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Review

Consequences of "natural" disasters on aquatic life and habitats

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Abstract

"Natural" disasters (also known as geophysical disasters) involve physical processes that have a direct or indirect impact on humans. These events occur rapidly and may have severe consequences for resident flora and fauna as their habitat undergoes dramatic and sudden change. Although most studies have focused on the impact of natural disasters on humans and terrestrial systems, geophysical disasters can also impact aquatic ecosystems. Here, we provide a synthesis on the effects of the most common and destructive geophysical disasters on aquatic systems (life and habitat). Our approach spanned realms (i.e., freshwater, estuarine, and marine) and taxa (i.e., plants, vertebrates, invertebrates, and microbes) and included floods, droughts, wildfires, hurricanes/cyclones/typhoons, tornadoes, dust storms, ice storms, avalanches (snow), landslides, volcanic eruptions, earthquakes (including limnic eruptions), tsunamis, and cosmic events. Many geophysical disasters have dramatic effects on aquatic systems. The evidence base is somewhat limited for some natural disasters because transient events (e.g., tornadoes and floods) are difficult to study. Most natural disaster studies focus on geology/geomorphology and hazard assessment for humans and infrastructure. However, the destruction of aquatic systems can impact humans indirectly through loss of food security, cultural services, or livelihoods. Many geophysical disasters interact in complex ways (e.g., wildfires often lead to landslides and flooding) and can be magnified or otherwise mediated by human activities. Our synthesis reveals that geophysical events influence aquatic ecosystems, often in negative ways, yet systems can be resilient provided that effects are not compounded by anthropogenic stressors. It is difficult to predict or prevent geophysical disasters but understanding how aquatic ecosystems are influenced by geophysical events is important given the inherent connection between peoples and aquatic ecosystems.

Key words: Geophysical disasters, natural disasters, natural hazards, aquatic ecosystems, ecosystem services, threats

Introduction

"Natural" disasters can be defined as "some rapid, instantaneous or profound impact of the natural environment upon the socioeconomic system" (Alexander 2018) usually with a restricted temporal and spatial scale (i.e., rarely global; Turner 1976). These events are often of great magnitude and can thus be further defined as "any manifestations in a geophysical system (i.e., lithosphere, biosphere, or atmosphere) which differs substantially or significantly from the mean [state of the system]" (Alexander 2018). The term "natural disaster" is, of course, a misnomer, because every aspect of the impacts—what translates a hazardous event into a disaster—are heavily conditioned by human factors (Smith 2006). Thus, herein, we use the term *geophysical disaster*. For there to be a disaster, there must be a geohazard, whereby the physical process has a direct or indirect impact on humans. In its most obvious form, one could think about the direct harm of a hurricane, where humans are killed and injured, key infrastructure is destroyed or damaged, and essential services such as water, electricity, and communications are disrupted. As the human population has expanded and settled in diverse environments around the globe, the risk posed by geophysical disasters has risen (e.g., Donner and Rodriguez 2008). Encroachment on coastlines, floodplains, forests, and mountains all represent increased exposure of humans and human infrastructure to hazardous phenomena such as floods, landslides, and tsunamis. The United Nations declared 1990–2000 the Decade for Natural Disaster Reduction (Mitchell 1988) emphasizing the heavy toll of disasters on society (Pelling 2001) and the economy (Benson and Clay 2004) along with the recognition that through better planning the impacts from such hazards could be mitigated (Oaks and Bender 1990; Board on Natural Disasters 1999).

Given the massive toll of geophysical disasters on humans (average annual mortality of ~ 60 000 people; Ritchie and Roser 2019), hundreds of billions in economic costs, (Guha-Sapir et al. 2013) and the apparent growing frequency and magnitude of these events (some of which is driven by anthropogenic climate change; Van Aalst 2006; Banholzer et al. 2014)—or human activities such as drilling (Ellsworth 2013), it is not surprising that there has been a surge of research on the topic with a focus on prediction, preparedness, management, and mitigation (Sahil 2021). However, geophysical disasters also have direct and indirect effects on plants and animals. The environment is constantly changing for plants and animals; slow changes such as gradual temperature warming or changes in oxygen and salinity may be described as ramp stressors (Bender et al. 1984). Many geophysical disasters occur rapidly (Niemi et al. 1990) and require animals to adopt emergency life history stages (Wingfield et al. 1998) as their environment undergoes dramatic and sudden change. For example, wildfires, avalanches, and landslides can displace or kill terrestrial organisms and these effects have been well documented (e.g., reviewed in Zhang et al. 2018; Kaur et al. 2019; Rondeau et al. 2020). However, geophysical disasters can also impact aquatic ecosystems. These disasters have an important role in the succession of ecosystems and the maintenance of biological diversity, but the increasing frequency and severity is troubling given that much of the human infrastructure system is not designed or prepared for increasing severity or frequency of disastrous geophysical conditions. There is much great interest in documenting the response of these aquatic systems to disasters as well as understanding the capacity for species to detect or prepare for sudden changes in their environment.

Water covers 71% of the earth and some geophysical disasters (e.g., hurricanes, floods, and tsunamis) by definition involve interaction with aquatic systems. Aquatic systems contain much life that is often cryptic yet generates numerous ecosystem services including those of direct benefit to humans including nutritional security and supporting livelihoods (Peterson and Lubchenco 1997; Lynch et al. 2016). This is particularly the case in developing countries, which is also where disproportionate effects of geophysical disasters are often felt (Benson and Clay 2000). Aquatic species, especially in freshwater (Woodward et al. 2010; Doney et al. 2012) or in specific marine habitats (e.g., coral reefs (Hoegh-Guldberg 1999) and estuaries (Dyer 2021)), are known to be among the most vulnerable taxa on the planet to ongoing climatic change, which may be exacerbated by stressors that result in sudden and potentially irreversible changes to the stable states of lakes, rivers, estuaries, or marine environments. However, to the best of our knowledge, there has yet to be a review of what is known about the effects of geophysical disasters on aquatic systems. To that end, we provide a synthesis on the effects of the most common and destructive geophysical disasters on aquatic life and habitat. Our approach spans realms (i.e., freshwater, estuarine, marine) and taxa (i.e., plants, vertebrates, invertebrates, and microbes). We focused on floods, droughts, wildfires, hurricanes/cyclones/typhoons, tornadoes, dust storms, ice storms, avalanches (snow), landslides, volcanic eruptions, earthquakes (including limnic eruptions), and tsunamis (see Fig. 1). We have excluded discussion of cold and warm snaps and routine weather events (e.g., snow, lightning, and hail), given that there is much written about the effects of temperature and short-term environmental variability on aquatic life (e.g., Fry 1971; Bhaud et al. 1995; Tittensor et al. 2010). Epidemics, although timely and relevant to aquatic life (i.e., the COVID-19 pandemic; Cooke et al. 2021), are also outside the scope of this paper given that they have a largely biological basis unlike the other disasters that we cover here.

