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Policy analysis

Overcoming the concrete conquest of aquatic ecosystems

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ABSTRACT

In reflecting on the human domination of our planet in the Anthropocene, some have argued that concrete is among the most destructive materials created by humans. Here we explore this idea, specifically in the context of what we consider "the concrete conquest of aquatic ecosystems." The ubiquitous use of concrete in transportation and building infrastructure has contributed to alterations in freshwater and coastal marine systems. Yet, in some cases, there are no appropriate alternative building materials such that concrete itself is confounded by its application. For example, as the foundation for most dams, concrete fragments rivers and channelizes streams, often creating unnatural systems, yet dams are necessary for hydropower generation and flood control with few alternative materials for construction. In riparian and coastal environments, concrete harbours and inland canal systems are often used to address erosion or reclaim areas for human development. Even when removed (e.g., dam removal, naturalization of shorelines), concrete dust is a major aquatic pollutant. Instances do exist, however, where concrete has been used to benefit aquatic ecosystems – such as the installation of fish passage facilities at barriers or the development of fish-friendly culverts – though even then, there is a movement towards nature-like fishways that avoid the use of harmful materials like concrete. There are also opportunities to achieve conservation gains in the development of seawalls that include more natural and complex features to benefit biota and allow for essential biogeochemical processes to occur in aquatic environments. There have been several innovations in recent years that increase the permeability of concrete, however these have limited application in an aquatic context (e.g., not relevant to dam construction or erosion control but may be relevant in stormwater management systems). We provide a brief overview of the history of concrete, discuss some of the direct and indirect effects of concrete on aquatic ecosystems, and encourage planners, engineers, developers, and regulators to work collaboratively to explore alternatives to concrete which benefit aquatic ecosystems and the services they offer. The status quo of concrete being the default construction material is failing aquatic ecosystems, so we recommend that efforts are made to explore alternative materials and if concrete must be used, to increase structural complexity to benefit biodiversity.

1. Introduction

Land use associated with human development (e.g., settlement, urbanization, transportation, manufacturing) can lead to dramatic changes in the landscape (Vitousek et al., 1997; Foley et al., 2005). Some of these changes, like deforestation and agriculture, may be reversed at least to some extent, if the activity ceases or vegetation is replanted. In contrast, changes that involve physically covering or replacing natural areas with human infrastructure and manufactured materials (e.g., metals, concrete) are considered by many to be "permanent" (at least on relevant human timescales; Meyer and Turner, 1992). Although these are clearly "radically changed landscapes," they are also "novel ecosystems," which in some cases support various biotic and abiotic functions even if different than natural systems (Morse

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et al., 2014). There is growing interest in revisiting the materials used in construction and how they are used in an effort to reduce the environmental effects of human development (Horvath, 2004; Kibert, 2016). At the centre of this discourse is concrete: a widely used construction product recently described as "the most destructive material on Earth" (Watts, 2019).

Concrete represents one of the most permanent building materials created by humans. There is no doubt of its important role (past and present) in the development of modern society, namely the constructing of buildings, road networks, water supply systems, sanitary infrastructure, and dams. However, in the Anthropocene, it is clear that human interactions with the biosphere must be revisited (Johnson et al., 2017), and critical rethinking of how we use materials like concrete to benefit biodiversity, instead of only reducing its use, is one step forward. Human settlement is almost always near water given its relevance to consumption, electricity, irrigation, manufacturing, transportation, health, recreation and culture. We submit that concrete has had particularly deleterious consequences on aquatic ecosystems, whether coastal marine, riverine, wetland, estuarine, or freshwater habitats, and that concrete use has contributed substantially to these systems being among the most altered, degraded, and threatened worldwide (e.g., Dudgeon et al., 2006; Lotze et al., 2006; Coverdale et al., 2013; Reid et al., 2019).

Here we explore what we consider to be the "concrete conquest of aquatic ecosystems." We provide a brief overview of the history, production, and composition of concrete, including a discussion of its life cycle. We then consider some of the effects of concrete on aquatic ecosystems, spanning marine and freshwater habitats, and discuss how the use of concrete has contributed to both environmental problems and solutions. We conclude by providing an overview of research needs and discussing a path from concrete conquest to compatibility. Our approach is inclusive but not exhaustive. Although there is previous broad-scale research on how the environmental effects of concrete can be reduced (e.g., Mehta, 2001; Suhendro, 2014), this is the first examination of the implications and future of concrete in aquatic ecosystems. We acknowledge that it is difficult to decouple the effects of concrete from its application and in many cases there are no alternative materials that can be used in lieu of concrete. Nonetheless, there are opportunities for biodiversity gains if we are more purposeful in how concrete is used in or near aquatic systems.

2. Overview and history of concrete

The most popular artificial material on Earth is not aluminum, steel, or plastic: it's concrete (Gambhir, 2013; Gagg, 2014; Geyer et al., 2017). After water, concrete is the most widely used substance on our planet (Wangler et al., 2016; Baker, 2018) and has been described as the most abundant novel rock type of the Anthropocene (Waters and Zalasiewicz, 2018). Concrete is a composite material typically composed of three elements: (1) a siliceous aggregate (e.g., sand, gravel, crushed stone, shale), (2) a cement (i.e., a binder or mortar, most commonly Portland cement), and (3) water (Pierre-Claude, 2000; Waters and Zalasiewicz, 2018). When the aggregate is combined with dry cement and water, the mixture creates a fluid slurry that can be easily poured and molded into a variety of shapes. The mixture hardens and solidifies into concrete through the chemical process termed "hydration." During cement hydration, interlocking crystals form that bind together, bonding the components to create robust, stone-like concrete (Weerheijm and Van Breugel, 2013).

Cements, the binding component of concrete, are "adhesive substances capable of uniting fragments or masses of solid matter to a compact whole" (Trout, 2019). By this definition, anthropological evidence shows that humans have been producing concrete-like materials for thousands of years. There are numerous examples of the use of cementitious binders in ancient civilizations. Earliest cases include a religious structure in Anatolia erected in 12,000–10,000 BCE, the city of Catal Hayuk built in 9000 BCE, and a double-layered concrete floor in Galilee constructed in 7000 BCE (Trout, 2019). Quicklime, created from burning limestone in wood-fired kilns at 850 °C–1000 °C, was often used as the binding element in ancient times. Although surrounded by an abundance of limestone in the Nile Valley, the primary cementitious material used in ancient Egyptian structures (e.g., Pyramids of Egypt; Regourd et al., 1988) was gypsum-based. While limestone was abundant, the fuel required to reach high temperatures to burn it was not, and impure gypsum ($CaSO_4$) could be easily burned with lower temperature, small fires (170 °C) to produce an effective binding material. Although water-soluble (compared to the more waterproof quicklime), gypsum plasters were successfully used in the arid climate of Egypt until the Roman Period (Blezard, 1998; Trout, 2019).

