EXECUTIVE SUMMARY

Managing Watersheds for Coral Reefs and Public Health

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The health and integrity of coral reef ecosystems are in decline worldwide due to an increasing suite of human activities, which threaten biodiversity and human wellbeing. One of the major drivers of coral reef ecosystem decline is poor water quality from human activities on land. Land-based pollutants from human activities travel downstream via watersheds - through groundwater flow and land areas drained by streams – and are funnelled into coastal environments. There is now ample evidence of the linkages between human activities in watersheds and elevated levels of pollutants in water discharged to coastal marine ecosystems. There is also a growing understanding of the myriad and often interacting impacts these pollutants have on coral reef ecosystems and the critical services they provide for associated dependent communities. This white paper reviews the linkages between land-based runoff and coral reef ecosystems, with four specific objectives to: (1) review how sediments, nutrients, chemicals, and pathogens affect corals and reef-associated organisms at a variety of life stages; (2) assess how these processes impact associated dependent human populations; (3) identify existing knowledge needs; and (4) provide science-based management options.

Improving the management of upstream human activities within watersheds has great potential to alleviate the severe local threats of poor water quality on coral reef ecosystems and preserve the critical functions and services they provide (e.g., tourism, fisheries, and coastal protection). Improving water quality can reduce coral disease risk and increase vital biological functions needed for corals to grow (e.g., reproduction), which also improves the resilience of corals to global impacts such as climate change. Yet, despite the breadth of research demonstrating critical land-sea linkages for coral reef ecosystem health, there are few standout examples of successful improvements to coral reef ecosystem condition that can be directly linked to upstream management action. This is largely because investments in both interventions and monitoring often need to be large in scale and sustained over long (i.e., decadal) periods to detect measurable downstream impacts.

> **Poor water quality is a major contributor to global disease burdens** and is conservatively estimated to cost US$12B in economic losses annually, a cost disproportionately borne by the poorest countries.

There are also a variety of human health impacts resulting directly from poor water quality flowing within watersheds onto coastal environments. The direct impacts to human health from declining water quality include: (1) enhanced transmission of diseases (e.g., gastrointestinal and upper respiratory diseases); (2) reduced food availability and nutritional deficit from decline of fisheries associated with coral reef habitat; and (3) food poisoning from consumption of seafood contaminated with pollutants and pathogens. Poor water quality is consequently a major contributor to global disease burdens and conservatively estimated to cost 12 billion USD in economic losses annually, a cost disproportionately borne by the poorest countries (Alhamlan et al. 2015). The overlapping drivers of coral reef and human health from watershed alteration provides an opportunity to create strategic management interventions within watersheds that will address the goals of both the conservation and public health sectors and enhance human and ecosystem health outcomes.

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This paper presents innovative solutions that incentivize the large-scale, sustained action required to both improve water quality in watersheds and prevent water quality impacts on coral reef ecosystems. The solutions use holistic approaches to integrated watershed management that bridge social and ecological systems and provide important co-benefits to human wellbeing. **Focusing on the combined economic, human health and wellbeing impacts across linked watersheds and reef areas can motivate action and leverage investment that result in co-benefits across multiple sectors**. **Designing appropriate solutions, therefore, requires taking a multi-sector, systems approach, that accounts for both social and ecological systems, with collaboration required across environmental, agricultural, public health, and water, sanitation and hygiene (WASH) sectors, and across the land-sea interface.**

Having a wide range of informed stakeholders sharing resources and taking an integrated approach will assist in buffering risks and create more effective and proactive governance. We provide several recommendations of key actions to promote successful outcomes for nature and people from improved watershed management:

- **Undertake risk assessments to identify main sources of land-based impacts to coral reef ecosystems, and consider where these risks overlap with risks to public health, especially in the context of future climate change scenarios.**
- **Ensure engagement of the full range of actors, landowners, and beneficiaries within watershed boundaries and provide platforms for transparent, participatory planning, and decision-making.**
- **Develop guidance materials to integrate coral reef ecosystem health into integrated watershed management, public health, and WASH planning.**
- **Engage and/or establish multi-sector management authorities (e.g., watershed commissions) with the mandate and resources to coordinate action across marine resource users/managers, logging, mining, agricultural, public health, and WASH sectors.**
- **Undertake policy gap analysis to improve implementation of existing policies and identify opportunities to strengthen best-practice management guidelines for land use including logging, mining, food production, and wastewater treatment to properly account for downstream human and ecosystem health impacts.**
- **Conduct research and synthesis to improve the quantity and quality of data available on thresholds and indicators of water quality and impacts on coral reef ecosystems, and make the information easily accessible (i.e., through an open-source water quality database) to support monitoring and assessment programs.**