Disaster types and consequences on aquatic life and habitats

Disaster types are organized in what we deem a logical order, focusing initially on events that are largely driven by climate (e.g., floods, drought, hurricanes, etc.) and then moving on toward geologically driven events (e.g., volcanic eruptions and earthquakes) and ending on cosmic events which is somewhat unique. We acknowledge that the evidence base associated with these topics is highly variable. For example, floods, droughts, and wildfires have been quite well studied with respect to their impacts on aquatic systems while for others very little is known. Nonetheless, we attempt to provide equal coverage but necessarily refer readers to other focused syntheses for some of the more studied disasters (see Table 1 for list of key syntheses where relevant).

Drought

Drought generally encompasses prolonged dry periods, where there is a shortage of water often as a result of a lack of precipitation (Kallis 2008). While drought is a natural process, it has been exacerbated by humans through effects on global warming, construction of impervious surfaces, and water extraction, which affect the frequency, severity, and duration of drought (Bond et al. 2008). Impacts occur across spatial and temporal scales with most studies focusing on short duration droughts (months to a year) in local stream reaches (Matthews and Marsh-Matthews 2003). In standing water, drought associated with water abstraction may decrease lake levels and alter habitat for organisms (Glassic and Gaeta 2019). In flowing water, drought may also reduce habitat availability (Bond et al. 2008). Drought not only affects freshwater systems, but alterations to freshwater inflow also impacts estuarine and marine ecosystems

Fig. 1. Natural disasters have diverse impacts on aquatic ecosystems as highlighted in the examples illustrated here.

(Gillanders and Kingsford 2002; Lennox et al. 2019). Droughts contribute cumulatively to other extreme environmental perturbations (floods, cyclones, heat waves, fire, and dust storms). Severe drought can increase conditions suitable for wildfires. For example, severe drought led to fires in a tributary of the Amazon River that killed most of the floodplain forest trees with little evidence of regeneration even after a decade of recovery (Flores et al. 2014).

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Table 1. Summary of how different types of disasters impact life in different aquatic realms, the relative level of knowledge we have about those impacts, and key synthesis articles on the impacts of a given type of disaster (where available—we only cite truly synthetic papers such as reviews).

Type of disaster	Aquatic realm	Level of knowledge	Key syntheses
Floods	Inland waters (especially rivers) and estuaries	Very well studied, particularly in inland riverine systems	Wydoski and Wick 2000; Talbot et al. 2018; Merz et al. 2021
Droughts	Inland waters and estuaries	Very well studied, particularly in inland rivers, lakes, and wetlands; much of the research based in Australia	Bond et al. 2008; Lake 2003, 2011
Wildfires	Inland waters, estuaries, and coastal marine	Well studied with much recent research reflecting increasing intensity of such events	Gresswell 1999; Bixby et al. 2015; Gomez Isaza et al. 2022
Hurricanes (including cyclones and typhoons)	Inland waters, estuaries, coastal marine, and offshore marine	Well studied with much recent interest on impacts on vertebrate life	Waide 1991; Greening et al. 2006; Mallin and Corbett 2006; Wang et al. 2016
Tornadoes	Inland waters, estuaries, and coastal marine	Poorly studied—a few empirical studies	NA
Dust storms	Inland waters, estuaries, coastal marine, and offshore marine	Some research although tends to focus on long-term changes in water chemistry rather than biological impacts; most research from Middle East region	Griffin and Kellogg 2004
Ice storms	Inland waters (usually small rivers)	Poorly studied—a few empirical studies	NA
Avalanches	Inland waters, estuaries, and coastal marine	Poorly studied—a few empirical studies	Muller and Straub 2016
Landslides	Inland waters, estuaries, and coastal marine	Some research on aquatic impacts although mostly from the Pacific Northwest of North America	Geertsema and Pojar 2007; Geertsema et al. 2009
Volcanic eruptions	Inland waters, estuaries, and coastal marine	Extensive research but typically focused around long-term study sites (e.g., Mount St. Helens in the USA)	Swanson and Crisafulli 2018; Carrillo and Díaz-Villanueva 2021
Earthquakes	Inland waters, estuaries, coastal marine, and offshore marine	Poorly studied	Freund and Stolc 2013
Limnic eruptions	Inland waters (usually volcanic lakes)	Some research with focus on lakes that are subject to such events—mostly in Africa and South America	Rouwet et al. 2014
Tsunamis	Inland waters (near coasts), estuaries, coastal marine, and offshore marine	Increasing body of research following relatively recent tsunamis over last decade, mostly in Asia	Urabe and Nakashizuka 2016
Cosmic events	Inland waters, estuaries, coastal marine, and offshore marine	Relatively little research on this topic, mostly lab based	NA

Reduced freshwater inflow leads to low allochthonous organic matter and nutrient inputs which may impact nearshore phytoplankton (Wetz and Yoskowitz 2013). For example, reduced freshwater discharge into the Nile delta, which was similar to prolonged drought, meant that seasonal phytoplankton blooms did not occur, impacting Mediterranean fisheries (Oczkowski et al. 2009). It was not until anthropogenic nutrient loadings through fertiliser and sewage discharge increased that the fishery started to recover (Oczkowski et al. 2009). Stream organisms including fish and invertebrates are impacted by changes to flow and subsequent impacts on water quality (Bond et al. 2008). Food resources for organisms may also be depleted, increasing potential for biotic interactions (competition and predation). In coastal marine systems, habitats including mangroves, saltmarsh, and seagrass have all been impacted by drought (Duke et al. 2017). Saltmarsh dieback associated with drought has been recorded along the Gulf Coast and South Atlantic Bight in the USA during the early 2000 s (McKee et al. 2004; Silliman et al. 2005; Hughes et al. 2012). Studies have also reported reductions in seagrass associated with drought linked to reductions in freshwater and nutrient inputs (Hirst et al. 2016), high salinity (Wilson and Dunton 2018), or failure of a facultative mutualistic relationship (de Fouw et al. 2016). Reductions in extent of habitats will presumably impact aquatic organisms.

Floods

Rivers flood when water input exceeds the capacity for the system to drain or buffer the sudden increase in water input, either from rapid melting of snow or ice, torrential rain, or sudden changes in regulation by dams. Floods cause numerous changes to fluvial systems including increasing water depth, accelerating water velocity, widening channels, regrading sediment, and reducing water temperatures. There may also be potential changes to turbidity, pH, conductivity, salinity, and concentration of pollutants. Lateral expansion of the water into the floodplain may draw pollutants into the water, as was recorded in the 2002 flood on the River Elbe (Einsporn et al. 2005). Extreme flooding has also been implicated as a major catalyst for invasions of non-native species where rivers connect with artificial ponds, rearing facilities, or impoundments (e.g., Kumar et al. 2019). Freshwater effluent in estuaries will also suddenly freshen these ecotones and alter coastal marine communities in the interim (Pollack et al. 2011; Bailey and Secor 2016). The incredible force of water to move silt, sand, gravel, and even boulders has a crucial role in the form and function of rivers (Gupta and Fox 1974; Hauer and Habersack 2009) and estuary mouths, which drives the ecology of the species that live there.