The Roman Empire is commonly cited as the first to develop and implement the widespread use of hydraulic setting cements in concrete, comparable to modern Portland cement (~150 BCE; Mallinson, 1986; Gani, 1997; Moropoulou et al., 2005; Jackson et al., 2014). Hydraulic setting cements, which are fast-setting, tough cements that can set and harden underwater, were evidently first developed by the Greeks (700–600 BCE) and later passed down and refined by the Romans (Kirby et al., 1956) where they were used in the construction of famous Roman structures including the Pantheon and the Colosseum (Drysdale et al., 1994). Composed of volcanic ash (pozzolana; Gotti et al., 2008), slaked lime, and sand, hydraulic cements were far superior in strength and durability compared to previous lime and sand mixtures (Gani, 1997). In his *Ten Books on Architecture* (25 BCE), the Roman author, architect, and engineer, Vitruvius provided important insights into Roman building materials and methods (Vitruvius, 1960 (reprint); Delatte, 2001). The use of mortars and plasters in ancient Greek structures is described in detail in Vitruvius' book, indicating that initial development of modern concrete was indeed identified prior to the Roman Empire (Moropoulou et al., 2005). Additionally, the construction of a pozzolanic concrete cistern in the ancient city of Kameiros, Greece has been dated back to 500 BCE (Malinowski, 1981).

From the fall of the Roman Empire (~400 CE) through to the conclusion of the Middle Ages (~1500 CE), the quality of cement, mortar, and concrete materials declined (Gani, 1997; Trout, 2019). Concrete products remained inferior and were rarely used until the Industrial Revolution in the United Kingdom when concrete technology was rediscovered and reinvented. In 1759, the British engineer John Smeaton took one of the greatest steps forward in concrete technology when he erected a new lighthouse, Smeaton's Tower, on Eddystone Rock (Gani, 1997; Blezard, 1998; Li, 2011). Driven to find a robust hydraulic setting cement capable of withstanding frequent storms and high tides, he conducted a series of experiments to investigate properties of masonry mortars. Smeaton found that the best mortars were made from impure limestones containing clay, and he demonstrated that using these materials in the formation of hydraulic cement produced a material that had rapid set times, and could be set in extreme conditions, including under water (Smeaton, 1791). Following Smeaton, the British bricklayer Joseph Aspdin patented Portland cement – the most famous and widely-used cement to date (Trout, 2019). Humans have produced a total of 500,000 Tg of concrete, with the majority of production occurring post-1950s, and with more than half of the 500,000 Tg having been created in the past 25 (1995–2020) years alone (Steffen, 2016). This equates to ~1 kg m^{-2} of the planets' surface currently being concrete covered (Waters et al., 2016).

2.1. Life cycle analysis, environmental efforts, and decommissioning of concrete

Global use of concrete has been estimated at 25–30 gigatons per year (IEA WBCSD, 2009; Miller et al., 2018; Waters and Zalasiewicz, 2018), with China alone using 6.6 gigatons in just three years (2011–2013; Gates, 2014; Swanson, 2015). The environmental burden of concrete is therefore significant in terms of resource use, pollution, greenhouse gas (GHG) emissions, and waste generation (Meyer, 2004; Gursel et al., 2014; Lee et al., 2018). Production of concrete requires copious amounts of fresh water with a water footprint estimated at 2.0–2.6 L of water per kg of cement (Bosman, 2016), and because of the sheer quantity of concrete used, its production is estimated to be responsible for ~9% of global industrial water use (Miller et al., 2018). Water demand for concrete production is increasingly being localized in regions that are already experiencing, or are projected to experience, water stress (Miller et al., 2018). Another important issue is the extraction of aggregates used in concrete, such as the sand mining in the rivers of Southeast Asia regarded as an emerging threat to riverine biodiversity (Padmalal et al., 2008). The production of concrete has been documented to release heavy metals and other toxic emissions (e.g., nitrogen oxides, sulphur dioxide) into the atmosphere (Stajanča and Eštoková, 2012), and recent research revealed that effluent from a cement plant contributed to elevated pH, increased concentrations of phosphates, nitrates, and heavy metals (e.g., lead), and higher levels of turbidity in nearby rivers (Ipeaiyeda and Obaje, 2017). In addition, concrete production is responsible for 8–9% of global CO_2 emissions, making it a primary contributor to the world's climate change crisis (Monteiro et al., 2017).

With the vast amount of concrete in use and in stock worldwide, an enormous amount of waste is generated when concrete is decommissioned. In the 1970s, the concrete industry began to address this issue, and by the 1990s, substantial research and technical advances made the recycling of concrete feasible (Tomosawa et al., 2005). However, the removal of aging concrete infrastructure is a complex process as it can release concrete fragments and dust into the air (Wu et al., 2016) that has the potential to end up in rivers, streams, and lakes. Concrete fragments and degrading cement structures can leach alkaline substances and base cations (e.g., calcium) into soils and waterways, and as a result of runoff and the dissolution of these impervious concrete surfaces, contribute to river alkalinisation (Davies et al., 2010; Kaushal et al., 2014). The long- and short-term effects of these removals are not well understood, but with dam removal becoming more common, the evidence base is growing.

