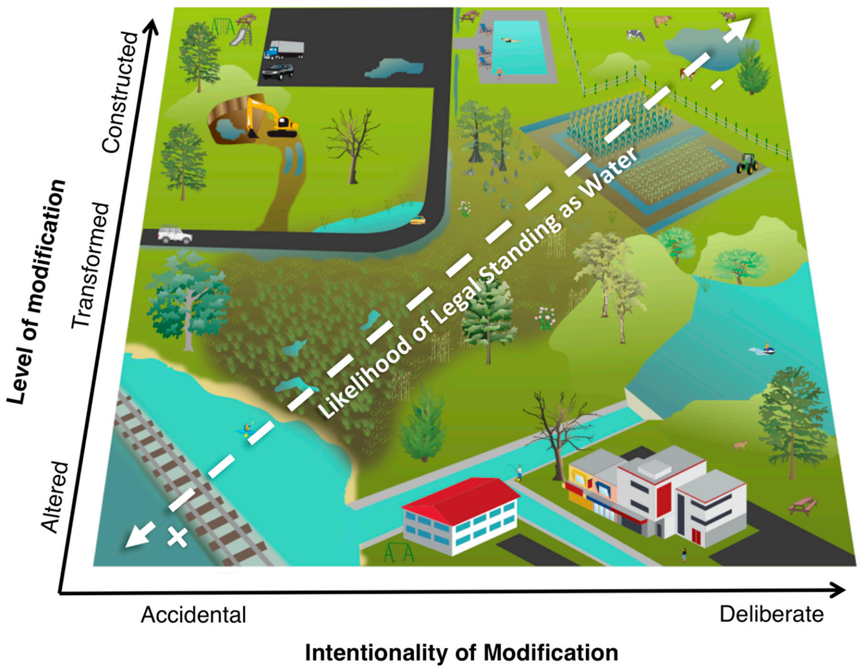

Figure 1. Classification of artificial aquatic systems. Level of deliberateness of modification increases from left to right, and degree of modification increases from bottom to top. These two axes combined yield a third axis, likelihood of legal standing as a water for regulatory purposes in the U.S., running from unlikely among deliberately constructed ecosystems like swimming pools and upland farm ponds in the upper right, to likely among accidentally altered ecosystems, like a lake bisected by a railroad causeway, in the lower left. Other potentially influential characteristics, such as size and permanence, may influence regulation in both natural and artificial systems.

Construction, Transformation, and Alteration

The most clearly artificial aquatic systems are those that humans construct where none existed before. Even the existence of these constructed artificial ecosystems relates to other natural waterbodies because they represent water that could have gone or stayed elsewhere, on the landscape, underground, or to other parts of the hydrologic cycle. Deliberate examples of construction include fountains, many roadside ditches, rain gardens, stormwater treatment areas, many farm ponds, and all designer ecosystems [10]. Conservation-oriented water regulation typically exempts such constructs outright; they usually do not count as water [7,23,24]. Accidental examples include logging ruts, erosional gullies in building sites and agricultural fields, poorly drained impervious surfaces, and even bomb craters [25]. Some of these accidental features represent failures of water conservation regulation or other damaging abstraction from natural water sources. Nonetheless, left unmaintained, in time, such accidental waterbody construction in relative uplands can "naturalize" to a seemingly "wild" ecosystem [25–27]. Waterbodies that humans have constructed accidentally, but that appear relatively free from human intent, are more likely to be regulated than waterbodies that humans have constructed on purpose [23,24].

Transformation occurs when human intervention changes waterbodies from one type to another, fundamentally different in morphology and flow, such as from a lake to a wetland, or a wetland to a stream. Deliberate transformations include ditching of wetlands for agriculture, conversion of wetlands to ponds during development, damming of streams to build reservoirs, piping of creeks, and many restorations. The impoundment of the Everglades behind Tamiami Trail, a road that interrupted sheet flow, is one prominent such example [28]. Similarly, humans accidentally transformed the bed of the Salt River, dried through damming upstream, into wetlands, at stormwater outflows [15]. Transformed waters generally retain their regulatory status [23,24] regardless of intent. Such transformations are often considered degrading and thus may require regulatory permission [23,29,30].

The least modification that might make a waterbody appear artificial is alteration, in which fundamental morphology and flow are retained. Deliberately, people straighten and channelize rivers, harden riverbanks and shorelines, and dredge lakes. Accidentally, sedimentation from agriculture, mining, or construction makes streams and lakes shallower [31]; mill dams clogged river valleys all over the eastern U.S. [32]. Meanwhile, "urban stream syndrome", including incision, flashiness, and other changes largely in response to stormwater drainage, has become a well-known issue in developed areas everywhere [33]. In one particularly grand example of accidental alteration, a railroad causeway divides the Great Salt Lake into mostly independent halves with very different chemistry and community assemblages [34]. Alterations generally do not remove jurisdiction of regulation from waterbodies, and instead likely invoke regulatory oversight [23,29,30]. Of the range of artificial aquatic systems, altered waterbodies are often the easiest to imagine in their "natural" state, the likeliest to be labeled as simply "degraded", the most likely to attract conservation, restoration, and related scientific interest, and, depending on context, possibly the most appropriate for restoration [35–37].

Together, these two axes of artificiality—Degree and intent of modification—may help explain the regulatory protection afforded to various aquatic ecosystems (Figure 1) in U.S. water law [23,29,30]; increasing modification with increasing intent renders waterbodies less likely to be protected [38]. Scientists, regulators, legislators, and other policymakers often do not explicitly acknowledge the value judgement implied by differential treatment of waterbodies according to their type of artificiality. Other traits such as technology, purpose, age, size, and permanence may also figure into value judgments and policy decisions people make about aquatic systems, and so might serve as a basis for further regulatory classification of artificial waterbodies. Some of these attributes, like small size and impermanence, may disproportionately characterize artificial aquatic systems, but also apply to most natural waterbodies [6,39]. Regulatory standards that omit smaller, less permanent waterbodies may do so as much because of their biological, geomorphological, and chemical features [23], or due to their dense distribution inconveniences property and land use considerations [40], as because of their human origins per se.

3. The Ecological Significance of Artificial Aquatic Systems

Understanding the ecological and socio-ecological value of artificial aquatic systems requires that we understand their extent and distribution, their physical and chemical condition and how they relate to biotic communities, and the range of ecosystem services that they provide, but considerable uncertainty surrounds all of these characteristics [8]. Artificial aquatic systems are likely to be ecologically important, due to their extent, which may rival that of natural drainage systems and waterbodies. The ecological functions of artificial systems likely have social significance, often as ecosystem services and disservices, due to their frequent placement near large numbers of people. Moreover, the extent, distribution, and characteristics of artificial waterbodies are likely changing rapidly, in conjunction with those of natural waterbodies. Interdisciplinary understanding of the services and disservices of artificial aquatic systems, the factors that influence them, and their distribution in space and time could foster decisions that increase their ecological value.

3.1. The Extent and Dynamics of Artificial Aquatic Systems

Our understanding of the extent of artificial aquatic systems is piecemeal. Available estimates are largely limited to the U.S. and other developed countries, and largely for intentionally designed aquatic features that are ubiquitous in agricultural, industrial, urban, and recreational land uses, but not their accidental counterparts, including in forests. Even with these incomplete inventories, it is clear that the deliberately constructed or altered fraction of the hydroscape is both large and growing, and must be included in any comprehensive assessment of aquatic resources.