When flooding occurs, animals may take refuge and survive in eddies, backchannels, or tributaries where the rapid increase in flow is buffered, eventually recolonizing when flows diminish (Koizumi et al. 2013) unless they have been washed beyond barriers that restrict upstream passage. For counterparts remaining in the main channel exposed to the full force of the flood, including larvae and eggs, many will be carried downstream and will likely die in harsh environments or become stranded in areas that dewater when floodwaters recede (Nagrodski et al. 2012; Death et al. 2015). Immobile species such as plants and sessile invertebrates will be forced to adapt to the conditions or die. For example, coral bleaching in Hawai'i was exacerbated by the synergistic effect of warm temperatures and freshwater input from flooding in 2014 (Bahr et al. 2015). Eastern oysters (*Perkinsus marinus*) in a Texas estuary responded to flooding with reduced oyster abundance and growth but their rapid life cycle facilitated rapid recolonization (Pollack et al. 2011). As mobile species recolonize following catastrophic floods, they are likely to find themselves occupying new habitat as the river channels have changed course, with re-graded sediments and new structure adopted from the flood debris (Death et al. 2015) as well as shifting delta and estuary structure (Cooper 2002).

Wildfire

Fire is a natural disturbance in many forests across the globe; however, uncontrollable and high intensity wildfire can have catastrophic impacts on social, economic, and environmental systems (United Nations Environment Program 2022). The effect of wildfire on aquatic ecosystems will depend on the fire characteristics (extent, duration, and severity) as well as local factors (e.g., physical, biochemical and chemical elements of the watershed and previous evolutionary exposure to fire regimes; Gresswell 1999; Bixby et al. 2015; United Nations Environment Program 2022). Short-term, immediate effects of wildfire can include a reduction in plant biomass and canopy cover, increased runoff and erosion, altered soil and sediment dynamics, nutrient mobilization, and ash deposition (Bixby et al. 2015). Wildfires that occur near human activities such as homes and mining increase the risk of toxicants (e.g., benzene, arsenic, and lead) accumulating in the watershed (Burke et al. 2013; Murphy et al. 2020*a*). Collectively, these acute wildfire effects tend to negatively impact aquatic life. Fish, amphibian, and invertebrate populations as well as algal cover and biomass all commonly decrease immediately after wildfire (Gresswell 1999; Verkaik et al. 2013; Bixby et al. 2015; Silva et al. 2020). Over the longer term (years), stream biota recovery dynamics from wildfire are highly variable (Robinne et al. 2020) and have been linked to the burn severity of the riparian vegetation, whether debris flows occurred, and the connectivity of the watershed (Dunham et al. 2003; Minshall 2003; Verkaik et al. 2013). Severely burned riparian vegetation results in canopy removal and thus increased light and altered temperature regimes (Verkaik et al. 2013). Heavy rains after a fire can cause floods and scouring, resulting in channel reorganization and sediment deposition (Tuckett and Koetsier 2018). More severely impacted streams may have delayed recovery and altered macroinvertebrate aquatic community composition, even 10 years after a fire (Tuckett and Koetsier 2018). However, in connected watersheds, fish recovery can occur within a few years (Dunham et al. 2003).

Hurricanes/cyclones/typhoons

Hurricanes or tropical cyclones are destructive storms characterized by excessive wind speeds (typically with winds exceeding 119 km/h). Geophysical effects of hurricanes on aquatic systems include rapid fluctuations in temperature, drops in barometric pressure, and heavy rains as well as wind-driven disturbances to surface and subsurface waters (e.g., currents, waves, and surge), substrate and adjacent land. Such geophysical effects can have direct and indirect biological impacts on aquatic life. Storm impacts are greatest for immobile species or life-stages and/or those confined to closed systems, which cannot flee the path of a hurricane. For example, coral reefs can experience breakage and dislodgement with the extent of damage related to wind intensity (Fabricius et al. 2008). In Florida, USA, the passing of a hurricane shifted macroinvertebrate and benthic fish communities via reduction to water salinity and increases in depth (Zink et al. 2020) while a hurricane passing over saltwater marshes in Galveston Bay, Texas reduced nekton abundance but increased diversity (Oakley and Guillen 2020). Peierls et al. (2003) documented increases in phytoplankton following hurricanes with return to normal coinciding with when salinity increased to pre-storm levels more than 1 year after disturbance. Off the west coast of Florida, 69% mortality to pre-hatchling sea turtles was attributed to drowning from storm surge flooding of nests (Milton et al. 1994). Mobile species, able to flee in the wake of the storm, are seemingly less vulnerable to hurricanes. For example, when Hurricane Irene hit the US Mid-Atlantic Bight, many satellite-tagged juvenile and adult loggerhead sea turtles (*Caretta caretta*) moved north of their pre-storm foraging grounds (Crowe et al. 2020). In response to dropping barometric pressure in advance of a hurricane, common snook (*Centropomus undecimalis*) have been found to move down river, potentially exiting the river for deeper marine water that is less exposed to physical

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disturbance (Massie et al. 2020). Similarly, juvenile blacktip (*Carcharhinus limbatus*) sharks have been found to flee shallow water nursery habitats for adjacent deep-water areas in response to a dropping barometric pressure in the wake of a hurricane (Heupel et al. 2003). However, some juvenile sharks failed to return to their nursery areas following the hurricane, possibly due to predation. Unlike smaller sharks, Gutowsky et al. (2021) found variable responses of large sharks to hurricanes, with adult tiger sharks (*Galeocerdo cuvier*) remaining in shallow waters of the Bahamas, even when the eye of a hurricane passed overhead, with numbers of these apex predators at the site increasing for 2 weeks following the storm. The study hypothesized that these tiger sharks may have been scavenging on animals that died from the storm (Gutowsky et al. 2021). Teasing apart the relative consequences of physical damage versus changes in water chemistry arising from flooding have proved challenging but will be important for determining how to best mitigate future hurricane damage (Liu et al. 2021).