Given the many effects of concrete on the environment, coupled with humanity's high dependence on it, there is great interest in improving the sustainability of concrete production. To this end, researchers can implement the life-cycle assessment (LCA) technique. LCA is a widely used, comprehensive method for evaluating and comparing environmental effects associated with all stages of a material's lifespan including extraction of raw materials, processing, production, distribution, use, repair and maintenance, and the final steps of waste disposal and/or recycling (La Rosa, 2016). Fortunately, many decision-makers and manufacturers, including those in the construction industry, are concerned with understanding and lowering the environmental effects of concrete and other building materials (Tomosawa et al., 2005; Ortiz et al., 2009). By applying LCA to concrete, it is possible to optimize social, economic, and environmental aspects, from ‘cradle to grave’ (Pacheco-Torgal, 2014) or ‘cradle to cradle’ (McDonough and Braungart, 2010). Two recent critical reviews on LCA of concrete production by Ortiz et al. (2009) and Gursel et al. (2014) indicate that most studies focus on quantifying and reducing energy consumption and GHG emissions, often failing to acknowledge other important issues like heavy metal and toxic emissions during concrete manufacturing. Furthermore, Naik and Moriconi (2005) describe concrete as a “strong, durable, low environmental impact, building material,” but explain how the production of Portland cement, an essential element of concrete, leads to the release of significant amounts of CO_2.

In addition to reducing emissions and energy usage, infrastructure designers are working to incorporate more environmentally benign, ‘green’ materials (e.g., non-polluting, lower energy demand) into concrete production. Historically, reinforcing materials, most commonly steel, would be embedded passively into concrete before it sets to ensure toughness and durability (Wang and Salmon, 1979). Today, in place of steel (an industrialized substance), recycled fibers including carpet fibers, feather fibers, and wood fibers from paper waste (Wang et al., 2000), as well as bamboo (Ghavami, 2005), have been successfully substituted as the reinforcing material. Additionally, recent studies have investigated the feasibility of using wastewater in cement production processes instead of extracting from freshwater sources (Ghrair and Al-Mashaqbeh, 2016; Babu and Ramana, 2018). Further, instead of using high-emission Portland cement, ‘biocement’ can be fabricated by special bacteria through microbially-induced calcite precipitation (MICP) which produces minerals by bacterial metabolic activity (Lee et al., 2018). Biocement is interesting in that it may not only offer a suitable alternate cementing material, but may also provide nesting habitat for ecologically important species, such as wild bees (see Hung et al., 2018).

3. Effects of concrete on aquatic ecosystems

As outlined above, the production of concrete is a global phenomenon, and aquatic ecosystems experience several interacting effects as a result. Marine and freshwater habitats are impacted directly through water extraction and pollution during concrete production, and indirectly through the role of concrete production in contributing to anthropogenic climate change. As we discuss below, these applications can alter the natural structure and functioning of aquatic ecosystems.

3.1. Alteration of fluvial systems

Some of the most important effects of concrete on fluvial ecosystems comes from the many ways that it is used in rivers and their watersheds for water management, transportation infrastructure, and hydropower generation. Concrete is used to form impoundments through the construction of dams and weirs, to channelize systems for improved stormwater management, and to manage drainage of urban centers with culverts and pipes – all of which affect the structure and function of freshwater ecosystems (Meyer, 2004; Fig. 1). There are few other alternatives to concrete for these applications which makes it difficult to decouple the effects of concrete versus its application to dam construction. Realistically, if dams were constructed out of any other semi-permanent material (e.g., steel), they would still be dams and function as barriers to organism movement. Around the world, large proportions of watersheds are covered by impervious surfaces, and streams and rivers are frequently diverted and controlled through the use of concrete infrastructure designed to efficiently drain waters away from urban areas (Paul and Meyer, 2001; Tippler et al., 2012; Fletcher et al., 2013; Reid and Tippler, 2019). This causes high levels of water runoff into drainage systems, ultimately leading to ‘urban stream syndrome’ characterized by altered hydrological regimes, channelized flow paths, elevated levels of contaminants, changes to water quality (chemistry, temperature), and losses of riparian vegetation, stream channel habitat, and biological communities (Booth and Jackson, 1997; Paul and Meyer, 2001; Walsh et al., 2005; Reid and Tippler, 2019). Yet, there are also innovations in pervious cement that create potential for infiltration (Henderson et al., 2009).

Dams and impoundments are among the most widespread uses of concrete in freshwater ecosystems, causing major habitat changes to rivers worldwide (Dynesius and Nilsson, 1994; Van Looy et al., 2014). The most obvious effects include drastic changes to channel flow paths, altered river geomorphology, and inundation of surrounding terrestrial habitats. Dams slow water velocity and alter the duration, magnitude, and frequency of flood events (Nilsson and Berggren, 2000; Stanley and Doyle, 2003; Mbaka and Wanjiru Mwaniki, 2015). Slowed flow rates cause sediments that would normally be flushed downstream to settle out and collect within reservoirs (Elosegi and Sabater, 2013; Mbaka and Wanjiru Mwaniki, 2015). These sediments often contain chemicals from urban runoff, excess organic matter, and other nutrients (e.g., fertilizer) that can cause reservoir eutrophication. Changes in flow regime can also impact temperature and dissolved oxygen concentrations both within the reservoir and below the impoundment (Petts, 1984; Nilsson and Berggren, 2000; Elosegi and Sabater, 2013; Mbaka and Wanjiru Mwaniki, 2015). Taken together, these alterations can affect the abundance and diversity of biotic communities, including fish and invertebrates (Poff et al., 1997; Nilsson and Berggren, 2000; Mbaka and Wanjiru Mwaniki, 2015). For instance, reduced connectivity among river reaches prevents organisms from migrating up and downstream as they search for optimal sediment sizes, appropriate water levels for spawning, and areas with abundant food supply or lower predation risk