3.1.1. Deliberately Modified Waterbodies

Deliberately constructed and transformed channels constitute a significant portion of the U.S. hydroscape (Figure 2). The U.S. National Hydrography Database includes 5525 km of ditches and canals, or approximately the length of the Missouri River through the Mississippi to the Gulf of Mexico. This aggregation is probably a substantial underestimate, as many smaller ditches do not appear in the database. In 2010, ditches in U.S. agricultural lands occupied about 115,760 km^2 [41], a surface area similar to that of Lakes Superior and Huron combined, or 2.67 times the surface area of all U.S. streams combined [39]. Channelization, another deliberate transformation, has altered the geomorphology of upwards of 26,550 km of rivers and streams in the U.S. [31,42], more than seven times the length of the Mississippi River. Humans have channelized more than 500,000 km of rivers worldwide, and built more than 63,000 km of canals [43–45]. The U.S. also has 6.5 million km of roads [46], many of which have ditches or gutters along both sides that contain water at least occasionally and often for much longer periods. Thus, it is likely that road drainage in the U.S., which effectively serves as urban headwaters, is of comparable length to the 5.3 million km of the country's rivers and streams. The U.S. EPA estimates that 77% of the approximately 1.8 million km of wadable streams in the U.S. are in poor (42%) or fair (25%) condition [47]. Some of these poor and fair streams are likely geomorphically modified enough to fall within our gradients of artificiality. Within this inventory, the remaining degraded "natural" streams, and even perhaps "natural" streams in good condition as well, likely occupy less length than artificial channels. Known lengths of "natural" streams, especially ephemeral and intermittent ones, likewise underestimate their extent [8].

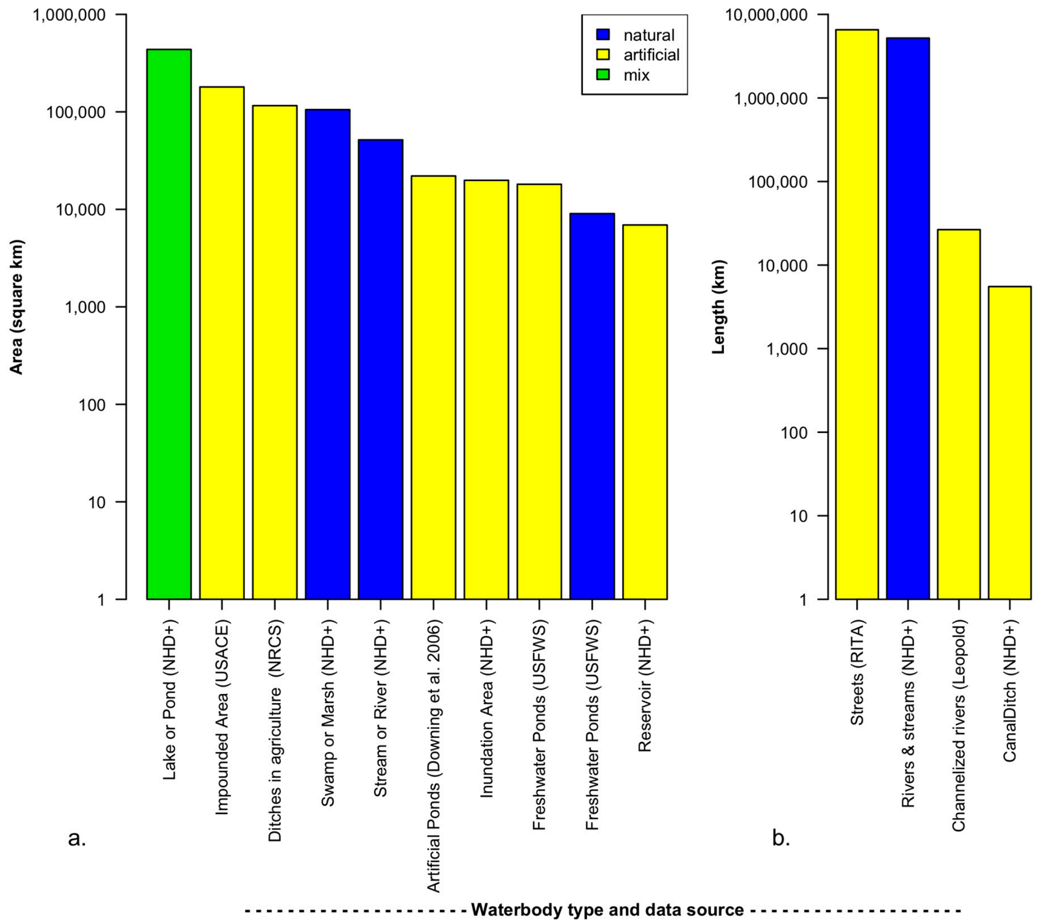

Figure 2. Extent of artificial as compared to natural waterbodies in the U.S. Data drawn from a variety of sources, shown in parentheses. (**a**) areal features; (**b**) linear features. Data are taken from the National Hydrography Dataset (NHD+) [48], U.S. Army Corps of Engineers National Inventory of Dams (USACE) [49], U.S. Department of Agriculture Natural Resources Conservation Service (NRCS) [41], Downing et al. [6], U.S. Fish and Wildlife Service (USFWS) [50], Research and Innovative Technology Administration (RITA) [46], and Leopold [42].

The extent of constructed lakes and ponds are similarly significant in comparison to natural waterbodies (Figure 2). The U.S. has about 22,000 km^2 of deliberately constructed or transformed farm ponds an area similar to that of Lake Michigan; the world as a whole has about 76,830 km^2 of farm ponds [6]. In total, for the U.S., the U.S. Army Corps of Engineers inventories an impounded (deliberately transformed) area in excess of 180,000 km^2 [49], for purposes including irrigation, hydroelectricity, flood control, navigation, water supply, and recreation [49]. The world had approximately 258,570 km^2, or slightly more than the area of the Great Lakes, of impounded water in the mid-2000s [6], before the completion of the Three Gorges Dam in China and other projects. In 2009, the U.S. Fish and Wildlife Service estimated that only 31% of the country's 27,151 km^2 of freshwater ponds were natural. Of the artificial pond area, about the size of Lake Ontario, farm ponds took up about 1.5 times the space as natural ponds; urban ponds occupied about half the area of natural ponds despite the relatively small amount of urban space, and industrial and aquaculture ponds made up significant fractions as well [50]. This estimated aquaculture pond area, of just over a thousand square kilometers, is much smaller than that of many countries'; globally, 1.7 million km^2 of the world's 2.7 million km^2 of irrigated land goes to rice production, and is flooded seasonally, at least [4].

3.1.2. Accidental Waterbodies

The abundance and extent of accidentally created aquatic systems is extremely poorly quantified. Human earth movement has risen in the last 150 years, from a historic background level of less than 5 tons per capita to more than 30 tons per capita annually in the U.S. [1], creating the potential for the formation of local low areas and water accumulation. Moreover, earth movement has become more common in wet spaces [51], where the potential for accidental creation of waterbodies is higher. Water infrastructure, such as stormwater or water supply pipes, can create accidental wetlands wherever leakage occurs [27]. Accidental creation of aquatic ecosystems is perhaps most likely in abandoned areas, where anthropogenic depressions and impoundments that accumulate water may remain, often with minimal human interference. Better information about the density of accidental waterbodies, combined with estimates of the land area over which they might occur, would allow us to estimate their extent, but that information is currently lacking.

3.1.3. Change

The distribution of artificial waterbodies, like and reciprocally with many natural systems, is dynamic in time, owing to both seasonal and event-driven hydrologic change, as well as longer-term changes in land cover. Some of these changes involve the destruction or reduction of natural waterbodies; net effect of growth in artificial waterbodies includes what they replace and from whence they divert water, including those accidental changes that typically go unmeasured. Between 1984 and 2015, North America as a whole, home to 52% of the world's non-ocean permanent surface water, added a net 17,000 km^2 to this area. The area of permanent surface water in the U.S. as a whole grew 0.5%, even as six of its western states lost 33%, or over 6,000 km^2, of their permanent surface water [52]. Farm ponds, in particular, are highly dynamic in use, creation, and abandonment [53]. In commercial and residential developments, ponds and other stormwater features too small to appear in the above analysis, wink in and out of existence too quickly for inventorying, or further scientific study [54].