- **Develop/enhance sustainable and innovative financing mechanisms, through impact investment and private sector engagement, business case studies and integrated resource mobilization strategies, to provide the resources required to implement phased, integrated watershed management interventions across nested scales.**
- **Advocate for integrated watershed management in places where pollution is likely to undermine other conservation interventions being implemented (e.g., within marine protected areas).**
- **Document the process of developing and implementing integrated watershed management strategies in order to create communication materials for the broader conservation, WASH and public health communities on lessons learned.**

MANAGING WATERSHEDS FOR CORAL REEF AND PUBLIC HEALTH

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Introduction and Scope

Coral reefs form unique structures that support almost a third of all marine species (Fisher et al. 2015) and provide vital ecosystem goods and services for millions of people (Moberg and Folke 1999; Cesar et al. 2003). Many coastal nations depend on the health of coral reef ecosystems to support their economies through fisheries and tourism, in addition to critical services such as food security, coastal protection, and livelihoods (Moberg and Folke 1999; de Groot et al. 2012; Teh et al. 2013; Spalding et al. 2017). Yet the health and function of coral reef ecosystems is in decline worldwide, increasingly threatened by a suite of local, regional, and global human activities (Bellwood et al. 2019). Many small island developing states are highly dependent on the integrity and resilience of their coral reef ecosystems for economic development, with over a quarter of some island nations' GDP being generated through coastal/marine tourism (UNWTO 2014).

Poor water quality is a primary driver of coastal ecosystem degradation and is threatening over 30% of coral reef ecosystems worldwide (Andrello et al. 2022). Although coastal and marine activities such as dredging can also degrade water quality, land-based activities are the major source of global declines in coral reef ecosystem water quality. Poor water quality is mainly driven by land clearing, poor food production practices, urban development, mining industries, and poor wastewater management (domestic and industrial). These human activities release pollutants (sediment, chemicals, pathogens, and nutrient run-off) into surface and groundwater which are then transported downstream to coastal environments.

Watersheds describe the geographic boundaries of drainage systems from which groundwater and river runoff flow from land to coasts and coral reefs. Watersheds are therefore a critical area for intervention in managing coral reef ecosystem health, as the condition of watersheds (e.g., human activities, native vegetation) regulates land-based runoff. Watershed condition also regulates many processes that affect human health and wellbeing, including water purification, flood management, and provision of important cultural and recreational services. Through these services, watersheds play a

KEY DEFINITIONS

Social-ecological systems:
Interdependent systems inclusive of societal (human) and ecological (biophysical) components that are nested across scales and linked through interactions and feedbacks.

Systems health:
The emergent result of functioning interdependencies, interactions and feedbacks between ecological and socio-cultural settings, behaviour, and physiology, nested across microlevel (e.g., communities of microbes), meso-level (e.g., watersheds) and macro-level (e.g., global climate patterns) domains.

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significant role in both human and ecosystem health, and can serve as a focal area for place-based management interventions that are expected to provide benefits across different sectors for nature and people (Cadham et al. 2005; Parkes and Horwitz 2009; Jenkins et al. 2018a,b; Jordan and Benson 2020). Improving watershed management can mitigate local threats (e.g., sediments and nutrients) and improve the resilience of corals to global impacts such as those associated with climate change (Edinger et al. 2000; Le Grand and Fabricius 2011; Wiedenmann et al. 2013).

This white paper synthesizes and summarizes the latest science regarding water quality impacts on coral reef ecosystems and pathways to improve systems health through policy implementation and direct management actions. It provides suggestions for strategic investments in watershed interventions across sectors and innovative sustainable finance solutions that can optimize simultaneous achievement of multiple Sustainable Development Goals and other global commitments and targets relating to biodiversity, marine pollution and public health (e.g., through the Convention of Biological Diversity, United Nations Environment Assembly Resolution on Sustainable Nitrogen Management, and Resolution 64/292 of the United Nations General Assembly on the human right to water and sanitation).

Land-Sea Linkages

There is a large body of evidence showing the mechanisms by which different human activities within watersheds and on the coast affect the quantity and quality of water that reaches coral reef ecosystems (Table 1). The natural characteristics of a watershed, such as geology, rainfall, soil type, vegetation (type and quantity), and slope normally determine the quantity and quality of runoff flowing from the land into adjacent coastal ecosystems (Douglas 1967). However, human activities within watersheds alter this process by removing native vegetation, changing the hydrology, altering the community of microbes, and adding/increasing pollutants within runoff (Liao et al. 2020; Figure 1).