Tornadoes

Tornadoes and waterspouts (defined as tornadoes that cross from land onto water or originate over water) can have profound impacts on aquatic ecosystems and life within them. For example, people have been recording instances of fauna—including snails, jellyfish, crabs, frogs, and fishes—falling from the sky ("animal rain") for hundreds of years (Gudger 1929), a phenomenon largely attributed to waterspouts and other strong wind events (Morgan 2012; Allaby 2014). Such events have become the focus of books (e.g., Dennis 2013) and are frequently documented in the popular media. "Animal rain" events, primarily of fish, have also been documented in the academic literature (e.g., James 1894; Bajkov 1949; Dees 1961; Pigg and Gibbs 1998; Roberts 1999). Yet, our understanding of this mode of dispersal is poor (Unmack 2001). Wind-induced movement may be an important method of dispersal over short distances for some taxa such as zooplankton (Havel and Shurin 2004). The extreme wind velocities and intense rain associated with tornadoes can cause physical damage to aquatic and riparian habitats including aggradation (Pierce 2016), boulder dislodgement (de Lange et al. 2006) and possible rockslides that could damage aquatic life and habitat; vegetation removal (Nelson et al. 2008) that could allow more solar radiation to reach the water's surface and thereby increase water temperatures; and changes in water levels associated with the seiche effect (Chaston 1979). Although there are several potential negative consequences associated with tornadoes, they can also create new opportunities for plants and animals to thrive. For example, Nelson et al. (2008) observed both increases to woody stem density following soil disturbance and more shade-tolerant and -intolerant plant species with canopy removal. Enhanced plant growth in riparian zones may benefit aquatic systems by creating more shade and thus reducing water temperatures. Blowdowns from tornadoes can also deposit coarse woody debris, which serves as important habitat for fishes (see Harmon et al. 1986) and increases the amount of allochthonous nutrient inputs. In some cases, tornadoes can create habitats such as breeding pools for Cope's gray tree frogs *Hyla chrysoscelis* (Smith 2013) and new sediment layers (Card 1997). Overall, there is a paucity of research on the impact of tornadoes on aquatic life and habitats, but the impact of tornadoes will likely be variable, localized, and short-term.

Dust storms

Dust or sand storms involve major meteorological processes (e.g., wind) that move inordinate amounts of particles such as dust and sand, especially in the drylands of north Africa and the Arabian peninsula (Goudie 2009). Dust storms transfer massive volumes of particulate matter into lakes and seas given that sediment chronology can be used to detect such events going back as far as 2000 years ago (e.g., Chen et al. 2013). In addition to transporting dust particles, dust storms can disperse metals (Gunawardena et al. 2013), nutrients (Shi et al. 2013), prokaryotic and eukaryotic algae (Rahav et al. 2016), and even pathogenic microorganisms (Gonzalez-Martin et al. 2014) all of which could impact aquatic systems. Algal blooms in marine systems are reasonably common following dust storms as a result of a pulse of nutrient inputs (Bali et al. 2019). Hallegraeff et al. (2014) documented fungal blooms in coastal water following a major dust storm in Australia which did not prove harmful (e.g., non-toxic to fish, minor impacts on algae and coral symbionts), but raised the possibility of other dust storm-driven pathogens that are more pathogenic being transported in future dust storms. Given the transient nature of these events, there is little known about effects on most aquatic animals (Goudie 2009). Interestingly, the creation of reservoirs in areas that typically have dry stream beds have led to reductions in dust storm activity in Mexico (Jáuregui 1989). There is no doubt that dust storms play important roles in distributing nutrients and sedimentary materials (on a global scale) that are key elements of freshwater and marine systems yet in general any negative effects (e.g., algal blooms and microbe deposition) tend to be rather localized and short lived.

Ice storms

Ice storms occur at locations with precipitation events along frontal transition zones separating warm and cold air masses. Most attention to the biotic impacts of ice storms has focused on the extensive breakage of tree canopy branches in forested ecosystems (Rhoads et al. 2002) that subsequently deposits wood throughout forested watersheds, including stream and lake shoreline environments (Kraft et al. 2002; Millward et al. 2010). As a result, this wood accumulation has substantial impacts on biota within these aquatic ecosystems. Accumulations of wood in streams—commonly referred to as debris dams—are more frequent in number and larger in volume following ice storms (Kraft et al. 2002). These large accumulations of wood have been shown to increase the diversity and abundance of aquatic invertebrates in forested headwater streams (particularly taxa such as Ephemeroptera, Plecoptera, and Trichoptera) compared to riffle habitats (Baillie et al. 2019). Debris dams have been consistently demonstrated to provide habitat for many species of fish

(Bisson et al. 1987), and brook trout abundance in forested stream habitats increased in response to the presence of debris dams resulting from an intense ice storm in the northeastern U.S. (Warren and Kraft 2003).

Another set of well-studied biotic impacts from ice storm disturbance events has focused on the intersection of tree damage and altered forest processes that reduce nutrient uptake, thereby increasing primary production in downslope streams. This was extensively documented at the Hubbard Brook Experimental Forest in New Hampshire, USA, where increased downstream export of dissolved inorganic nitrogen was observed following an intense ice storm (Houlton et al. 2003). Tree canopy damage also increases light availability, reducing light limitation of primary production in streams within forested watersheds (Stovall et al. 2009). Although the Intergovernmental Panel on Climate Change places low confidence in predicting whether climate change will increase the frequency of ice storms (Ranasinghe et al. 2021), IPCC model projections indicate that the location of freezing rain events responsible for ice storms will change in Europe and North America (Ning and Bradley 2015; Kämäräinen et al. 2018).

Landslides

Landslides involve disturbances in the stability of a slope and are often triggered by other disasters (e.g., droughts and earthquakes) whereas mudslides tend to be induced by the rapid accumulation of water in the ground. These events are sufficiently well researched that there is a realm of study known as "landslide ecology" (Walker and Shiels 2012) with diverse environmental effects well documented (Geertsema et al. 2009). Slides are most common in areas with steep slopes such as river valleys. A major landslide on the Fraser River of British Columbia around 1911 (the Hells Gate slide; see Evenden 2004) temporarily impeded the upstream spawning migration of Pacific salmon in the largest salmon producing river in Canada. A second major landslide on the Fraser River in 2018 (the Big Bar slide; Murphy et al. 2020*b*) is still being addressed as of January 2022, but only with efforts to remove both the 1911 and 2018 slides has fish passage been somewhat restored. Nonetheless, the effects of the Hells Gate slide are still evident today given the collapse of some populations (Hobbs and Wolfe 2008) and the legacy of the reach being the most hydraulically complex and physiological challenging in the Fraser (Hinch et al. 1996). Landslides are known for their recruitment of coarse woody debris to fluvial systems (Ruiz-Villanueva et al. 2014) which helps to create diverse and complex habitats that benefit invertebrates and fish (Harmon et al. 1986; Gurnell et al. 1995). However, they can also mobilize sediment which can degrade habitat and smother spawning grounds for lithophilic fish (Schuster et al. 1989). In some alpine areas, slides can lead to full damming of fluvial systems such that they lead to the development of lakes (Butler and Malanson 1993; Shapley et al. 2019), which represents a major aquatic transition (i.e., from lotic to lentic) but also creates new habitats that can be exploited by some species and cause phase shifts in the plant and animal communities (see Logan and Schuster 1991).

Landslides can also impact marine life. An inland landslide in California during the Pleistocene not only impeded the migration of anadromous fish leading to genetic change, but also impeded the downstream transport of sediment to the estuary and offshore areas (Mackey et al. 2011). Landslides instigated by storms have been attributed with the transport of sediment and coarse woody debris to the ocean (West et al. 2011), while coastal landslides have led to pulses in sedimentation (Hapke et al. 2003) and contributed to coastal degradation (Nichols et al. 2019) by smothering plants such as macro algae (including kelp forests; Oliver et al. 1999). Indeed, marine coastal organisms are often impacted by the so-called "triad of sediment inputs from landslide activity: direct burial, sediment scouring, and suspended sediment plumes" (Schuster and Highland 2003) that can impede respiration (e.g., of fish or invertebrates) and light penetration (Oliver et al. 1999). Slides can also happen entirely underwater (i.e., submarine landslides) but they are often at great depth and we know more about their physical properties than their biological consequences (Shuster and Highland 2003).