Emerging technologies and modeling approaches have the potential to improve inventories of small and accidental waterbodies and better characterize the distribution and dynamics of hydroscape change. Advances in remote-sensing technology, such as the increasing availability of high-resolution lidar data, may very soon yield much better maps of small and otherwise over-looked waterbodies over broad extents [55–57].

4. The Condition of Artificial Aquatic Systems and Its Drivers

The perceived poor condition of artificial aquatic systems matches the reality of poor water quality and altered ecological structure in many man-made waterbodies [58,59]. Many artificial waterbodies support species-poor [60] or otherwise undesirable communities or organisms, including disease vectors [58,61,62], and can spread pest species to natural habitats [63,64]. Some have also contributed to, accelerated, or facilitated flow of excess nutrients and other pollutants [65,66], activation of toxicants [58], interrupted desirable species' movement and dispersal [67], increased greenhouse gas emissions [27,68], yielded bad smells [69], and even concealed crime [70]. Other examples of ecosystem disservices proffered by artificial water bodies appear in Table A1. While natural waterbodies can possess the same undesirable characteristics, we are more likely to assume that artificial waterbodies have a negative influence without investigation [71].

Are artificial aquatic systems intrinsically less biologically diverse and less functional than natural ones? It is at least plausible that humans cannot create a waterbody that supports communities as diverse or provides as many ecosystem services. Certainly, when transforming, altering, or removing a functional natural aquatic ecosystem, one should expect a reduction in current ecosystem services provisioning, unless or until scientific study confirms a better outcome possible from the change. One important constraint on artificial aquatic systems is that with their anthropogenic origin comes a severely shortened evolutionary, ecological, and geophysical history [72,73]. To the extent that diversity and other aspects of ecosystem structure depend on slow processes of physical change and community assembly, the recent origin of most artificial systems will likely limit their function.

There are other potential limits on the condition and value of artificial aquatic systems. First, imperfect understanding of how differing designs and constructions affect ecological outcomes, and imperfect ability to reproduce natural structures and conditions, may constrain the most ecologically-motivated projects, as may be the case for many ecosystem restorations [13]. Second, artificial aquatic systems are often embedded in intensively used landscapes, potentially exposing them to anthropogenic stressors and disconnecting them from diverse natural populations [13]. Finally, and perhaps most importantly, many artificial aquatic systems may support limited diversity and ecosystem function because they are not designed or managed to do so; in many cases, their intended function may preclude or limit the provision of other services [27]. As a result, scientists, policy-makers, and the general public have tended to accept that artificial aquatic systems will necessarily and inherently have limited value. However, these assumptions are often not subject to the same critical assessment and process-based explanations that are applied to explanations of the condition of other aquatic systems.

The poor condition of artificial aquatic systems is far from universal, and at least some, perhaps many, artificial aquatic systems also have clear ecological value. Constructed and transformed aquatic systems, whether agricultural, industrial, urban, or recreational, can sustain biodiversity [74], sometimes including rare and desirable species [18]. In Europe, manmade farm ponds serve as primary or important habitat for amphibians [75], birds [76], invertebrates [77–79], plants, and other species [80,81]. Indeed, European conservation proceeds from the assumption that "artificial", "man-made" ponds are not fundamentally ecologically different from "natural ones" [82]. Some species now apparently depend primarily on deliberate artificial aquatic ecosystems for habitat [83–85]; even species new to science continue to emerge from ditches [86–88]. Equally in the U.S., habitats that we presently tend to overlook, such as stormwater treatment wetlands, can sometimes be the best available sites for reproduction of amphibians and other species with specific hydrologic needs [89]. Artificial aquatic systems, whether designed for the purpose or not, have improved water quality in critical watersheds like the Mississippi River basin [90–92]. Additional examples of ecosystem services provided by artificial aquatic systems appear in Table A1. Without more intensive and systematic study, it remains unclear whether good ecological conditions, and the desirable ecosystem services that derive from them, are a negligible, rare, or even commonplace occurrence in artificial aquatic systems. Similarly, their net impacts, and value relative to natural counterparts, remain undetermined.

Making artificial aquatic systems more functional and valuable will require a mechanistic and predictive understanding of their condition and their capacity to provide ecosystems services and disservices. We propose that the science of artificial ecosystems should entertain and evaluate hypotheses about what drives variation among them as well as their differences from their natural counterparts. Like their natural counterparts, the ecological characteristics of artificial aquatic systems are likely to depend on their physical structure, the characteristics of the watershed and landscape in which they are embedded, their age and trajectory over time, and the ongoing interventions of humans for various purposes (Figure 3). While all of these mechanisms are shaped by human design decisions, they also have clear analogs to factors commonly invoked to explain the condition of natural aquatic systems. This re-casting of rationales for why artificial aquatic systems are assumed to be in poor condition as testable alternative mechanisms allows us to consider how different decisions about the design, placement, and longevity of artificial aquatic systems might improve their condition and value. The poor condition and seemingly inherent limitations of artificial aquatic systems could be simply a syndrome of those decisions. In our exploration of these possible causal variables for the ecological condition of artificial aquatic systems here, we focus on this management-oriented way of examining the causal variables, and barely begin to explore the possible interactions between them. We recognize that scientists with different foci could propose other valid testable hypotheses, and indeed invite them to do so, but we consider setting, time, physical design, and subsequent management of artificial waterbodies to be good intellectual places to start trying to understand these ecosystems.

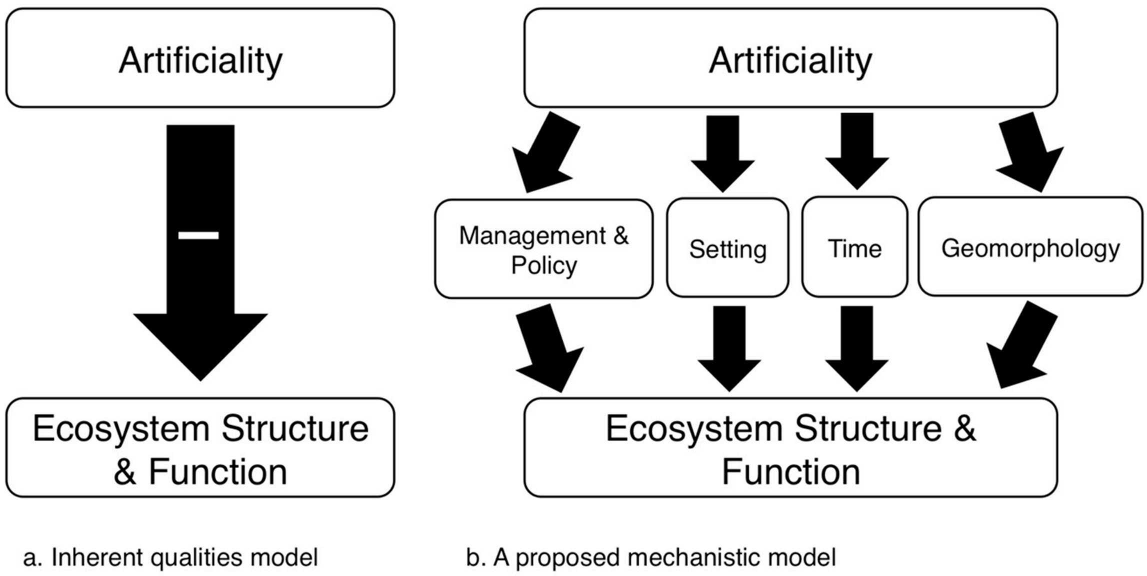

Figure 3. Inherent vs. process-based models of the condition of artificial aquatic systems. (**a**) inherent qualities model; (**b**) process-based model. We suggest that scientists and policy-makers have too readily accepted model (**a**), in which the inherent qualities of artificiality negatively impact ecosystem structure and function, rather than scientifically exploring a mechanistic model such as the one we propose in (**b**), which breaks the influence of artificiality down into multiple processes.