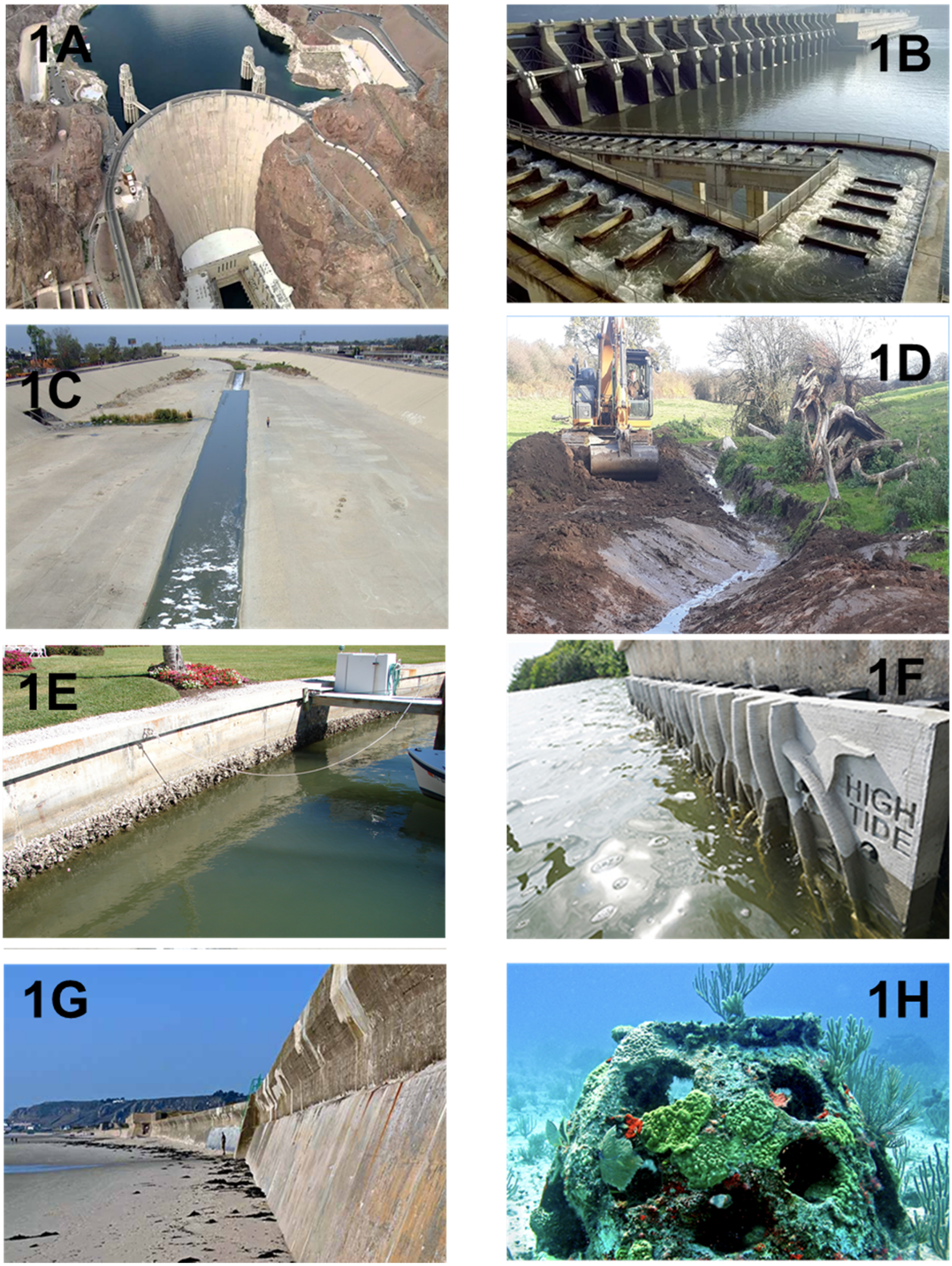

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Fig. 1. Examples of some of the ways in which concrete has been used that tends to have negative consequences on aquatic ecosystems (left column) and in ways that either replace or mitigate negative consequences of concrete (right column). (A) The Hoover Dam on the Colorado River, USA is a classic example of how concrete can facilitate the fragmentation of rivers and alteration of flows (Credit: http://redgreenandblue.org/2018/07/28/la-wants-turn-hoover-dam-worlds-largest-facility-pumped-energy-storage/). (B) A concrete fishway at the John Day Dam on the Columbia River, USA enables the upstream movement of diadromous fish species (Credit: US Army Corp of Engineers – Wikimedia Commons). (C) The Tijuana River in Mexico is channelized with concrete creating a highly modified fluvial system (Credit: Blazersand2000 - Wikimedia Commons). (D) A natural channel design installation project replacing a concrete culver in the UK (Credit: Tweed Watershed Council). (E) Canals walls are often lined with concrete and create homogeneous habitats void of complex structure (Credit: Garland Marine Construction). (F) Canal walls can be redesigned to include more habitat complexity and better emulate the function of natural systems (Credit: K. Van de Riet). (G) A concrete seawall on the English channel island of Jersey (Credit: Oliver Dixon – Wikimedia Commons). (H) Artificial reefs such as reef balls constructed out of concrete create complex habitats for aquatic organisms and can be used in lieu of seawalls to dissipate wave energy and reduce erosion (Credit: Siim1234567 – Wikimedia Commons).

(Poff et al., 1997; Nilsson and Berggren, 2000; Mbaka and Wanjiru Mwaniki, 2015). Further, altered temperatures can confound emergence and growth cues for animals in downstream reaches (Petts, 1984).

For streams and rivers running through cities, storm waters need to be directed to receiving waters rapidly to prevent flooding, and typically in urban areas floodplains will have been paved over (Scarlett et al., 2018). Excess water from urban runoff is traditionally managed through the construction of stormwater drainage networks consisting primarily of hydraulically-efficient concrete gutters, culverts, sewer pipes, and channelized rivers (Paul and Meyer, 2001; Barron et al., 2013; Braud et al., 2013). These drainage systems are designed to remove water from urban centers as efficiently as possible, with little attempt to maintain original flow patterns, preserve connections to groundwater, or to retain organic matter for filtration, a nutrient source, or habitat provisioning (Gurnell et al., 2007; Reid and Tippler, 2019). Moreover, stormwater typically receives very little treatment before being released into nearby rivers and lakes, leading to increased concentrations of pollutants in urban streams and their receiving waters (Scarlett et al., 2018). Urban catchments also have a complicated matrix of subsurface infrastructure running beneath the ground including sewage pipes, trenches, deep foundations, and tunnels (Bonneau et al., 2017). The interactions of groundwater with this underground concrete network has been named the ‘urban karst’ (Kaushal and Belt, 2012) and comprises one of the least-understood aspects of concrete effects on freshwater ecosystems (Bonneau et al., 2017).