Avalanches (snow)

Similar to landslides, snow avalanches are a slope disturbance and a source of debris. Snow avalanches are a common disturbance, where avalanche paths intersect with water, but, to the best of our knowledge, there has been no research on the effects of snow avalanches on aquatic systems. Nevertheless, we propose direct and indirect effects of these disturbances on aquatic systems below. An example of a direct effect of snow avalanches is the abrupt natural damming of mountain rivers (Butler 1989; Richardson and Reynolds 2000). Outburst floods caused by failure of snow avalanche dams have been reported for several mountain ranges (Andes of Argentina (King 1934); the European Alps (Allix 1924); northern Scandinavia (Rapp 1960); the Himalayas (Richardson and Reynolds 2000); and the New Zealand Alps (Ackroyd 1987)) and may have profound impacts on aquatic organisms and their habitats.

Indirect effects of snow avalanches on aquatic life likely occur based on the physical disturbance avalanches cause to wetted and riparian habitats in streams, lakes, and marine coastlines. For example, snow avalanches structure riparian vegetation communities in their paths and termini ("snow avalanche ecology"; Butler 1979; Johnson 1987). Landform creation and modification is another indirect link between snow avalanches and aquatic systems given the important role of geomorphology in the maintenance of aquatic habitat for vertebrates and fishes (Vannote et al. 1980). For example, snow avalanches that terminate in stream channels redistribute and add debris on the stream bed (Luckman 1978). Boulders and woody debris stabilize channels and create pools that provide cover for fish and invertebrates (Ackroyd 1987; Lanka et al. 1987). The recurring action of avalanches at the foot of slopes can also form erosional depressions that become water-filled ponds known as snow avalanche impact pools (Johnson and Smith 2010). Snow avalanches that terminate in lakes or reservoirs contribute to sediment budgets (Vasskog et al. 2011). Disturbances from snow avalanches

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are likely a contributing factor to the vertical and horizontal heterogeneities found in the substrates of mountain lakes. Avalanches that terminate in the ocean occur in mountainous coastlines (e.g., Iceland; Johannesson 2001). The literature on marine-terminating snow avalanches is focused on hazards to public safety, but snow avalanches could modify the physical structure of coastlines, potentially affecting marine invertebrates, fishes, corals, and plants. We suggest that snow avalanches have a subsidiary role in modifying aquatic life because they have a localized spatial distribution (Luckman 1978) and many snow avalanches contain no debris because they do not come into contact with underlying ground and the ground is typically frozen (Rapp 1960). The contribution of snow avalanches to the physical landscape tends to be masked by the more obvious geomorphic processes involved in debris transport such as landslides/rockfalls, mud-debris flows, and fluvial activity (Luckman 1978).

Volcanic eruption

Volcanoes are incisions in the Earth's crust where gas and magma can move between the lithosphere and the biosphere. Volcanic eruptions, when gas and matter are discharged from subterranean chambers onto land or into the sea, involve numerous geophysical processes including lava flows, sector collapses and debris avalanches, pyroclastic density currents, lahars (volcanic mudflows), tephra falls, dome building, and chemical plumes, and all or a subset of these may occur during any single eruption event (Swanson and Major 2005; Crisafulli et al. 2015). Volcanism may stand apart from many other forms of natural disturbance because of its diversity of disturbance processes, large spatial extent (tens to thousands of kilometers), and potentially interacting physicochemical processes that can generate massive impacts and enduring effects. The majority of scientific inquiry on biotic response to volcanism has been in terrestrial ecosystems, with a strong emphasis on vegetation and arthropods and succession following volcanic disturbance (Crisafulli et al. 2015). Nonetheless, there is a growing body of literature on riverine, lacustrine, and marine environments to complement this knowledge and establish a broader understanding of how the physical and chemical impacts of volcanism affect water and its inhabitants.

A primary driver of change in both lakes and rivers is inputs of inorganic ejecta (tephra fall) or flow material (debris avalanche, lahar, pyroclastic flow deposits; matter subsidies), as well as inputs of biological constituents of the surrounding terrestrial biota (i.e., nutrient subsidies; Dale et al. 2005*a*; Crisafulli et al. 2015). The effects of these inputs range from highly ephemeral to protracted in duration, and from relatively minor to profound in volume and extent. Volcanic effects on biota vary between flowing and non-flowing aquatic systems. For example, the deposition of volcanic products into lakes and oceans often have a fertilization effect from nutrient and mineral enrichment of the allochthonous matter (Olgun et al. 2013) that has a bottom-up effect on community structure. On the other hand, large tephra fall events may reduce phytoplankton primary productivity by reducing light transmission because of suspended ash or by extensive mats of floating pumice (Carrillo and Díaz-Villanueva 2021). Whether enrichment or alteration of optical properties, these effects are relatively ephemeral compared to lakes that experience changes in basin morphometry, gross biogeochemical transformations, and enormous log rafts as happened at Spirit Lake following the 1980 eruption of Mount St. Helens, USA (Dale et al. 2005*a*,*b*). For river systems, sediment is the primary driver of ecological responses and may be a protracted problem lasting years to decades in the case of sector collapses from eruptions (Major et al. 2018) or > 10 m thick pyroclastic deposits (Hayes et al. 2002) versus thinner deposits (<1 m) established by tephra fall events (Arnalds 2013). Sediment directly kills biota through abrasion of the epidermis of smothering of the respiratory organs and indirectly through habitat alteration by filling stream bed interstices and changes to channel morphometry (Bisson et al. 2005). In high-gradient streams, fines are moved through the system during freshets or floods, exposing coarse substrates and altering habitat conditions. Many aquatic organisms are vagile (e.g., insects, amphibians, and fish) and quickly recolonize depopulated systems once the physical conditions improve via local immigration. However, volcanic blockages may create barriers to dispersal leading to long-term community reorganization. In the case of both lakes and rivers, different volcanic processes can lead to enormous recruitment of wood or partial to complete removal, with long-term consequences for biotic reassembly and community structure.