***Figure 1**. Diagram depicting flow of impacts from key land-based activities on water quality properties that reach coral reef ecosystems*

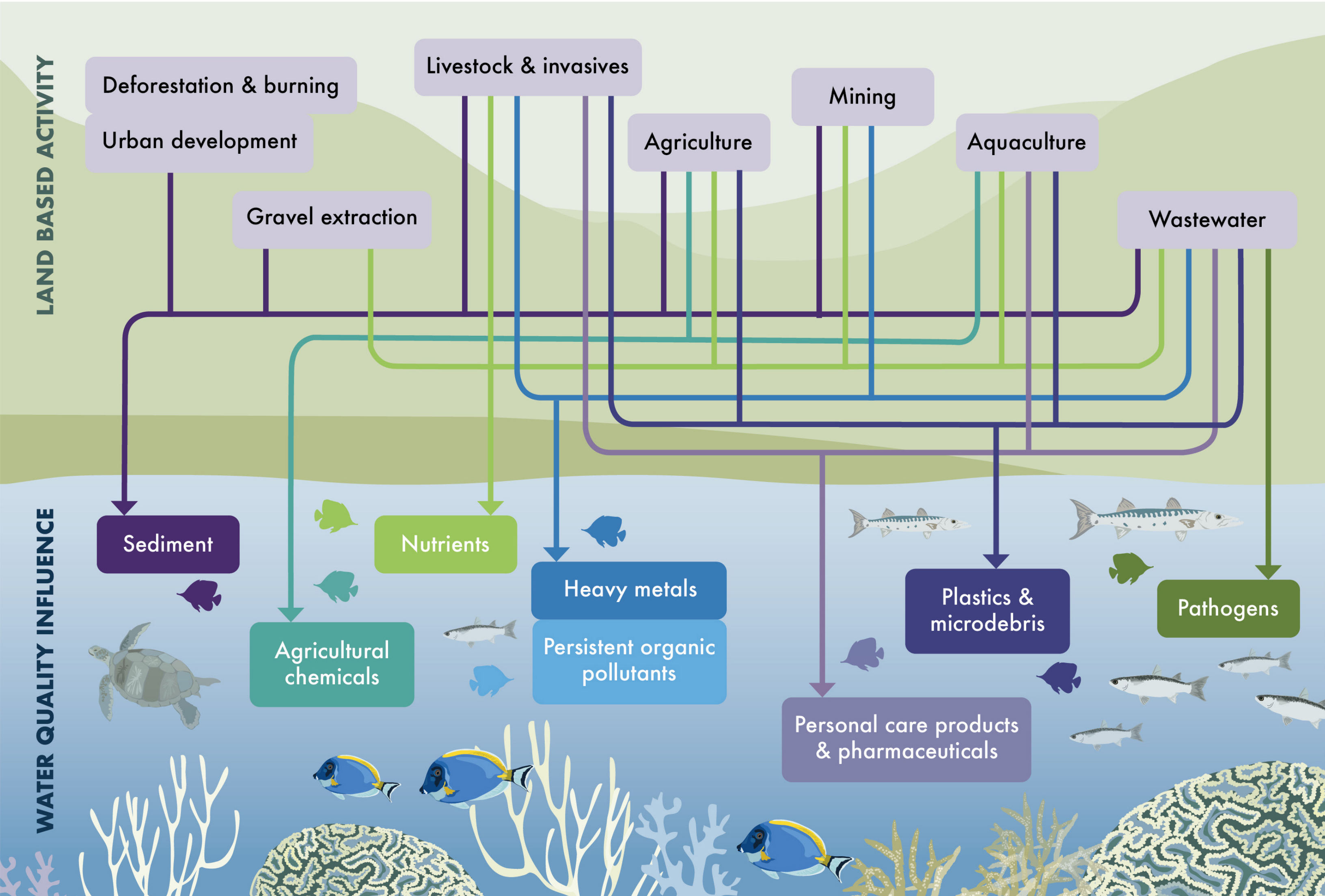

Table 1. *Key references documenting global/regional linkages between human activities within watersheds and elevated levels of pollutants in runoff to coastal waters.*