Concrete infrastructure has several well-documented biophysical and geochemical effects on freshwater ecosystems. Concrete can affect water temperature through multiple mechanisms, including the replacement of riparian vegetation along streambanks which decreases shading and slows discharge rates (LeBlanc et al., 1997), both of which promote warming. In addition, riverbanks in riparian systems serve as important ecotones between terrestrial and aquatic ecosystems (Florsheim et al., 2008). Degradation of riparian areas, loss of contact with natural substrates, and removal of bottom complexity (e.g., removal of cobble) leads to reduced capacity for nutrient processing and uptake as well as pollutant filtering (Tippler et al., 2012; Reid and Tippler, 2019). Rivers that are extensively channelized have a lower capacity to retain sediments, nutrients, and other organic matter, reducing availability of suitable habitats and/or food sources for many macroinvertebrate (Brown, 2003; Davies et al., 2010; Tippler et al., 2012) and fish species (Elosegi and Sabater, 2013). The accumulation of pollutants is exacerbated by the higher input of contaminants to waterways dominated by concrete infrastructure where it facilitates transport, leading to alterations of water chemical regimes including elevations in pH, specific conductivity, and concentrations of bicarbonate, potassium, and calcium (Paul and Meyer, 2001; Walsh et al., 2005; Tippler et al., 2012; Reid and Tippler, 2019). Due to concrete being chemically complex and susceptible to degradation (i.e., dissolution of base cations (e.g., calcium) to surrounding waters; Grella et al., 2016), several studies have revealed that concrete is itself a direct source of pollution (Wright et al., 2011; Davies et al., 2010; Tippler et al., 2014). In sum, concrete has been shown to bring in high concentrations of pollutants through urban runoff, reduce natural filtration capacity of streams and rivers, and undergo direct chemical leaching acting simultaneously as a conduit, source, and intensifier of freshwater ecosystem pollution (Davies et al., 2010; Wright et al., 2011).

3.2. Alteration of coastal systems

The erosion of coastal shorelines is primarily driven by sea level rise, sedimentation, the building of infrastructure for commercial activities, and other climate-related impacts (e.g., large storm events). As a result, managers and city planners are tasked with finding mitigation techniques to slow or stop these processes and preserve coastal infrastructure (i.e., buildings and communities). This has been traditionally achieved through the engineering and installation of hard stabilization structures like concrete seawalls, rock armours (riprap), and breakwaters, and this is happening at an increasing rate due to a growing human population and an influx of people to coastlines despite rising sea levels and increasingly extreme weather events (Pilkey and Cooper, 2012; see Fig. 1). The installation of these structures has a wide range of effects on coastal ecosystems. There is no greater example of the direct and indirect costs of erosion control as the destruction of mangrove forests, which provide crucial habitat for a variety of recreationally and ecologically important fish as well as key ecosystem services such as buffering from storms and carbon sequestration (Rodriguez et al., 2016). Erosion control structures restrict the movement of species using these areas as migration corridors and they diminish habitat used by nesting birds and reptiles (Florsheim et al., 2008). In shallow estuarine systems, the diversity and biomass of benthic fauna can be lower in habitats using erosion control systems compared to natural shorelines (Gittman et al., 2015). For example, threatened species like sea turtles showed lower nesting success and reproductive output on beaches with seawalls when compared to those without anthropogenic barriers (Mosier, 1998). Newer, alternative measures such as “living shorelines” incorporate natural elements like planted vegetation and/or coral reefs and may provide a less-invasive way to address coastal erosion (Temmerman et al., 2013).

Docks, jetties, and piers, which are common in harbours worldwide, are either entirely or partially composed of concrete, and can directly and indirectly effect aquatic environments. These physical structures can directly alter the physical environment in numerous ways. One such way is their alteration of natural hydrologic water flows around the pilings (Ramos et al., 2016). Conversely, concrete structures like reef blocks or settlement plates may also provide new habitat for colonization of sessile microorganisms, such as coral, ascidian (sea squirt), and scyphozoan (jellyfish) larvae, which can promote their growth and additionally support other reef-related species (Reyes and Yap, 2001; Lam, 2003; Chou, 2006; Holst and Jarms, 2007; Chase et al., 2016; though see Siddik et al., 2019). For example, floating pontoons (urban marine structures made of concrete) create novel habitat for subtidal epibiota compared to rocky reefs (made of sandstone; Connell, 2000). Similarly, these structures promote attachment of epibiota, like copepods, bivalves, and bryozoans which provide opportunistic food for small fishes (Moreau et al., 2008). Docks, pilings, and jetties are also well known to attract and aggregate predators, like large teleosts and sharks (Martin et al., 2019; Wilson et al., 2019). By concentrating predators, such structures may pose a significant threat to populations of vulnerable species. In particular, predation on newly hatched flatback sea turtles (*Natator depressus*) in Australia was seven times higher adjacent to jetties compared to unmodified sections of coast because the jetties provided daytime refuges for predators that hunted along the nearshore at night (Wilson et al., 2019). Docks, jetties, and piers also indirectly affect aquatic systems by providing an unnatural platform from which recreational fishers can reliably encounter species aggregating to the structures (Barwick et al., 2004; Martin et al., 2019). This may present an "ecological trap" for species that would otherwise not be as spatially aggregated close to shore.

Coastal wetlands are among the most productive yet highly threatened ecosystems in the world (MEA, 2005), and in many areas only a fraction of the ecological productivity remains due to urbanized shorelines. Within the United States, coastal urban areas have undergone a dramatic increase in hardened shorelines, with some counties exceeding 80% of wetlands converted into concrete and riprap through infilling and shoreline alterations (Gittman et al., 2015). Conventional concrete seawalls tend to have deeper water (intentionally and unintentionally) with no natural habitat and may provide favorable conditions for the spread of invasive species (Byrnes et al., 2007; Sheehy and Vik, 2010; Vaz-Pinto et al., 2014; though see Marsden and Lansky, 2000).

The legislation designed to protect ecologically important tidal vegetation in coastal wetlands can be complicated to navigate and create mutually exclusive competition between environmental enhancement and individual property rights (Kimbel, 2000). In many cases, regulations reinforce current patterns of development in coastal areas, permitting the replacement of concrete seawalls with generous exemptions and often disincentivizing property owners from replanting tidal vegetation because of strict guidelines and costly penalties for improper trimming, removal, or alterations of the landscape (Fisher, 1998; Florida DEP, 2018). Far greater leeway exists to support an individual's right to rebuild a seawall, whereas tidal wetlands and vegetation tend to be viewed as heavily regulated and potentially risky investments. As such, there are opportunities for policy and legislative changes that could incentivize use of concrete (or alternatives) in ways that benefit biodiversity.