4.1. Setting

Understanding how the watershed setting of artificial aquatic systems affects their ecology is important both because understanding will be essential for better policy and management, and because the effects of setting may obscure the ecological effects of other factors such as design, management, and time. The condition of the watershed and landscape around any waterbody influences its condition [93], and artificial aquatic systems should be no different in this respect. Since humans tend to create artificial aquatic systems in and around heavily modified landscapes with substantial chemical inputs like agricultural fields, roads, and parking lots, artificial aquatic systems such as ditches tend to have lower water quality than their natural counterparts [94–96]. The communities of artificial aquatic systems also tend to reflect the local and regional species pools, yielding, for example, more exotic species in a restoration in a developed area [97].

Available evidence suggests that setting does exert a strong and often overwhelming influence on artificial waterbodies, and that these effects are similar to those observed in natural systems. Water quality of artificial aquatic systems such as ditches responds to catchment land use in much the same way as that of waterbodies of natural origin [8,98], and agricultural land cover impacts reservoirs food webs [99]. In the Salt River in Arizona, level of urbanization explained much of the variance in communities of plants, birds, non-avian reptiles, and amphibians, for reference, restored, and accidentally restored river reaches alike [15]. A study in the Florida panhandle found that natural streams, altered streams, and ditches within the same forested region had similar macroinvertebrate and fish assemblages [100]. Agricultural intensification around fishponds has contributed to the rapid decline in breeding populations of black-headed gulls (*Chroicocephalus ridibundus*) in central France [101]. More such comparisons between artificial and natural waterbodies in similar settings are needed to disentangle the effects of watershed setting from other factors that influence the condition of artificial aquatic systems.

The predictable responses of artificial aquatic systems to their watershed setting has implications for how these systems are managed and how that management could be improved. The importance of watershed land cover for reservoir water quality shapes economically motivated conservation, like New York City's efforts to prevent development in the watersheds of its reservoirs upstate [102]. More generally, stream restoration is more effective in undeveloped than developed catchments [103]. While more studies are needed, the available evidence suggests that the condition of artificial aquatic systems depends strongly on their setting, and that those conditions, and the ecosystems services that depend on them, could be improved by the same watershed-scale policy and management that protects natural waterbodies.

4.2. Time

Most artificial aquatic systems are young, both because most land use change and earth moving has occurred within the past few hundred years [1] and because artificial aquatic systems turn over more quickly than natural ones [93]. Given the timescales over which community assembly occurs in newly formed natural streams and lakes [104], it is likely that limited diversity of some artificial aquatic systems simply reflects their recent origin. Understanding the consequences of recent formation requires that we understand the timescales over which newly created ecosystems develop, whether they arose from anthropogenic or from geologic processes, and potentially attain the characteristics of their older counterparts. At present, we lack both general and system-specific models of these trajectories, as well as criteria with which to judge that an artificial aquatic system has "naturalized".

A relatively limited set of long-term and chronosequence studies indicate that artificial aquatic systems can change in important ways over timescales that are similar to those in natural ecosystems, and that are relevant to decision-making [105–107]. In restored wetlands, for example, ecological structures and functions such as carbon sequestration can improve with time since intervention, and soil characteristics approach natural properties over decades [108]. Re-configured two-stage ditches can achieve soil formation and a geomorphological "quasi-equilibrium" within a decade [109]. Agricultural ditches also undergo a relatively predictable succession of plants and associated invertebrate communities [110]. Accidentally created waterbodies also change over time, often acquiring more 'natural' characteristics. For example, gravel quarries develop more structurally complex and diverse vegetation over several decades [111]. At some point in time, artificial aquatic systems may be difficult to distinguish from natural systems. Many of the small, ephemeral wetlands that sustain populations of amphibians in the Piedmont of the U.S. Southeast are likely legacies of historical human disturbance [26]. Such examples suggest that time eventually erases many signatures of anthropogenic origin, and that this naturalization may change how aquatic systems are perceived and valued.

Better understanding of how time constrains the characteristics of artificial aquatic systems, and the mechanisms by which they evolve, could improve our ability to manage them, individually and as part of the broader aquatic landscape [112]. Properties associated with age may elude newly created waterbodies, and expectations that artificial waterbodies adequately replace natural ones should be tempered accordingly. Goals and expectations of restorations and other interventions might need to reflect the differential responses to the same management technique, as has been observed in young and old artificial aquatic systems [113]. Deliberate management of successional stages has been used to increase the abundance and diversity of desirable species [107]. Wider adoption of such approaches will require better models of succession and its dependence on design, setting, and management.

4.3. Design

Design is a goal-oriented process with multiple stages, including the establishment of goals, a plan to achieve those goals given constraints, implementation (including initial construction and subsequent maintenance), and, ideally, subsequent iterations of goal-setting and redesign [14]. Decisions, whether unconscious or deliberate, at each of these stages have the potential to shape the outcomes of later stages, and ultimately the ecological character of artificial aquatic systems, including their trajectories over time and how they respond to the forcings imposed by their watershed setting. The physical structure and management of accidentally created waterbodies obviously does not depend directly on goal-oriented design, though their structure may reflect design decisions and management regimes of which they are not the object.

4.3.1. Design Goals

Historically, many deliberate artificial aquatic systems have been designed and maintained to provide one or a few services, such as water conveyance and storage [27,114]. The exclusion of many such artificial waterbodies from protection within the U.S. apparently reflects that policymakers and legal frameworks value these systems almost exclusively for their intended, fully human-oriented purposes [23]. Planning for only one or a few ecosystem services, such as water storage and conveyance for flood control, can limit the ability of a deliberate artificial aquatic ecosystem to provide other services, especially when designers overbuild that system for its given purposes [27]. In many cases, the design goal itself can inherently produce a major ecological cost, as in wetland drainage by agricultural ditches [115,116], or can result in unintended disservices arising from synergies and trade-offs in ecosystem services [117,118]. Nonetheless, many designed artificial aquatic systems also provide a range of additional ecosystem services beyond the purpose of their design [15,89].

The designs of aquatic ecosystems, including both newly constructed waterbodies and restoration of degraded systems, increasingly seek to provide a portfolio of ecosystem services and functions through redesign of physical structure as well as changes in management [119,120]. Urban dwellers appreciate open expanses of water in spaces where they go for recreation [121], and even modified or constructed waterbodies can mitigate pollutants and floods, cool the air, and provide spaces for recreational, spiritual, and community-building activities [70]. For example, the Los Angeles River, converted to a concrete flood chute and movie set for car chases in the mid-20th century, has recently become the focus of an ambitious revitalization project to improve water quality and sustain wildlife while also providing a greenway and other recreational opportunities [120]. Similar redesigns of channelized rivers have already demonstrated the benefits of design for a range of ecosystem services [122]. The Landscape Architecture Foundation has endorsed projects throughout the U.S. and around the world with similar methods and goals, specifically including stormwater management, water conservation, water quality, flood protection, and groundwater recharge alongside other environmental, social, and economic goals [22]. Deliberate artificial aquatic ecosystems like these tend to remain primarily human oriented, and not ecologically oriented, in their goals, however. Even restoration designs often explicitly and unapologetically include human-specific concerns, such as ease of maintenance, accessibility, recreational appeal, aesthetics, regulatory standards, finances, and property lines, alongside more ecologically oriented values [123–125].