Human Watershed Activity	Water Quality Threat	Key references
Agriculture	Sediments, nutrients, agricultural chemicals (e.g., pesticides, insecticides, fungicides), and plastics and microdebris	Thorburn et al. 2013; Kroon et al. 2014; Macleod et al. 2021
Livestock and invasive ungulates	Sediments, nutrients, pathogens, and pharmaceuticals (e.g., antibiotics), and plastics and microdebris	Agouridis et al. 2005; Bartley et al. 2014
Aquaculture	Nutrients, agricultural chemicals (e.g., pesticides), pharmaceuticals (e.g., antibiotics), plastics and microdebris	Primavera 2006; Lusher et al. 2017; Wang et al. 2020
Deforestation and burning	Sediments	Suárez-Castro et al. 2021
Urban development (surface hardening and channel modification)	Sediments	Freeman et al. 2007; Kroon et al. 2014; McGrane 2014
Mining (including gravel extraction)	Sediments, nutrients, persistent organic pollutants, and heavy metals	Todd et al. 2010; Shumway 2020
Wastewater (domestic, industrial, and stormwater)	Sediments, nutrients, pathogens, persistent organic pollutants, heavy metals, personal care products and pharmaceuticals, and plastics and microdebris	Todd et al. 2010; Loya 2004; Wear and Thurber 2015; Boucher and Friot 2017; Littman et al. 2020; Wear et al. 2021; Tuholske et al. 2021

Water Quality Impacts on Coral Reef Ecosystems

There is a large body of evidence on the multiple impacts and interactions of water quality on coral reefs and reef-associated organisms (Table 2). Threats from poor water quality are seldom present in isolation, especially in urbanized watersheds, and many of the anthropogenic sources of poor water quality release multiple types of contaminants and, within watersheds, there may be multiple different sources present (Table 1).

Synergistic impacts and interactions occur when multiple pollutants are present at elevated levels, which can exacerbate harm to corals and associated organisms (Huang et al. 2021), or when pollutants are layered onto the impacts of climate change, disease, invasive species, change in land use and overfishing. For example, herbivory is an important ecological process within coral reef ecosystems and can have complex interactions with poor water quality (Table 1; Mumby et al. 2007). When reefs are exposed to poor water quality and fewer herbivores from overfishing, coral reefs can become overgrown and replaced with macroalgae and sediment-laden turfs (McField et al. 2020). This can create a positive feedback loop within which herbivory is further suppressed due to the dominance of algae and sediment, thus causing a shift to and potentially maintaining an algal dominated state (Tebbet and Bellwood 2019; Wenger et al. 2020).

Climate change – particularly sea level rise and ocean warming – will further increase the sensitivity of coral reef ecosystems to poor water quality. Land-based pollution can lower the threshold for thermal stress and increase coral sensitivity to infection, resulting in increased bleaching (Fisher et al. 2019; Nalley et al. 2021; Watkins and Sallach 2021; Zhao et al. 2021), coral mortality (Claar et al. 2020), and outbreaks of disease on coral reefs (Redding et al. 2013; Pollock et al. 2014; Lamb et al. 2016, 2018; Vega Thurber et al. 2020). Corals that have been bleached through warming also have reduced capacity to cope with sediment pollution (Bessell-Browne et al. 2017c). Nutrient pollution can result in brittle corals that are less resilient to the impacts of climate change such as sea level rise and the increased severity and frequency of cyclones (Table 1; Fabricius 2005; Rice et al. 2020).

Table 2. *Documented impacts of poor water quality on coral reefs and coral reef organisms.*

Water quality category	Main impacts to coral and reef organisms*	Subsequent impact to coral reef ecosystem	Subsequent impact to humans	Key references
Terrestrially derived sediment	Reduced fertilization for coral and reef building species	Reduced reef accretion and coral cover reduces habitat complexity and the capacity of coral reef ecosystems to recover from disturbances	Reduced coastal protection, tourism, and fisheries services	Gilmour 1999; Fabricius 2005; Ricardo et al. 2018
	Reduced settlement for coral and reef building species			Gilmour 1999; Hodgson 1990;, Fabricius 2005; Todd et al. 2010; Bessell-Browne et al. 2017b
	Reduced coral growth rate			Rogers 1990; van Woesik and Done 1997; Fabricius 2005
	Reduced colony size			van Woesik and Done 1997
	Partial mortality			Wesseling et al. 2001; Jones et al. 2019
	Reduced photosynthetic yield			Philipp and Fabricius 2003; Todd et al. 2010
	Extended larval development and reduced settlement of fish	Reduced fish recruitment, biomass and diversity, which impacts capacity of reef ecosystems to recover from disturbance	Reduced fisheries and tourism services	Hess et al. 2015; Wenger et al. 2015; Moustaka et al. 2018
	Gill damage and mortality of fish			
	Increased susceptibility to disease of larval fish			
	Reduced foraging ability			
	Reduced fish species richness			
	Altered coral complexity and community composition	Reduced ecosystem diversity and habitat complexity, which impacts the capacity of coral reef ecosystems to recover from disturbances	Reduced fisheries services	Rogers 1990; Edinger et al. 1998; West and van Woesik 2001; Golbuu et al. 2008; van der Meij et al. 2010
	Reduced coral species richness			Rogers 1990; West and van Woesik 2001; Golbuu et al. 2008; van der Meij et al. 2010
	Suppression of herbivory by reef fish	Proliferation of coral-inhibiting algae, reducing coral cover and the capacity of coral reef ecosystems to recover from disturbances. Can result in a "phase shift" from coral reef ecosystem to alga-dominated ecosystem. Reduced structure and nutrition also leads to reduced fish populations and diversity	Reduced coastal protection and fisheries services	Wenger et al. 2015; Moustaka et al. 2018; Wenger et al. 2020
	Reduced abundance of herbivorous fish species			
	Accumulation in algal turfs			Tebbet and Bellwood 2019