In contrast to the challenges of legislating coastal development, opportunities to adapt the built environment exist at multiple scales. The conversion of wetlands into high-value, developed land in many cases replicated or exceeded the linear dimension of natural edges (Layman et al., 2014). Consequently, human-made structures may have the capacity to support diverse marine life and increase filtration capacity beyond that of existing natural edges. However, the formal and material attributes of the shoreline play a critical role in the successful establishment of tidal habitat within these environments. Conventional construction standards tend to neglect ecological factors and mostly prioritize human development.

4. Concrete and environmental solutions

An obvious but often unrealistic environmental solution to the use of concrete is to simply use alternative materials or approaches. For various reasons, this is often not possible, though some positive examples do exist. For example, the last few decades have seen great developments in the realm of natural channel design in freshwater systems (Rosgen, 2011). Concrete lined, often strait, trapezoidal channels designed for rapid conveyance of water from urban areas are being transformed into meandering systems that emulate natural ones. To be clear, these systems are still engineered but use more natural materials and provide detectable biodiversity gains (e.g., Baldigo et al., 2008). Similarly, in coastal systems there have been great advances in bioengineering approaches that address coastal erosion while simultaneously creating opportunity for biodiversity gains (e.g., Barrett, 1999; Hall et al., 2017). Clearly, avoiding the use of concrete is only possible in some situations, but we encourage efforts to explore using natural alternatives consistent with bioengineering practices.

As described above, concrete has manifold negative effects on aquatic ecosystems. Yet, there are ways in which concrete can also be used to abate some of these impacts (see Fig. 1). For example, when rivers are fragmented with dams (typically constructed out of concrete), it is possible to engineer various concrete fish passage facilities (for upstream passage) and bypasses (for downstream passage) to enable ecological connectivity at barriers. Not all fish passage facilities achieve their goal (Bunt et al., 2012; i.e., in that context, connectivity is rarely restored entirely and usually represents restoration of partial connectivity), and there is a movement towards using more nature-like fish passes where possible, but fish passages constructed out of concrete remain an important tool for attempting to maintain ecological connectivity in fragmented systems, especially for migratory species. Similarly, various bypass facilities have been built to provide pathways for safe downstream passage for fish (Schilt, 2007). It is also worth noting that dams can be used to intentionally block the spread of invasive species (Rahel and McLaughlin, 2018).

In urban settings, concrete has been used to create retention (or detention) basins for stormwater management. Such basins allow for sediment (and associated contaminants) to settle, reduce downstream erosion, and can help to achieve downstream thermal targets (Griffin Jr et al., 1980; Maxted et al., 1999). Sometimes, dams are constructed for purposes beyond water extraction or electricity generation, which can carry cryptic benefits to aquatic life. For example, some dams are created with a goal of low flow augmentation to ensure adequate flows for aquatic life (and human use) during low water periods (Ponce and Lindquist, 1990).

For coastal applications, examples of recent designs that integrate natural systems into concrete structures include freestanding and modular reef blocks, tidal pools, and habitat wall panels. In instances where erosion protection or channelization is needed, there are opportunities for conservation gains by using novel concrete designs that improve erosion control and enhance habitat complexity. For example, Waltham and Sheaves (2018) found that seawalls could be successfully eco-engineered with water-retaining rock pools (i.e., inexpensive household flower boxes) to provide habitat suitable for colonization by a variety of mobile and sessile species. Additionally, researchers have been testing concrete panels that resemble the prop root structure of mangroves (see https://www.reefwall.com/about.html; https://www.sun-sentinel.com/local/broward/fl-fake-mangroves-20161223-story.html) or positioning of concrete cylinders that mimic mangrove roots (Kazemi et al., 2018; https://www.biorxiv.org/content/biorxiv/early/2018/08/22/397661.full.pdf). The prop root-like structures provide places for fish and other aquatic organisms to feed and hide, and the added features of the habitat wall panels increase the surface area of the seawall by orders of magnitude over the typical featureless seawall. Further, wall panels which integrate crushed oyster shells can temper the pH of the concrete and accelerate shellfish development on the walls. Mixed media wall panels that include fibrous and softer substrate materials (e.g., fuzzy ropes) are currently being developed with the mangrove prop root form. The approach could presumably be adapted for freshwater systems where similar environments exist or with modifications to match local conditions. See Elliott et al. (2016) for more examples of research which successfully used ecological engineering for aquatic conservation.

There have also been efforts to develop concrete tide pools that serve as natural tide pools (e.g., https://www.algemeiner.com/2019/02/08/tel-aviv-uses-underwater-concrete-structures-to-increase-marine-biodiversity/; https://sharkresearch.rsmas.miami.edu/seawalls-allowing-humans-to-build-closer-to-water-but-altering-processes-along-shorelines/). In some cases, these structures have been built directly into retaining walls (Bulleri and Chapman, 2010). Artificial reefs made from concrete castings have also been adapted to seawall applications as "living seawalls" (https://reefinnovations.com/archives/3091), and researchers showed that increasing the physical complexity (i.e., from flat to structured with crevices and ridges) of seawalls facilitated cryptobenthic fish usage by providing refuge (Ushiama et al., 2019). Essentially, any opportunity to use concrete to emulate the structure of natural systems that have since been modified (e.g., dam, hardened shoreline) could be beneficial provided that the designs are ecologically informed (Browne and Chapman, 2011). Designers and engineers must creatively explore innovative materials and applications to shift waterfront construction towards more sustainable practices.

Another excellent example of benefits accruing from use of concrete are "reef balls" (patented in 1996; Barber and Barber, 1996) to create/restore habitat for reef fish. These simple-to-construct balls have been deployed widely in coastal marine systems and there is even a foundation (i.e., the Reef Ball Foundation; https://www.reefball.org/) supporting their adoption. In the short term they provide physical structure/shelter for a variety of mobile organisms, and in the long term then serve as a substrate for the establishment of sessile organisms. There are several studies that report rapid use of these structures by fish including early life stages (Hackradt et al., 2011) as well as invertebrates (Ortiz-Prosper et al., 2001), though there is insufficient evidence regarding whether they increase productivity over the long term or are simply aggregating organisms. There is also research exploring different forms and compositions of concrete substrates to benefit coral reef restoration, although more research is needed (Spieler et al., 2001). In addition, reef balls and large concrete blocks (~100 t) have been used to dissipate energy in coastal systems (e.g., as a breakwater) and thus reduce erosion and protect coastal infrastructure (Harris, 2004, 2009; Firth et al., 2012; Pilkey and Cooper, 2012). It is worth noting that other concrete reef designs (e.g., block structures, piles of concrete aggregates) have also been shown to benefit some aquatic organisms (Sherman et al., 2002; Walker et al., 2002), further emphasizing the diverse ways in which concrete can play a role in coastal restoration.