Earthquakes

Earthquakes trigger changes of the hydrological regime of springs, streams, lakes, groundwaters, and marine waters (Wang and Manga 2010*a*; Lubick 2011; Zhang et al. 2021), and are mainly related to the dynamic responses associated with seismic waves (Wang and Manga 2010*b*). Marine earthquakes alter the structure and function of deep-sea ecosystems (Chunga-Llauce and Pacheco 2021). However, knowledge of their effects on mobile large vertebrates are scant, with the exception of the fin whale (*Balaenoptera physalus*) for which disturbance from strong sounds produced by earthquakes may kill individuals, inducing high speed swimming as a seismic-escape response (Gallo-Reynoso et al. 2011). Sperm whales (*Physeter macrocephalus*) in New Zealand altered their spatial distribution and diving behaviour following habitat changes that occurred as a result of deep-sea canyon "flushing" triggered by the Kaikoura earthquake in 2016 (Guerra et al. 2020). In addition, canyon "flushing" and a resulting turbidity current triggered a massive eradication of benthic invertebrates (Mountjoy et al. 2018). The Kaikoura earthquake affected the intertidal marine vegetation with a massive disruption of the habitat-forming fucoid seaweeds. Epiphytes associated with seaweeds became functionally extinct after the earthquake with less than 0.1% of the population surviving. The same occurred among seaweed-associated invertebrates (Thomsen et al. 2020). The meiofauna (Giere 2009) seems to be very sensitive to habitat alterations generated by ground shaking, as observed in the marine meiobenthos, mostly represented by the small-sized crustacean copepods after the 2011 Tohoku earthquake in Japan (Kitahashi et al. 2014) likely due to the combination of an increase in organic matter in the surface layers and siltation among sediment particles where these invertebrates live.

In inland freshwaters, different biological alterations were related to "earthquake hydrology" (see Mohr et al. 2017; Ingebritsen and Manga 2019). For example, the Mw 6.3 Christchurch earthquake in New Zealand altered the spawning habitat requirements (i.e., salinity gradients) of "īnanga" (Galaxias maculatus), an anadromous riparian-spawning fish. The species was forced to migrate 2 km upstream in rivers where several anthropogenic land uses threatened the populations (Orchard et al. 2018). In urban streams, invertebrate taxonomic richness decreased, and benthic Ephemeroptera, Plecoptera, and Trichoptera disappeared due to post-earthquake siltation. Fish richness and density decreased significantly, with fish absent from some heavily silted streams (Harding and Jellyman 2015). Brancelj (2021) observed species replacement in the zooplankton of Slovenian lakes after earthquakes, with severe changes in the zooplankton biomass likely related to a pulse input of nutrients and resuspension of fine sediments. After earthquakes, the increase in groundwater discharge was documented on many occasions (Mohr et al. 2017). The co-seismic aquifer strain *biotriggered* a flushing of the groundwater meiofauna, with a dramatic decrease in subterranean species abundance (Galassi et al. 2014; Fattorini et al. 2018). The repercussions of this event were impressive, given the low resilience of the subterranean communities, being the species characterized by considerable longevity and low fertility. In groundwater-fed springs, a lower abundance of obligate groundwater-dweller microcrustaceans four years after the main shock was observed, together with a higher post-seismic niche overlap among groundwater- and surface-water species at the spring outlets (Fattorini et al. 2017).

Limnic eruptions

A limnic eruption is not necessarily related to a volcanic eruption and it does not refer to the expulsion of magma, but to the "explosion" in some lakes of dissolved gases which are toxic for humans, aquatic and terrestrial invertebrates and vertebrates. For this reason, these crater lakes (Kusakabe 2017) are called "killer lakes" or "exploding lakes" (Shanklin 1989). They are somehow silently toxic under various conditions that occur suddenly. The gas originates from magma at great depth, and dissolves into groundwater near the Earth's surface (Kling et al. 2005). The CO_2-enriched water enters the lake bottoms through springs. These rare events are well known from Lake Nyos and Lake Manoun in Cameroon, despite similar events being known from Lake Averno in Italy (Tassi et al. 2018) and Lake Kivu (4000 years ago) at the border between Rwanda and the Democratic Republic of the Congo (Hirslund 2020). In Lake Nyos and Lake Manoun water mixing is very limited, either because they are tropical lakes where the temperature remains high year-round, and show also a chemocline, where the deep water is more dense due to the presence of CO_2, CH_4, other volcanic gases, and total dissolved salts. The condition at the lake surface may remain relatively stable until unexpected events such as earthquakes or landslides occur and trigger the rupture of the stratification (lake overturn), thus allowing toxic gases to reach the surface waters and the atmosphere around the lake. Degassing through the lake surface occurs by bubbling or by diffusion through the water/air interface (Hernández et al. 2021).

Very little is known about their communities both in the planktonic habitat and in the deeper benthic layers. In both lakes, proteobacteria for bacteria and Crenarchaea for Archaea were dominant and present at all depths but in different proportions. In these meromictic lakes pH, O_2 or CO_2 concentrations, ions and nutrients would affect the abundance, activity, and diversity of bacterial and archaeal populations (Nana et al. 2020). Fish are routinely introduced with breeding populations, but whenever this has happened a subsequent lake overturn deoxygenated the surface water and killed all the invertebrates and vertebrates living there. This may be also the case of the planktonic cladoceran crustacean recorded from this lake (Green and Kling 1988). Interestingly, gaps in plankton fossil recording at the bottom of Lake Kivu suggest that such sudden events occurred more than once in several lakes with similar characteristics in the last 5000 years (Nayar 2009). Lake Kivu is known to host more than 28 fish species and a diversified planktonic community (Sarmento et al. 2006; Darchambeau et al. 2012). The lake biodiversity is likely supported by its higher altitude if compared to other African lakes with the same characteristics, and its greater depth, thus determining cooler temperatures at the surface that may support a stronger stratification between the oxic and predominantly autotrophic (Borges et al. 2014) mixolimnion up to 70 m and the deep monimolimnion rich in CH_4 and CO_2. From data of recent studies, it seems that methane and carbon dioxide concentrations in Lake Kivu are currently close to a steady state (Bärenbold et al. 2020).

Tsunamis

Tsunamis are massive and powerful waves that are most commonly generated by earthquakes, and less commonly by submarine (or terrestrial) landslides or aquatic cosmic impacts. The magnitude of tsunami effects on aquatic life have been relatively well documented in a few specific regions, due to the geographically isolated extent in which they occur. Due to the damaging physical contact of a tsunami wave, coastal marine plants are often ripped out, destabilizing substrates and leading to drastic changes in community structure. Seagrass coverage decreased rapidly following a tsunami that hit Sumatra, Indonesia (Nakaoka et al. 2007). The coverage of corals and mangroves decreased ~10% and ~47% after a tsunami hit India in 2004 (Majumdar et al. 2018). The species composition of coastal fish communities was affected by this tsunami, yet overall fish diversity did not change (Sathianandan et al. 2012). The movements of marine sediments produced by tsunamis have the potential to make toxic metals bioavailable by stirring up sediments and resulted in an increase in the metal content in the muscle tissue of mollusks off of Chile (Tapia et al. 2019).