4.3.2. Planning and Construction

The reduced physical complexity of many artificial aquatic systems, such as concrete-lined channels, obviously limits their value as habitat and potential for improvements in water quality [126]. Restorations that seek to improve these values therefore often focus on the (re-) introduction of heterogeneous structures that are more similar to natural systems [120]. Such designs, and their implementation, can be constrained or flawed in ways that limit their ecological value, including by insufficient scientific understanding of how design features and subsequent management influence eventual outcomes [35,93,127,128]. However, many such systems are also affected by intensive land use and short lifespans [103]; artificial systems whose structure mimics that of natural systems can support similar biotic communities when water quality is high [100].

Conversely, engineering research on designer ecosystems constructed for a very specific subset of aquatic ecosystem services, such as water quality improvement, clearly demonstrates that design plays a role in how effectively these systems achieve their purpose. For example, plant species choice in wastewater treatment wetlands affects speed and removal efficiency of different forms of nitrogen [129]. In wetlands constructed to remove pharmaceuticals from water, design choices of substrate, plants, and regimes of hydrology, temperature, oxygen, and light all affected removal efficiency, which varied from compound to compound in ways apparently related to microbial processes [130,131]. While much variation remained unexplained even in these relatively controlled systems, they do demonstrate that how an ecosystem is constructed affects its ecological behavior.

Physical, legal, and cultural constraints exert strong control on goals and resulting designs. For example, restoration efforts are typically constrained and otherwise impacted by funding, land ownership, and other social and economic variables [13,93,103]; restorations can have a wide range of intended outcomes [97]. Morphology of stream restorations depends in predictable ways upon funding source and legal purposes, and whether the metric for success is stream length (resulting in very sinuous designs) or some other characteristic [124]. Stream restoration in general has tended towards a single-channel, S-shaped, meandering morphology that conforms to longstanding aesthetic concerns [125], reduces maintenance [123], and maximizes mitigation credits, rather than conforming with local natural history [124]. One indication of the limitations of many restoration projects is the finding that accidental aquatic systems can sometimes provide equal or greater services compared to deliberate, designed systems. For example, "accidentally restored" wetlands at stormwater outflows in the dry bed of the Salt River in Arizona had greater wetland plant richness and cover than comparable actively restored sites, though the reverse was true for birds, non-avian reptiles, and amphibians [15].

Changes in goals often dictate substantial changes in the physical structure of artificial aquatic ecosystems. Two-stage ditches, in which miniature floodplains are constructed alongside existing conveyances [132], can significantly reduce concentrations of phosphorus and other nutrients, turbidity, and total suspended sediments [133,134]. Their nutrient removal efficiency compares well with, and can complement, other farmland best practices, like planting cover crops [90]. When properly constructed according to fluvial principles, these ditches can remain functionally stable, without maintenance, for years [109]. Thus, water infrastructure of agricultural landscapes can be designed, and successfully re-built, to achieve a wider range of goals than water conveyance, though additional land area and design and construction effort may be required.

4.3.3. Management and Policy

Ecosystem function and services of artificial waterbodies likely depends on the management they receive after construction as well, just as management matters in natural waterbodies. In reservoirs, the ability of an artificial aquatic system to provide ecosystem services may depend more heavily on ongoing policy and management than on the specifics of the initial design [135,136]. In ditches, management strategies, including dredging, mowing, chemical weeding, burning, and regulation of water depth, can have significant impacts on ditch biodiversity and water quality [137,138]. However, ongoing management and maintenance, like initial design, often does not include these potential outcomes in its considerations, instead opting to continue to focus on relatively few, highly human-oriented goals [126]. Such decisions about ongoing management and policy, however, can, at least, in theory, be revised to reflect changing goals.

In complex landscapes, achieving a portfolio of ecosystem services often requires both structural changes and ongoing active management of artificial aquatic systems. Ditches and canals draining ranchlands in the watershed of Lake Okeechobee were not traditionally managed for water quality or conservation purposes, even though they house large native animals and other species of interest [139]. Establishment of Total Maximum Daily Loads for phosphorus in the lake and its tributaries [140,141] prompted creative responses including regional collaborations among various government agencies, nonprofit conservation organizations, a local scientific research station, and ranchers to raise and actively manage water levels to flood ditched wetlands. This strategy removed phosphorous more cost-effectively than did constructed storm water treatment areas [142], while also increasing wetland vegetated area and vertebrate abundance [143]. Multi-stakeholder management of artificial aquatic systems with ecologically oriented goals could prove a cost-effective way to increase ecosystem services at a similarly regional scale in other locations, perhaps as a complementary tool to traditional restoration.

Accidental waters, which often receive little to no management attention, can provide comparable but non-overlapping ecosystem services to both deliberate and more natural waterbodies. Abandoned features, especially within broader abandoned landscapes and even in the hearts of cities, can provide habitat for urban-avoiders and other organisms that survive best away from humans and human intervention [26]. Abandoned areas can contain accidental artificial waterbodies sustaining both human and nonhuman life, and functioning as little pockets of biodiversity [27]. Accidental urban wetlands can also mitigate nutrient pollution flowing from cities to downstream in natural waterbodies [27]. Two European species of damselfly were believed extinct for decades, until rediscovered, separately, in former industrial and mining areas "not usually explored by biologists". Other neglected artificial habitats in our midst could hold similar surprises. Notably, conservation interventions "focused on returning habitats to a 'natural' state" intended to boost one of those damselfly populations actually backfired [144]. These observations suggest that active intervention, for non-ecological and even ecological goals, can limit the ecological value of artificial aquatic systems.

4.3.4. Monitoring, Learning, and Iteration

One of the criticisms of many restorations is that they require ongoing, often expensive management to avoid reverting to a degraded state, which some scientists consider a failure of resilience. Part of the problem with declaring restoration success or failure is that goals for a specific restoration are often unclear and may change through time [145], but for most aquatic restorations are never evaluated [97,146]. Monitoring protocols often focus on easily quantifiable measures that ensure mitigation credit, rather than landscape-scale and long term ecological contributions [124]. Such monitoring designs may not adequately assess what was lost and what was gained. In all, current practices of stream and wetland restoration may not be well configured for learning and for adapting designs to improve environmental outcomes [14]. More broadly, the exclusion of artificial aquatic systems from policy protections eliminates an important motive for monitoring. In the UK, a recent precipitous decline in farm pond numbers and services in the UK sparked conservation concern and action [147]. The U.S. lacks the monitoring data necessary to characterize trends in its small artificial aquatic systems and to respond accordingly.

Moving forward, adaptive management, designed experiments [148], reconciliation ecology [149], and other ecologically based ways of improving designs may change the outlook for deliberate waterbodies. A future increase in the acceptance of novel ecosystems might allow the creation of new types of waterbodies designed to provide similarly novel suites of ecosystem services [10,150]. Even the tendency for less regulation of more highly and accidentally modified [23,29,30] and smaller waterbodies [7,8], particularly in the U.S., constitutes an opportunity; this quality could make them comparatively easy and low-cost systems in which to study, test, and implement novel ecological design ideas [148,151,152]. Together with the repetitive design and construction of many such waterbodies, like ditches and ponds, the manipulability of artificial aquatic ecosystems makes them prime sites for natural experiments [153] and designed experiments [148]. Irrigation canals can serve as "lotic mesocosms", ideal because of their known histories, predictability, and accessibility [152]. Ditch network structure recently served as a good system within which to model possible alternative stable states in primary producer structure [154]. Science in artificial aquatic ecosystems could contribute substantially to broader ecological theory and practice. While win–win design decisions to support multiple desired ecosystem services and other goals can prove challenging to envision and implement, even in artificial aquatic systems, these waterbodies remain sufficiently understudied that exploration of the many remaining questions around them likely has many win–wins, in terms of furthering both applied and theoretical science, left to yield. We hope that the conceptual structures introduced in this article will assist in future such work.