Nutrients (organic and inorganic) *	Reduced fertilization, settlement and reproductive success	Reduced reef accretion and coral cover reduces habitat complexity and the capacity of coral reef ecosystems to recover from disturbances	Reduced coastal protection and fisheries services	Harrison and Ward 2001; Koop et al. 2001; Cox and Ward 2002; Loya 2004; Todd et al. 2010
	Reduced coral growth rate			Koop et al. 2001; Loya 2004
	Partial or complete mortality			Koop et al. 2001; Loya 2004; Weber et al. 2012
	Reduced calcification and coral skeletal density	Brittle corals which are more susceptible to breaking and erosion. This reduces the capacity to recover from disturbances	Reduced coastal protection	Edinger et al. 2000; Koop et al. 2001
	Increased macrobioeroder density			Fabricius 2005; Le Grand and Fabricius 2011; Rice et al. 2020
	Increased algal growth	Proliferation of coral-inhibiting algae under reduced herbivory, reducing coral cover and the capacity of coral reef ecosystems to recover from disturbances.	Reduced coastal protection and fisheries services	McManus et al. 2000
Pathogens	Coral disease	Potential reductions in the composition, abundance, and ultimately the accretion of coral. Limited information at present	Reduced coastal protection services	Sutherland et al. 2011
	Increased pathogenic microbiota on fish gills	Potential outbreak of disease and reductions in fish recruitment. Limited information at present	Potentially reduced fisheries services and impacts to human health	Hess et al. 2015
Persistent organic pollutants	Reduced fertilization, settlement, and development of corals	Reduced coral cover and reef accretion. Ultimately reduces coral reef ecosystem capacity to recover from disturbances	Reduced coastal protection, and fisheries services	Fabricius 2005; Turner and Renegar 2017
	Accumulation in coral and coral reef organisms			Todd et al. 2010; Nalley et al. 2021
	Reduced chlorophyll concentration and symbiont density in corals			Ranjbar et al. 2018; Nalley et al. 2021
	Reduced growth of coral reef building organisms			Turner and Renegar 2017; NAS 2020, Nalley et al. 2021
	Partial and complete mortality of coral and coral reef organisms			Turner and Renegar 2017; Bejarano 2018; NAS 2020; Nalley et al. 2021
	Endocrine disruption in fish and other coral reef organisms	Could alter fish population dynamics and leave coral reef organisms vulnerable to additional stressors.	Potentially reduced fisheries services	Wenger et al. 2015
	Immuno-suppresion in fish			

Heavy metals	Reduced fertilisation, settlement, and development of corals	Reduced coral cover and reef accretion. Ultimately reduces coral reef ecosystem capacity to recover from disturbances	Reduced coastal protection and fisheries services	Negri et al. 2002; Nalley et al. 2021
	Coral bleaching			Nalley et al. 2021
	Reduced chlorophyll concentration and symbiont density in corals			
	Partial and complete mortality of corals			
	Embryo malformation and reduced hatching success in fish	Fish larvae and new recruits potentially more prone to predation. Limited information on chronic and lower levels of exposure at present	Reduced fisheries services	Wenger et al. 2015
	Olfactory impairment and behavioural changes in fish			
	Immuno-suppression in fish	Increased disease and death rates in fish		
Agricultural chemicals (e.g., pesticides, insecticides, fungicides)	Reduced fertilisation, settlement, and growth of corals	Reduced coral cover and reef accretion. Ultimately reduces coral reef ecosystem capacity to recover from disturbances	Reduced coastal protection and fisheries services	Nalley et al. 2021
	Reduced photosynthetic efficiency, chlorophyll concentration, and symbiont density in corals			
	Coral bleaching			
	Partial and complete mortality in corals			
	Olfactory impairment in fish	Short-term physiological and ecological processes. Limited information on chronic exposure at present	Potentially reduced coastal protection	Wenger et al. 2015
	Endocrine disruption of fish reproduction			
Personal care products and pharmaceu-ticals	Endocrine disruption of coral fecundity	May lead to reductions in the composition, abundance, and ultimately the accretion of coral. Limited information at present	Potentially reduced coastal protection and fisheries services	Tarrant et al. 2004; Wear and Thurber 2015
	Endocrine disruption of development and/or growth of coral and coral reef organisms			Wear and Thurber 2015; Downs et al. 2017; Watkins and Sallach 2021
	Reduced tissue regeneration in coral			Downs et al. 2017
	Mortality of coral			Watkins and Sallach 2021
	Coral bleaching			Downs et al. 2017, Watkins and Sallach 2021