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Some of the most comprehensive data for tsunami impacts on aquatic life resulted from research following the Great East Japan earthquake (magnitude 9.0) of March 2011, which generated a wave extending up to 20 m at maximum height as it struck the northeastern part of Honshu Island of Japan. Following the tsunami, the community structure of seagrass beds (*Zostera marina*) showed a decrease in vegetation coverage, as did the biomass and abundance of seagrass-associated fish species, relative to pre-tsunami levels (Shoji and Morimoto 2016). Sea urchin densities decreased rapidly after the event, leading to an indirect increase in kelp abundance, however these impacts were not seen at sites that were afforded greater protection from the wave impact (Muraoka et al. 2017). In other locations, the abundance, diversity, and species composition of shallow demersal fish assemblages did not appear to change significantly, which may be explained by the translocation or movements of more mobile fishes, enabling high survival rates (Okazaki et al. 2017). Juvenile growth rates of a regional flounder species off Japan showed no change up to two years after the event (Kurita et al. 2017). Populations of Pacific cod (*Gadus macrocephalus*) off northeastern Japan showed a remarkable four-fold increase in the three years after the tsunami, which was suggested to be linked to lower mortality resulting from a marked decrease in fishing mortality arising from damage to the fishing fleet (Narimatsu et al. 2017). In some areas, affected aquatic communities actually showed a gradual recovery to pre-tsunami levels (seven years; Shoji et al. 2021), suggesting that shallow shores may have long-term resilience to tsunamis. However, clear community-shifts in dominant fish species have been detected, suggesting local ecology and productivity may be profoundly affected at small spatial scales, leading to legacy effects (Shoji and Morimoto 2016).

Cosmic events

Lesser-known forms of geophysical disasters are of cosmic origin. The most extreme would be a strike from an asteroid or comet, which is credited with the Cretaceous–Paleogene mass extinction event that included aquatic organisms (D'Hondt 2005). In due course (e.g., the consequences of the strike on the atmospheric conditions such as temperature), such an event would likely be globally catastrophic to most forms of life (Toon et al. 1997) even if the strike occurred in the oceans (Patchett et al. 2016; Rampino et al. 2019). Meteors are smaller and much more common than asteroids and comets. We failed to identify any studies of meteors on aquatic life. Similarly, the impacts of solar flares on biodiversity of any sort have been little studied, although such events could lead to rapid changes in temperature (Somov 1991), which would presumably impact aquatic life.

Geomagnetic storms are a temporary disturbance of the Earth's magnetosphere and occur relatively frequently (several per year). Given the reliance of aquatic wildlife (ranging from microbes to fish to mammals) on the magnetosphere to assist with navigation via magnetoreception (Wiltschko and Wiltschko 2005; Monteil and Lefevre 2020), there is a reasonably large body of work on the effects of geomagnetic storms on aquatic life. For example, geomagnetic storm conditions are known to disrupt circadian biochemical processes which are believed to be mediated through melatonin and cryptochrome (Close 2012; Krylov 2017). Simulated geomatic storms alter the behaviour of fish (Fitak et al. 2020) and crabs (Muraveiko et al. 2013) and have been implicated in the mass stranding of cetaceans (Pulkkinen et al. 2020; Zellar et al. 2021). There are a number of studies that document developmental effects on fish embryos if exposures occur during early developmental stages; using rudd as a model, researchers have documented reductions in condition indices and morphological abnormalities (Krylov et al. 2017, 2019) which may be a result of alterations in digestive function (Golovanova et al. 2015). There are also documented effects on zooplankton life-history traits (via maternal effects; Krylov and Osipova 2019). Although research is still in its infancy, of all the cosmic events, geomagnetic storms appear to be highly relevant to aquatic life.

Cascading disasters

Some major disasters commonly involve more than a single geophysical driver or component, while others are made worse by preconditioning from previous events. Referred to variably as cascading, compound, or complex disasters (see Cutter 2018), they appear to be growing in frequency (Kumasaki et al. 2016). For example, the atmospheric river that affected much of southwest British Columbia and Washington State in late 2021 resulted in flooding in lowlands, as well as substantial mass wasting in upland terrain; it was the debris flows that severed multiple highways, leading to supply chain disruptions across much of Canada. While no research has yet been published, it is plausible that some of these debris flows originated in areas burned by wildfires in recent years (Gillett et al. 2022). In South Korea, wildfires and heavy rains caused landslides that extirpated a number of stream fish including rare and Endangered species (Cho et al. 2003). Similarly, flooding in Australia in 2020 following heavy precipitation was likely exacerbated by intense wildfires the previous summer. The floods resulted in substantial erosion and increased turbidity in streams, impoverishing water quality (Kemter et al. 2021). In coastal British Columbia, a complicated hazards cascade in November 2020 involving a landslide, which triggered a tsunami in a lake, and an outburst flood from that lake that resulted in intense scouring of about 8.5 km of salmon spawning habitat in Southgate River and Elliot Creek (Geertsema et al. 2022).

Assessing multi-hazard interrelationships is challenging, particularly in a predictive context (Tilloy et al. 2019). Nonetheless, given that water flows downstream, it is not surprising that such hazards can have diverse consequences on aquatic ecosystems when they involve inland aquatic systems. Threats to aquatic life compound, often in synergistic ways to yield outcomes that are somewhat unpredictable (Folt et al. 1999). Given that the intersection of hazards can occur over long time scales (e.g., wildfire or volcanic ash may not intersect with floods until years later when there is a large precipitation event) the actual and potential hazard risk to aquatic ecosystems can vary over time.

Human-mediated disasters

Given that we are in the Anthropocene, it is unsurprising that human activities are increasingly mediating disasters and their consequences on aquatic systems. For example, freshwater, estuarine, and marine ecosystems are already experiencing many anthropogenic threats. When hazards occur, it is on top of existing threats that can lead to exceedance of tipping points (Stelzer et al. 2021). Disasters themselves may be spurred by human activities. Rapid deforestation (and the installation of logging roads) can have dramatic effects on freshwater life (e.g., changes in hydrology, water temperature, and nutrient fluxes) in diverse systems ranging from boreal (Kreutzweiser et al. 2008) to tropical (Chapman and Chapman 2002) forests. However, logging can also set the conditions for hazards to develop including floods and landslides (Jakob 2000; Schuster and Highland 2007), exacerbating the impacts of logging on aquatic systems (Hartman et al. 1996). In the coming decades, climate change will increasingly be both a driver of hazards (e.g., fires, dust storms, ice storms, and hurricanes) but will also pressure aquatic systems because the impacts of hazards will be exacerbated as aquatic ecosystems become less resilient (Klein et al. 2003). Dale et al. (2001) noted how climate change can impact forests by altering the frequency, intensity, duration, and timing of fire, drought, introduced species, insect and pathogen outbreaks, hurricanes, windstorms, ice storms, or landslides. Forests are essential for aquatic systems and thus it is apparent how climate change may lead to additional hazards for aquatic life. Climate change may also contribute to more cascading hazards (Lawrence et al. 2020; see above). The full extent of climate change on natural hazards and cascading effects on aquatic systems are poorly understood but it is almost certain to make things worse.