5. Artificiality and Perception of Ecosystem Value

The concept of artificiality, its associated dichotomy between human and nature, and its connotations for valuation, have deep roots. One of the earliest abstract concepts U.S. children master is the difference between artificial and natural, in terms of origin; they learn to tell whether an object is "made by people or something that people can't make" [155]. Accordingly, Western culture has a long tradition of elaborating upon the natural/artificial dichotomy [156] and including it in value systems [157]. In American history, wild nature provided a divine purpose for European settlers, a spiritual rejuvenation for Romanticists and early conservationists like Muir, a source of strength to manage for technocrats, and a rallying point for complex unity among environmentalists [158]. Today, untouched wilderness "exists nowhere but in the imagination" [157]; every ecosystem is somewhat artificial, yet the concept of pristine wild nature continues to exert a strong pull. A recent psychological study found that subjects preferred environments when told that they were natural [159], perceiving them "less dangerous, cleaner, and more plentiful" than those already exploited by other humans. We argue that research and policy-making about artificial aquatic systems reflects this cultural subordination of artificial things to the natural and wild, inherited from broader contemporary Western culture [159,160].

The past several decades have seen ferocious clashes in environmental philosophy and conservation biology over the role of artificial ecosystems. In the 1980s, prominent ethicists lampooned restoration on the grounds that "faked nature is inferior" in much the same way that an art forgery is inferior because it is "a product of contrivance", lacking "causal continuity with the past" [161], and that man-made natural areas represent "domination, the denial of freedom and autonomy" that defines nature [162]. Some philosophers have since softened this dichotomy, viewing it as a gradient or broadening the criteria that constitute a necessary fidelity to nature [163–165]. While naturalness remains valuable by all standards of environmental ethics, many ethicists increasingly distinguish categories (or dimensions) of naturalness, including "as a physical property of species and ecosystems", such as native biodiversity, and "as a quality of processes that are free of human intervention" [74]. This particular pair of categories, posited as a distillation of values already in wide use, corresponds well with our proposed axes of degree of physical modification and level of intentionality, which U.S. policy tends to reflect [23,29,30].

Discussions of humanity's relation to authentic nature intermingle with and parallel debates within conservation biology and broader environmental science and policy. Proponents of traditional wilderness- and biodiversity-based conservation have reacted with alarm to "new conservation", a loose grouping of movements that include human and socio-economic goals, such as poverty reduction, in their conservation plans [73,166]. While restoration has become a widely accepted practice, novel and designed ecosystems are on the battle lines between "new conservationists" who would like to include them in conservation plans and more traditional conservationists who would not [167]. The difficulty in reconciling these perspectives [168,169] may arise in part from different priorities, i.e., the physical and ecological condition of ecosystems versus their freedom from human intervention, and in part from conflicting views about whether human intervention inherently degrades ecological condition.

Interactions between Perception and Condition in Artificial Aquatic Systems

The presumption that artificial aquatic systems have little ecological value matters because it promotes neglect. People make management decisions about aquatic systems not on the basis of perfect factual knowledge of the state of these systems and their impact on the broader hydroscape, but instead upon how they perceive them [170]. Natural aquatic ecosystems in poor condition often retain perceived potential value, which restoration seeks to regain, no matter how little realized value remains [171]. However, traditionally, scientists and policymakers have regarded artificial ecosystems as relatively low in ecological value [71], regardless of their actual function and services (Figure 4). Conversely, a high-functioning artificial system may be overlooked in conservation planning [18]. For example, the 250 km of canals of the North Poudre Irrigation Company near Fort Collins, Colorado, supported 92% of wetland area in the 23,300-hectare service area through leakage. In spite of the ecosystem services these wetlands provide, this leakage is considered an unacceptably inefficient use of a scarce resource, and may cease as irrigation practices change, without considering the value of lost accidental wetlands [17]. Perceived value influences design and management, which, along with any other more direct impacts of artificiality, in turn influence ecological condition (Figure 5). If, as appears prevalent among the ecologically minded, perceived artificiality downgrades perceived value of aquatic ecosystems, and management and policy decisions reflect this lower valuation in low expectations and low protections for artificial waterbodies, then assumptions of the low quality status of artificial aquatic systems could be self-fulfilling.

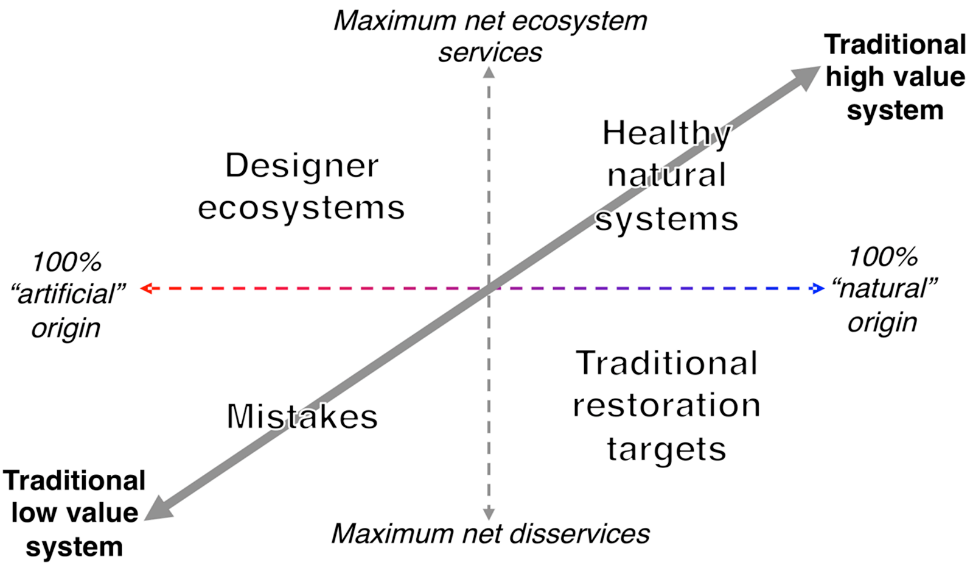

Figure 4. Value axes for aquatic ecosystems. The solid line represents a traditional axis for the value of aquatic ecosystems. The dashed lines parse out artificiality from ecosystem services provisioning along this traditional axis.

The divergent consequences of this positive feedback loop may be illustrated by examining water management policy in the U.S., where the Clean Water Rule prioritized the exclusion of many artificial aquatic systems from jurisdiction under the Clean Water Act [24]. In contrast, the European Union's 1996 Water Framework Directive resolved to gradually expand protection "to all waters, surface waters and groundwater" [172]. In line with this inclusive view of aquatic ecosystems, pond degradation [173] and loss is a stated conservation concern for the EU [147] and NGOs [174]. Freshwater Habitats Trust's Million Ponds Project aims to "to reverse a century of pond loss, ensuring that once again the UK has over one million countryside ponds", and claims more than 1000 ponds created in 2008–2012, housing about 50 rare and declining species [175].

Meanwhile, European researchers continue to explore pond conservation measures [82], including management options that improve habitat quality in existing ponds [105,176]. Similar research and conservation activity is progressing for British and other European ditches [177,178]. Assuming even modest success of such efforts, the condition of artificial aquatic systems in the EU is likely to improve, while the quality of artificial waterbodies in the U.S. is likely to decline. Europe's example suggests that how people regulate, perceive and manage farm ponds, and other artificial aquatic systems does impact conservation outcomes.