(cont.) **Personal care products and pharmaceu-ticals**	Endocrine disruption of development and/or growth in fish	May lead to changes in fish population dynamics and communities	Potentially reduced fisheries services	Wenger et al. 2015
	Altered predator–prey interactions and aggressive behaviour of fish			
	DNA alterations and reduced reproduction and development in crustaceans	May lead to changes in population dynamics of commercially harvested species	Potentially reduced fisheries services	Garcia et al. 2014; Ma-ranho et al. 2015
	Growth inhibition in algae	May lead to changes in fish population dynamics and communities, potentially causing trophic cascades in reefs.	Potentially reduced fisheries services	Aguirre-Martinez et al. 2015
Plastic and microdebris	Reduced reproduction and growth	May lead to reductions in the composition, abun-dance, and ultimately the accretion of coral. Limited information at present	Potentially reduced coastal pro-tection services	Todd et al. 2010; Lamb et al. 2018; Huang et al. 2021
	Disease, bleaching and tissue necrosis			
	Enhanced transport of other contaminants to corals	May lead to a range of con-taminant-specific impacts, such as reduced coral cover and reef accretion from sediment		Huang et al. 2021

** Contaminant dynamics are complex, with different impacts and response curves observed even between contaminants in the same group (e.g., different heavy metals generate different impacts, different types of nutrients generate different impacts). Different levels of exposure also generate different responses, with some nutrient species generating positive responses under certain exposure levels. Impacts reported here are a general summary of known impacts from the introduction of each contaminant group at harmful levels observed in the environment.*

Water Quality Impacts on Human Health

Water quality impacts on coral reef ecosystems are often not enough to motivate action and leverage adequate funding for management, and linking these impacts to human health can provide new opportunities. Currently, there are efforts to identify overlaps where there are watershed risks to both ecosystem health and public health (Case Studies 1 and 2). There is ample evidence from the public health literature that points to human disease burdens linked to poor water quality. Contaminated drinking water is a known major contributor to global disease burdens, particularly in young children (Prüss-Ustün et al. 2014; Liu et al. 2015; WHO 2016; Prüss-Ustün et al. 2019). Important water-related diseases include diarrhoeal diseases, cholera, and typhoid (WHO 2015a, 2016). Communities reliant on surface and groundwater sources for their drinking, bathing, and household cleaning water are most at risk, particularly in tropical environments (Ragosta et al. 2011; Herrera et al. 2017). One of the main contributors to water pollution and water-related disease is the poor coverage and construction of sanitation services in many parts of the world (Prüss-Ustün et al. 2019). Currently, two billion people lack access to safely managed sanitation services and over 1,000 children die each day due to preventable water and sanitation-related diarrheal disease (UN IGME 2019; WHO/UNICEF 2021). Recent work has also demonstrated strong links between higher incidences of water-related bacterial disease and ecosystem health, such as reduced upstream forest cover in watersheds and reduced ecosystem integrity (Jenkins et al. 2016, WHO 2016; Herrera et al. 2017).

Pollution of waterways from wastewater is also a major concern for human health as it can exacerbate the development of antibiotic resistant pathogens (Ocean Sewage Alliance 2021). Antimicrobial resistance is responsible for 700,000 deaths every year, which is predicted to increase with continued poor stewardship and environmental pollution (O'Neill 2016). The waste from animals, humans, and unregulated use of antimicrobials encourages antibiotic resistance in pathogens, and wastewater treatment plants and waterways can act as hotspots for proliferation of antimicrobial resistance genes and threaten neighboring communities (Berendonk 2015; Rodríguez-Molina et al. 2019; Sharma 2019).