Synthesis

Natural hazards (see Fig. 1) have been demonstrated to alter aquatic ecosystems and biodiversity in diverse ways. Of course, the intensity, scale (time and space), and frequency of natural disasters is highly variable and may be changing with altered climate systems. Similarly, not all ecosystems and biota will respond to disasters in the same way. Freshwater systems seem to be more vulnerable than marine systems when considering the impacts of natural disasters on aquatic life; however, the relative susceptibility of these two realms to different types of disasters is highly variable such that direct contrasts are challenging. For example, tsunamis are unlikely to have major impacts on freshwater systems (albeit some evidence of lake tsunamis; see Lockridge 1990), whereas avalanches are presumably irrelevant to marine systems. What is clear is that the evidence base remains diffuse with few studies that have occurred for a given disaster type, where responses have been examined using a variety of biological endpoints that transcend the individual to the assemblage. Examples such as those we have drawn upon for this synthesis are rarely replicated (a function of disasters rarely being predictable) and often lack experimental designs that include relevant comparators (e.g., using a before-after control-impact design; Smith 2002). Nonetheless, in most studies of the effects of natural hazards on aquatic systems a decline in biodiversity was detected usually in the form of reduced population sizes. Yet, there is little data at the level of the assemblage or changes in species' interactions and ecosystem functions. Moreover, sublethal effects (e.g., behavioural alterations in animals and changes in plant respiration) have rarely been studied for all but a few disaster types (e.g., fires, floods, hurricanes, and some cosmic events).

The review we conducted here was not systematic and there are certainly evidence clusters for some disaster types and endpoints (e.g., flood impacts on riverine fish populations; Rytwinski et al. 2020) that have enabled formal systematic review and meta-analysis. Unfortunately, we are decades away from being able to do that for most disaster types and endpoints. Building a robust evidence base that wherever possible employs an experimental approach (making use of so-called natural experiments) is needed recognizing the reality that many of the studies we referred to above were opportunistic. On occasion a disaster can lead to the development of a long-term research program, best exemplified by the extensive body of work on the biophysical impacts of the Mount St. Helens volcanic eruption in Washington State, USA (see Crisafulli and Dale 2018). However, this is relatively uncommon. There are certainly researchers that devote their lives to studying the ecological consequences of some disasters such as floods, droughts, and fires on aquatic systems. Yet, in most instances it is our suspicion that researchers drawn into such work are responding to a local need or opportunity. A good example arises from the work of several of the authors on this paper who were conducting a telemetry study on the spatial ecology of sharks in the Caribbean when several notable hurricanes happened to move through the area where the work was underway. Although not part of the initial study plan, the authors were able to assess behavioural responses of sharks to hurricanes using their data set (see Gutowsky et al. 2021). The opportunistic nature of such research has likely contributed to the evidence base being disparate and diffuse. To be clear, that is not a critique of any individual study but a recognition that much of the work done in this space occurs as discrete projects rather than as research programs. Laboratory experiments can be conducted for some disasters (e.g., simulated flood, drought and barometric pressure conditions, exposing organisms to electromagnetic fields to simulate cosmic events, exposing organisms to fire or volcanic ash) which are a useful complement to more opportunistic field studies. Research that combined lab simulations with field mesocosm research and studies of real events would be profitable.

Future research directions

Besides the aforementioned discussion about the evidence base and limitations with some of the studies, there are some notable research questions that need to be addressed. Each of these could represent many careers and research programs given the need for research on different disasters, in different ecosystems, in different regions, focused on different endpoints. We note that to tackle these questions in a fulsome way will require collaboration among disciplines, including ecology, limnology/oceanography, geosciences, physics, engineering, chemistry, and even social science. Questions are ordered in what we consider a logical progression but their order does not imply any prioritization.

- How does disaster type, magnitude, frequency, and spatial scale influence ecosystem resilience to an event?
- What is the relative resilience of different aquatic ecosystems (e.g., inland waters, estuaries, coastal marine, and offshore marine) and biological assemblages to various natural disasters?
- How does spatial and temporal extent of a given disaster influence aquatic ecosystems and biological assemblages?
- What are the mechanistic links between natural disasters and observed changes at the level of the organism, population, or assemblage?
- Can geophysical disasters lead to regime shifts in aquatic ecosystems?
- How do natural hazards intersect with anthropogenic stressors (e.g., land use change, invasive species, and pollution) to influence the scope and severity of impacts on aquatic ecosystems?
- How will climate change influence the frequency, severity, and consequences of natural hazards on aquatic ecosystems?
- To what extent are ecosystem services to humans directly or indirectly dependent on and/or disrupted by geophysical disasters to aquatic life?
- What are the best ways to prepare for natural disasters in ways that contribute to the resilience of aquatic systems?
- What is the potential of applying a Social Ecological Systems framework (sensu Ostrom 2009) to geophysical disaster responses to increase resiliency and mitigate potential negative outcomes to both humans and aquatic life?
- How may aquatic systems make communities and societies more resilient to natural disasters? (See Eriksson et al. 2017, e.g., on the role of fish and fisheries in enabling community recovery from natural hazard on Vanuatu.)

Conclusions

We documented diverse examples of how various natural disasters influence aquatic life at different levels of biological organization spanning the individual to the ecosystem. Effects were highly variable with different spatial and temporal impacts. In some cases there was evidence of resilience to disasters. In other cases, there was recovery ranging from short periods (days, weeks) to longer periods (years to decades). Given the patchwork of research on different taxa and levels of organization, it is difficult to draw strong conclusions. Some forms of natural disaster are well studied in terms of aquatic impacts (e.g., wildfires, flood, drought, and volcanic eruptions) whereas for some others (avalanches, cosmic events, and tornadoes), the evidence base is sparse (Table 1). As noted above, many research gaps remain. There is no doubt that natural disasters will continue to occur. Moreover, some types of disasters may become more common as a result of human activities and anthropogenic climate change. Given that many aquatic systems are already under threat as a result of pollution, invasive species, habitat alteration and exploitation, with associated losses in freshwater (Reid et al. 2019), estuarine (Kennish 2002), and marine (Crain et al. 2009) biodiversity, it is probable that the effects of natural disasters on aquatic life may become more pronounced, as they interact with the aforementioned stressors. Although it is difficult if not impossible to prevent many of the natural disasters discussed here, in areas where they are common (e.g., flood prone systems and areas subject to frequent hurricanes), some planning can be done in an effort to ensure that where possible, efforts are taken to attempt to mitigate impacts. This may be best achieved through win-win scenarios such as protecting mangroves along shoreline to mitigate effects of tsunamis and hurricanes, typhoons, and cyclones on both humans and aquatic life. Such actions are also regarded as nature-based solutions to climate change (Seddon et al. 2020). There are also opportunities to explore various restoration strategies as has been done extensively for volcanic eruptions and wildfires in an attempt to expedite recovery. Of course, addressing some of the aforementioned anthropogenic stressors and restoring aquatic ecosystems and biodiversity would help to make aquatic systems more resilient to natural disasters.

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Data availability statement

This is a narrative review paper and does not include any empirical data or analysis given a weak evidence base for most topics explored here.

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Competing interests

Cooke is on the editorial board of Environmental Reviews but was not involved in handling the manuscript.

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