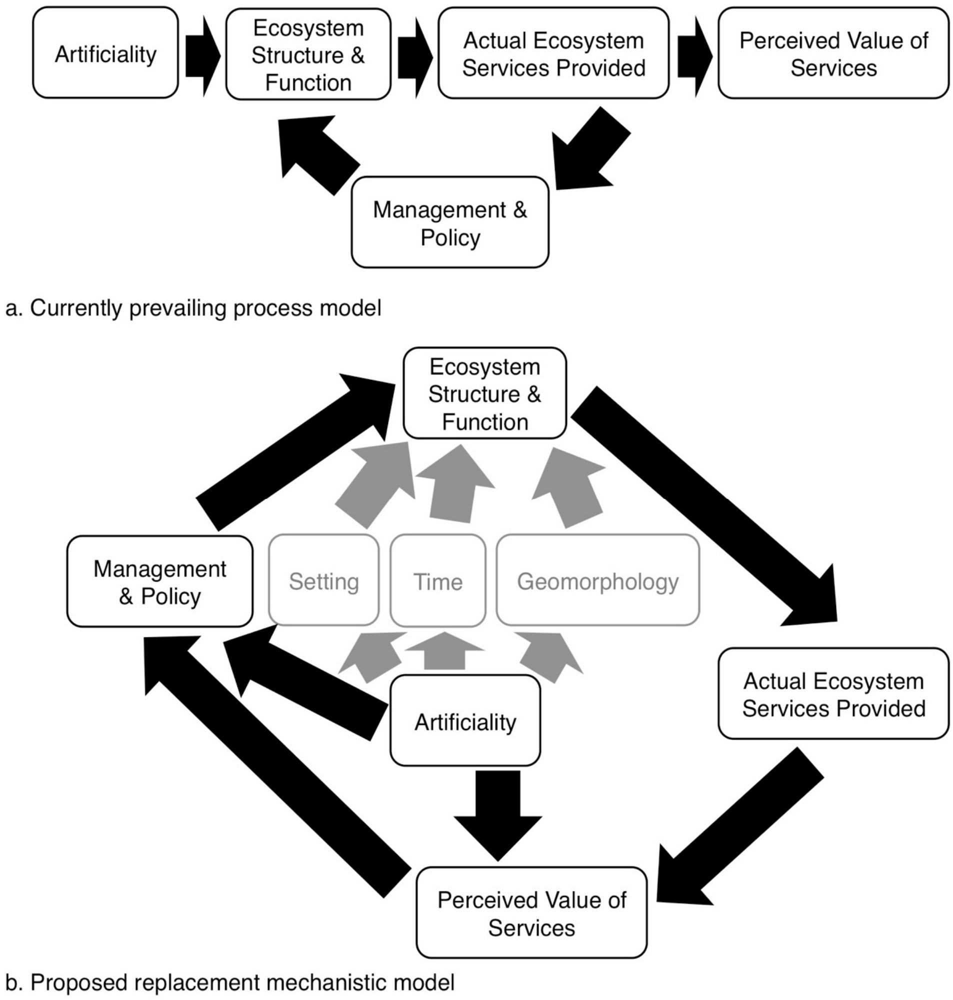

Figure 5. Conceptual diagram of the role of artificiality in the management and services provided by an aquatic ecosystem. (**a**) the currently prevailing process model depicts an approximation of how environmental scientists appear to typically think of the role of artificiality in impacting ecosystems; (**b**) our proposed replacement suggests that, while artificiality may impact ecosystem function directly through mechanisms yet little elucidated, we are more certain that it impacts the perceived value of ecosystem services. Because perception impacts policy, policy affects reality, and reality impacts perception, this proposed replacement process model for the role of artificiality in aquatic ecosystems sets up a positive feedback loop.

Getting the policy, management, and science around these systems right matters not just ecologically, but for social reasons as well. Under-managed artificial waterbodies, particularly environmentally hazardous ones, may often occur in already at-risk communities. Two well-studied examples of 20th-century environmental injustice in the United States, in Anniston, Alabama, and Hyde Park, Georgia, both involved predominantly black communities contaminated and sickened in part by ditches bearing water laced with toxic industrial waste [179,180]. Recently, hog waste lagoons associated with industrial swine facilities in eastern North Carolina have proved resistant to regulation despite repeated flooding during hurricanes and tropical storms and persistent strong detrimental effects on the health and quality of life of neighbors, who are disproportionately black and low in income [181,182]. Thus, what artificial aquatic systems go unregulated may say as much about what we socially undervalue as what we ecologically undervalue. Relatedly, the same accidental wetlands that host birds and remove nitrogen in the Salt River in Phoenix, Arizona, provide somewhat unsafe, legally unauthorized sources of water and cool places to rest for homeless people [15,16,27], which calls into question the design of non-aquatic infrastructure whose functions may have been deputized to or externalized on artificial aquatic ecosystems. When science and policy overlooks artificial aquatic systems, it risks overlooking the people impacted by them as well.

6. Conclusions—Artificial Aquatic Ecosystems in Hybrid Hydroscapes

Artificial aquatic systems comprise a substantial, perhaps predominant, and likely enduring component of the modern hydroscape. Because the sheer extent of artificial aquatic ecosystems may, by some measures, increasingly rival that of natural systems, they have the potential to play an important role in both conservation and in the provision of ecosystem services within these hybrid aquatic landscapes. The premise underlying reconciliation ecology [149] is the insufficient extent of relatively undisturbed habitats to preserve anything but a fraction of extant species. In some regions, it may be difficult to enact any sufficiently wide-reaching biodiversity conservation policy without inclusion of artificial systems [183]. Because artificial aquatic systems are interwoven with, rather than separate from, natural elements of the hydroscape, improvements in the condition of artificial systems may benefit natural waterbodies as well [75], or may degrade natural waterbodies through abstraction; the net effect of their creation must account for all of the above. Thus, plans to improve land and water management should target artificial aquatic systems as well as those of natural origin [183].

To realize greater socio-ecological benefits from artificial aquatic systems, we need to understand not just their current value, but their possible provisioning of ecosystem services. This understanding will require, first and foremost, better assessments of the extent and condition of artificial aquatic systems. Improving that condition will require that we suspend our conventional assumption that artificial aquatic systems are intrinsically inferior; instead, we need more hypothesis-driven study that evaluates the factors, such as watershed setting, physical structure and design, time, and management, that influence their ecological condition. We will need to move beyond this initial exploration to more thoroughly consider interactions among these drivers and alternative ways of framing the mechanisms underlying artificiality (e.g., physical vs. biological), first conceptually and then through well-controlled studies.

Because the very way we perceive artificial aquatic systems may affect their ultimate condition and value, effective management of the modern hybrid hydroscape may require reconsidering cultural norms about the concept of artificiality, even undoing our deeply held notions about a human/nature dichotomy. Environmental scientists, and our cross-disciplinary collaborators, must first take on such efforts in support of our own work, but can also play a role in helping policy-makers and others meet these challenges.

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Appendix A

Table A1. Documented ecosystem services and disservices of artificial aquatic systems. This list, while incomplete, provides examples of supporting, provisioning, and cultural services and disservices, including biodiversity, for a variety of ecosystems around the world. Actual monetary valuation of ecosystem services and disservices of artificial aquatic ecosystems, particularly of net effects of waterbodies and comparisons with natural waterbodies, remain lacking, and constitute an area inviting further study.