Elevated levels of endocrine disruptors and microplastics within waterways from wastewater pollution also pose an emerging human health concern (WHO 2016, Ocean Sewage Alliance 2021). Endocrine disruptors alter the functioning of endocrine systems in organisms, and while this has been researched in wildlife, the impacts on human health are not well understood.

Climate change is predicted to alter water-related disease dynamics and further increase global disease burdens (Semeza 2020). Changes in rainfall and temperature will threaten water security, enhance pathogen survival and virulence, and increase the exposure to contaminated water (Hofstra 2011; Levy et al. 2017). These impacts will be particularly acute within the tropics in places where increased cyclone intensity and floods are predicted under future climate change (Smith et al. 2014).

Polluted coastal ecosystems affect the health of coastal human populations through fisheries decline or ingestion of contaminated fisheries products (Hicks et al. 2019; Li et al. 2019). Millions of people depend on tropical coastal fisheries for essential protein and micro-nutrients (Kawarazuka and Béné 2010; Teh et al. 2013). More than 10% of the global population is likely to face micronutrient and fatty-acid deficiencies if current trajectories of fisheries decline continue, especially in the developing nations at the Equator (Golden et al. 2016). An estimated 180 million cases of upper respiratory disease and gastroenteritis occur each year due to humans bathing in polluted ocean waters or ingesting contaminated seafood (Shuval 2003; WHO 2015b). On a global scale, pathogens in ocean pollution cause an estimated $16.4 billion (2018 USD) in economic losses annually because of their direct impacts on humans alone (Shuval 2003). Better recognition of the economic cost and implications of water quality impacts is critical for prioritizing action and leveraging the necessary cross-sectoral partnerships and resources required for managing water quality at appropriate scales.

Management Interventions Within Watersheds

There are an array of site-based management interventions that can be implemented, at nested scales within watersheds (e.g., Case Study 1), to improve water quality, ranging from those that mitigate the introduction of pollutants into waterways to those that remove pollutants from contaminated water sources (Liu et al. 2017; Richmond et al. 2019). Mitigation efforts include policy instruments and place-based interventions.

Policy instruments, such as regulations, effluent discharge guidelines, best-practice land-use management strategies, or market-based incentives can be applied at any scale and are not necessarily spatially bound within watersheds. For example, policy instruments can be used to control, reduce and/or prevent pollution through improving the use, transport, storage and disposal of chemicals, such as pesticides and tailings within agriculture and mining (Taylor et al. 2012; Olmstead and Zheng 2021). Policy instruments can also initiate the implementation of soil conservation and erosion/runoff control strategies, such as contour banks and reforesting (Jokiel and Brown 2004; Richmond et al. 2019).

Place-based interventions are specifically applied at a range of nested scales, from landscape, residential, and even to individual scales (Figure 2). Landscape scale interventions are designed to minimise and filter sources of pollution.