In many of these examples, concrete is being used to make the best of a less than ideal situation. That is, concrete is being used to mitigate problems caused by concrete and other human activities, though the extent to which the examples presented here are "environmental solutions" can be debated. Nonetheless, there are ways in which concrete is being used to mitigate threats and in doing so benefits aquatic ecosystems. Nature is opportunistic, and in many cases, the adoption of even minor adjustments to articulate and soften coastal structures can increase the potential for organism colonization and environmental improvement. Furthermore, humans have much to gain from these enhancements, such as water quality improvement, erosion control, better recreational opportunities, and overall increased performance during the lifecycle of a seawall. Similar to a green roof on a building, integration of natural systems at the surface of a construction site can simultaneously sustain living systems while buffering the layers of construction behind them. Even so, the reality is that there is need to consider off-setting (Morris et al., 2006) in instances where concrete is used in or near aquatic systems.

5. Research needs and opportunities

Advances have been made in the concrete industry to mitigate some of the negative environmental effects of cement production and lifecycle costs of the material. For example, using fly ash and other additives can reduce the need for virgin materials in the mix, and alternatives to traditional Portland cement can increase strength and reduce the carbon footprint of the material. Stronger products lead to longer lifespan of the installations, which means lower costs, energy consumption, and pollution with greater timespans between replacement and repairs. Additionally, when properly mixed with pH tempering materials, concrete can provide a useable substrate for living organisms. Modifications in the production of concrete (e.g., using wastewater to produce cement) to prevent the overuse of water in the production stages may also be possible, yet more research is needed (Ghrair and Al-Mashaqbeh, 2016; Babu and Ramana, 2018). In these scenarios, designers and contractors can couple concrete infrastructure with living systems to promote more resilient designs in coastal areas, similar to oyster reef habitats (Seaman, 2007) which provide both a stronghold for numerous flora and fauna and stabilize coastlines. To shift construction towards a more ecologically-sound built environment, incremental steps, like those above, as well as paradigm-shifting alternatives (i.e., development of entirely new materials) need to be explored given that efforts to "green" the concrete industry (see Meyer, 2009) have failed to deliver the level of change needed to arrest the decline in global aquatic biodiversity.

The question of how to decommission existing concrete infrastructure in an environmentally-friendly manner exists and we must consider alternatives for future infrastructure activities. Dam removal is becoming increasingly common, yet there are many unknowns around how to best retire such facilities and reduce the release of concrete dust (Bednarek, 2001). There is also a need to develop methods for retuning infiltration and evapotranspiration towards pre-development conditions (Walsh et al., 2015) using other stormwater control measures (e.g., wetlands, ponds, infiltration systems, stormwater harvesting systems, green roofs, rain gardens, pervious pavement, infiltration trenches; Bonneau et al., 2017). Exploring alternate materials to use in stormwater management (e.g., PVC pipe; Davies et al., 2010), investigating ways to treat concrete to prevent leaching (e.g., epoxy treatment; Grella et al., 2016), and gaining a deeper understanding of the fate and condition of infiltrated water that travels through the urban karst (Bonneau et al., 2017) would be fruitful avenues for research.

There are also several outstanding research needs related to the effects of concrete on aquatic ecosystems. Very little is known about how the consequences of hardening shorelines or the use of dams varies by biome and climate regions because most research has been conducted outside of the global 'south' (i.e., countries seen as low and/or middle income in Asia, Africa, Latin America, and the Caribbean by the World Bank). Aggregate mining is also becoming common in large rivers (especially in Asia), though little is known about the effects of such activities on aquatic biodiversity or riverine processes. Identifying opportunities for mitigating concrete use – especially as it relates to use of concrete for shoreline structures – seems promising but more research is needed to determine the extent to which living seawalls or concrete artificial reef structures benefit biota and if similar benefits could be expected in freshwater ecosystems. One big question is whether such artificial habitats provide novel spawning habitat and consequentially facilitates population health or growth, or simply acts to aggregate organisms. Aggregating organisms around human-created habitats may lead to undesirable community-level interactions, particularly if habitats favour invasive species.

Documenting the extent of the problem is also an important step. Creating databases and GIS layers that include concrete-altered river reaches and shorelines would be useful for documenting the extent of the problem as well as for tracking progress in the extent to which concrete is used through time or the way in which it is deployed. For example, it would be useful to know that if there is X linear distance of seawall, how much of it is constructed in ways that increase structural habitat complexity and how its relative use is changing among regions and through time.

5.1. A path forward: from conquest to compatibility - weaning ourselves off a concrete addiction

Engineers use concrete widely in construction activities because it is dependable, robust (including resiliency to erosion and corrosion), easy to produce, and cost effective. Many of those characteristics also contribute to the manifold effects of concrete on aquatic ecosystems. It is perhaps the permanence of concrete structures that contributes to the gravity of the problem. Even the decommissioning and removal of long-standing concrete structures requires heavy equipment and/or explosives and can generate its own issues such as concrete dust (a major