Ecosystem Service/Disservice	Waterbody Type	Location
Supporting		
Biodiversity retention		
Rare damselfly habitat	Agricultural ditches	Czech Republic [144]
Mite diversity	Agricultural ditch and depression	Slovakia [184]
Diverse macroinvertebrate habitat	Agricultural ditches and peat lakes	The Netherlands [185]
Stickleback genetic diversity	Agricultural ditches	Japan [186]
Reduced fish diversity	Drainage ditches and dredged streams	Estonia [60]
Endangered turtle habitat	Mined peat bogs and drainage ditches	Canada [187]
Amphibian habitat and breeding area	Anthropogenic small isolated wetlands	USA [188]
	Rice paddies	Japan [67], Brazil [189]
	Carp aquaculture ponds	Poland [190]
Barriers to amphibian dispersal	Roadside ditches	Japan [67]
River fragmentation	Reservoirs & dammed rivers	Global [45]
Bird habitat	Open water salt marsh management and mosquito ditches	USA [191]
	Integrated marsh management	USA [192]
	Rice fields	Philippines [193], Brazil [189], China, Japan [194], France [195]
	Bomb craters	Hungary [25]
	Carp aquaculture ponds	Poland [190]
Macroinvertebrate/ zooplankton habitat	Bomb craters	Hungary [25]
	Rice fields	Brazil [189]
	Urban and agricultural ponds	UK [196]
Wetland plant dispersal	Agricultural ditches	Netherlands [197,198]
Wetland/aquatic plant habitat	Paddies and ditches	China [199,200], Brazil [189]
	Drainage ditches	China [201]
	Fen restoration and ditch	UK [202]
	Open water salt marsh management	USA [191]
	Bomb craters	Hungary [25]
Reduced plant diversity	Fish ponds and managed fens	Czech Republic [203]
Wetland habitat loss	Forestry drainage ditches	Southeast Asia [68]
	Shrimp aquaculture ponds	Mexico, Central America, Indonesia [204]
	Agricultural drainage	USA [205], Global [206]
	Rice fields	Brazil [189]
	Fish ponds and managed fens	Czech Republic [203]
Instream habitat loss	River channelization	Global [31,95]
Nutrient cycling		
Habitat for common collector-gatherers	Channelized agricultural headwater streams	USA [207]
Habitat for common aquatic vegetation	Agricultural ditches and peat lakes	Netherlands [185]
Soil erosion	Roadside ditches and culverts	USA [208]
	Peatland forestry ditches	Finland [209]
Reduced soil bulk density and mineral content	Salt marsh ditches	USA [116]
Groundwater recharge	Agricultural drainage ditches	Netherlands [210], China [115]
Lowered groundwater table	Forestry drainage ditches	Southeast Asia [68]
	Open water salt marsh management (sometimes)	USA [191]
	Hot springs swimming pools and baths	Turkey [211]

Table A1. *Cont.*

Ecosystem Service/Disservice	Waterbody Type	Location
Water overuse	Rice fields	USA [212]
	Impoundments and abstractions	Global [95]
	Mining and industrial diversion	Global [45]
	Swimming pools and golf courses	Turkey [211], Global [213]
Provisioning		
Fisheries		
Dispersal corridors for fish and shrimp	Paddy irrigation ditches	Taiwan [214]
Fish and mussel habitat and nursery	Irrigation ditch	Japan [215]
Nekton habitat (prey fish and shrimp)	Integrated marsh management	USA [192]
	Open water salt marsh management	USA [191]
Fish habitat	Agricultural ditches	Japan [216]
	Constructed wetlands, recycle pits, and ditches	
Hunting	Rice fields	USA [212]
	Abandoned ditches	USA [personal observation]
Animal aquaculture		
Catfish and prawns	Embankment ponds	USA [217]
Shrimp	Shrimp aquaculture ponds	Mexico, Central America, Indonesia [204]
Carp	Aquaculture ponds	Poland [190]
Duck	Integrated Rice-Duck Farms	China, Japan [194]
Crops		
Rice	Paddies / fields	China [194,199], USA [212], Philippines [193], Brazil [189], Japan [194], France [195]
Vegetables	Rice fields with High Diversity Vegetation Patches	Philippines [193]
Biofuel	Cutaway peatland, reed canary grass field and ditches	Finland [218]
Timber	Forestry drainage	Southeast Asia [68]
Regulating		
Pest control		
Dispersal corridors for diverse, mostly predaceous spiders and ground beetles	Agricultural drainage ditches	Belgium [219]
Habitat for frogs, spiders, dragonfly larvae	Paddy ditches	China [199]
Mosquito reduction	Salt marsh mosquito ditches and managed ponds	USA [191]
Reduced invasive plants	Integrated marsh management	USA [192]
Insectivorous birds	Rice fields	Philippines [193]
Weed/invertebrate control/spreading by ducks	Integrated Rice-Duck Farms	China, Japan [194]
Habitat for pest fish	Irrigation ditches	Japan [220]
Movement of invasive predator fish	Irrigation canals	USA [221]
Disease vector		
Fecal bacteria export	Roadside ditches	USA [222]
	Urban ditches and pond	USA [65]
Intestinal parasites	Open sewage	USA [223]
Liver flukes	Irrigation ditches	Southeast Asia [62]
Schistosomiasis	Paddies, ditches, ponds	China [224]
Malaria (mosquitoes)	Puddles, urban farms, construction sites, drains, ditches	Ghana [61]
Pollination	Rice fields with High Diversity Vegetation Patches	Philippines [193]
Pollutant removal	Paddy fields, ditches, and reservoirs	China [225]
Denitrification	Paddy ditches	China [199]
	Traditional and ecological agricultural drainage ditches	China [226]
	Agricultural drainage ditches	USA [227]
	Restored wetlands and two-stage ditches	USA [90]
Soil sorption of P	Traditional and ecological agricultural drainage ditches	China [226], USA [228]
P efflux	Agricultural drainage ditches	UK [202], Germany [229]
	Tile drains and ditches	USA, Canada, Sweden, New Zealand [230]
Plant uptake of nutrients	Aquaculture drainage ditches	USA [217]
	Traditional and ecological agricultural drainage ditches	China [226]
	Restored wetlands and two-stage ditches	USA [90]
	Vegetated agricultural drainage ditches	USA [231,232]
Nutrient export	Agricultural drainage ditches	Germany [229], China [233]
	Rice paddies	China [234]
	Roadside ditches	USA [235]
	Urban ditches and pond	USA [65]
Algal blooms and hypoxia	Urban ditches and pond	USA [65]
Organic matter and C retention	Agricultural drainage ditches	USA [228]
Greenhouse gas emissions	Rice paddies and drained peat	Southeast Asia [68]
	Reed canary grass field and ditches in drained peat	Finland [218]
	Drained peatlands	UK [236]
	Shrimp aquaculture ponds	Mexico, Central America, Indonesia [204]
DOC efflux	Drained peatlands	UK [236]

Table A1. *Cont.*

Ecosystem Service/Disservice	Waterbody Type	Location
Sediment/solids retention	Ecological drainage system (wetlands, ditches, ponds)	China [237]
	Agricultural drainage ditches	USA [228]
Sediment/solids export	Roadside ditches	USA [222]
	Peatland forestry ditches	Finland [209]
Salt export	Agricultural drainage ditches	China [233]
Organic pollutant attenuation	Vegetated agricultural ditch	Mexico [238]
Pesticide degradation	Stagnant ditches	Netherlands [239]
Antibiotic export	Agricultural ditches	Germany [66]
Hormone export	Tile drains and ditches	USA [240]
Bad smell	Industrial ditch	Taiwan [69]
Flood control	Drainage ditches	Netherlands [210]
Increased hydrologic flashiness	Roadside ditches	USA [235], Greece [241]
Flooding	Flooding irrigation	Mexico [242]
Cultural		
Scientific model system	Irrigation canal	USA [152]
	Agricultural drainage ditches	Netherlands [154]
Bird-watching, photography	Road borrow pit, reservoir	USA [243]
Sport	Canals	Netherlands [244]
Source of conflict	Impounded rivers	Global [95]

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