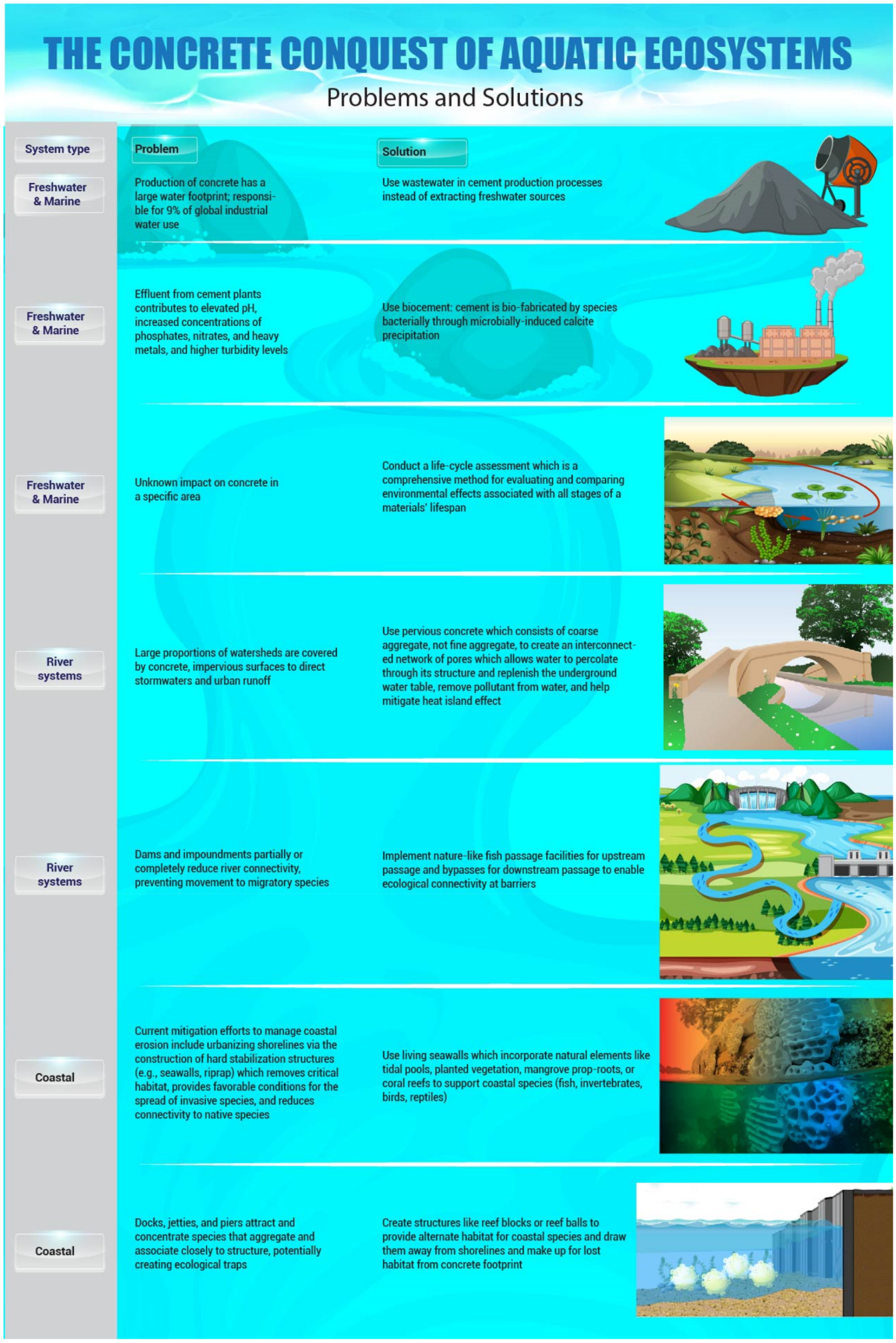

Fig. 2. Summary of key problems and solutions related to use of concrete in aquatic ecosystems.

aquatic pollutant). There is a need for continued innovation in alternative materials or the addition of constituents to concrete to make it more bio-compatible (and in some cases, pervious). Yet, central to the issue, is the need for candid discussions regarding human development in or adjacent to aquatic ecosystems. The use of setbacks and buffer zones that keep humans back from the water along with more natural stormwater conveyance systems could substantially reduce the negative effects of concrete on aquatic systems. In other words, this is as much about rethinking where, why, and how we develop cities and other infrastructure as it is about use of concrete (or a similar material). In China, the massive "sponge city" initiative is in direct response to the realization that concrete-hardened urban infrastructure and waters has contributed to massive flooding events (Xia et al., 2017). Sponge city is an ambitious initiative that aims to naturalize river corridors and create artificial wetlands to increase infiltration (Li et al., 2017). With that is potential for great benefits for aquatic biodiversity.

Our hope is that we will raise increased awareness to the continued "concrete conquest" of aquatic systems. A variety of opportunities exist to mitigate threats associated with how concrete is created and deployed (summarized in Fig. 2), though ultimately, we recognize it will likely be insufficient to stave off the biodiversity loss that is underway in our aquatic ecosystems. There is much scope for construction engineers, material scientists, urban planners, hydrologists, water resource managers, coastal zone managers, and biologists to work together to identify potential solutions that address human needs for infrastructure while also ensuring the sustained health of aquatic ecosystems. Ideally, the research needs identified here will be pursued and lead to promising developments that yield the necessary balance between what is needed to have a robust, hardened substance that can be used for construction and the reality that aquatic ecosystems require something very different. Opportunities exist to include aspects of concrete effects on aquatic systems in LEED (Leadership in Energy and Environmental Design) certification of buildings (Cidell, 2009). There are already examples of the concrete industry considering how concrete can be used to maximize LEED points (VanGeem and Marceau, 2002), so it is equally plausible to consider how points could be maximized for using materials that reduce negative effects on aquatic systems. Broader dissemination and use of emerging standards, such as the Living Building Challenge (https://living-future.org/lbc/) can also expand the definition of what sustainable, resilient, or regenerative development can be in coastal areas. Indeed, there are attempts to develop and certify "green" ports (Abood, 2007) which is an example of a coastal-specific opportunity for giving points for infrastructure choices that yield conservation gains and may exclude concrete (i.e., avoidance) or deploy it in a different manner (e.g., living seawalls). Given the global state of freshwater and coastal marine biodiversity and the manifold threats faced by aquatic systems (Beatley, 1991; Crain et al., 2009; Reid et al., 2019), it is time to consider how we can wean ourselves off of our concrete addiction and re-think how human development can be done in a manner that actually benefits aquatic resources. The status quo of concrete being the default construction material is failing aquatic ecosystems, so we recommend that efforts are made to explore alternative materials and if concrete must be used, to increase structural complexity to benefit biodiversity.

Declaration of competing interest

One of the co-authors (Dr. Keith Van de Riet) is the founder and principle researcher at "Mangrove Reef Walls," a company developing seawall/canal structures that use concrete to increase structural complexity. He was asked to join the authorship team given his expertise in the use of concrete in and around aquatic systems.

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