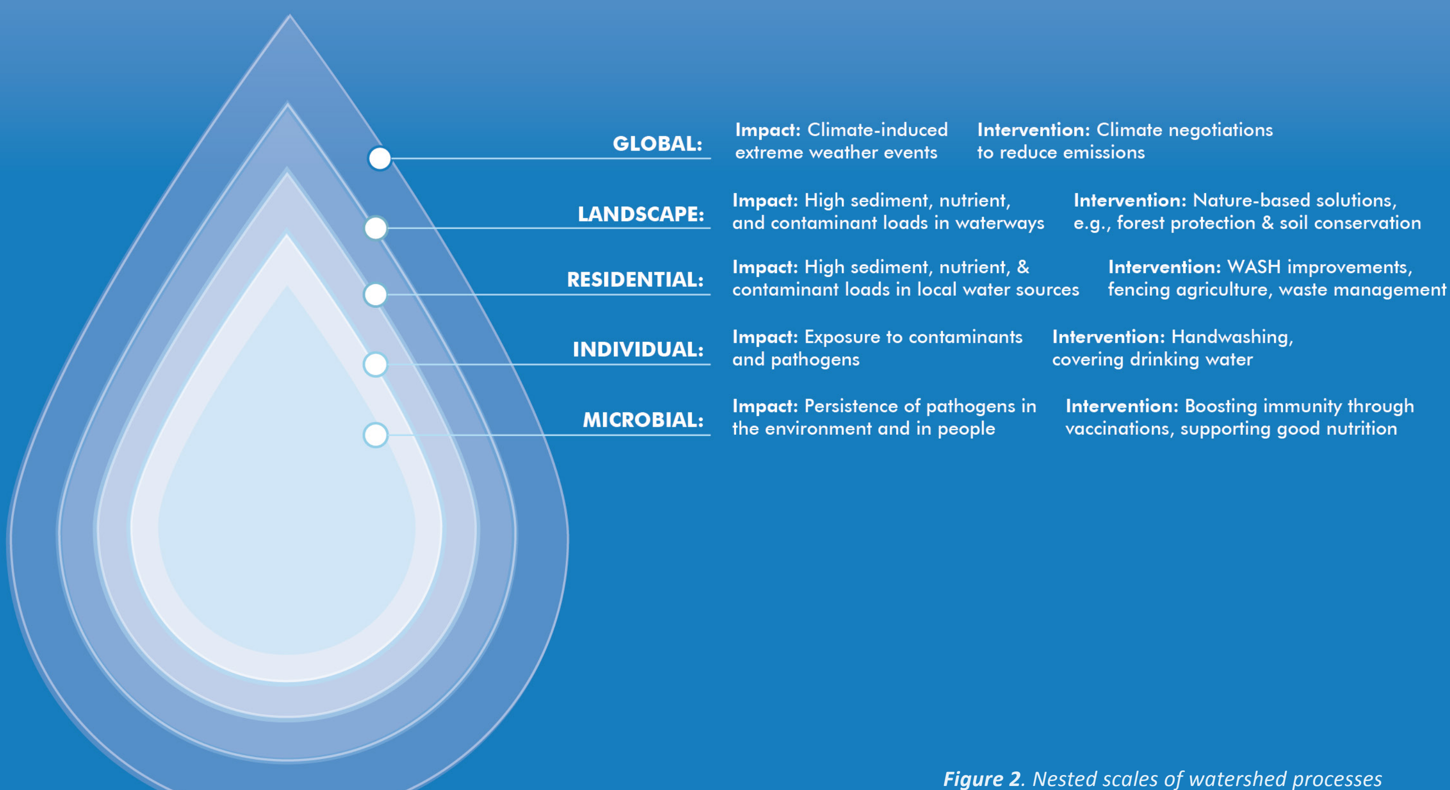

Figure 2. *Nested scales of watershed processes*

This includes mechanical filters such as drainage improvements (Romos-Scharrón 2012; Romas-Scharrón and LaFevor 2016) and sediment socks (Shelton and Richmond 2016), which trap or divert large debris and sediments. Biological filtering methods can also be used at a landscape scale such as natural or constructed wetlands, shellfish aquaculture, and plantations, which accumulate and sequester nutrients, pesticides, pathogens, and metals (Rose et al. 2014; Tarigan et al. 2016; Liu et al. 2017; Lamb et al. 2017; Leder et al. 2021). At a residential scale, pollution from sources such as wastewater and sewage can be minimised through the application of WASH infrastructure improvements and maintenance, such as the installation and upgrade of sewage treatment systems (Tomasko et al. 2018). Individual scale interventions include behaviour change campaigns targeting practices such as the disposal of personal care products and pharmaceuticals (WHO 2016). The incorporation of local actors (i.e., residential and individual) in management interventions leads to greater awareness and compliance with policies (e.g., Case Study 2).

Watershed management is also key to ensure the success of other policy and place-based interventions being implemented to protect coral reefs. For instance, poor water quality leads to a significant reduction in marine protected area effectiveness (Lamb et al. 2016; Wenger et al. 2016; Halpern et al. 2013; Suchley and Alverez-Filip 2018; Bégin et al. 2016). Poor water quality also causes degradation of coastal ecosystems such as mangroves and seagrass (Todd et al. 2010), which act as important nurseries for coral reef fish, and are gaining considerable attention in terms of their capacity for carbon storage (Barbier et al. 2011; Lau 2013; Macreadie et al. 2021).

Through the combined use of these policy and place-based interventions within watersheds, harmful pollutants entering waterways and flowing downstream onto coral reef ecosystems can be minimized. However, there are limited examples of water quality management that have seen successful recovery of coral reef ecosystems (Birkeland et al. 2013; Bahr et al. 2015; Vargas-Ángel and Huntington 2020; Reef Resilience Network 2021), and of those, the management interventions have primarily tackled only pollution arising from one discrete source, otherwise known as point-source pollution. Difficulties arise in designing and measuring the effectiveness of policy instruments for water quality management due to lack of compliance and information on contaminant thresholds and monitoring (Taylor et al. 2012; Olmstead and Zheng 2021). Place-based interventions are often impeded, particularly for non-point source pollution, by difficulties in engaging stakeholders, systematic/transparent planning, and funding (Jupiter et al. 2017).

Kāne'ohe Bay in Hawaii is a commonly cited case-study of point-source pollution management for coral reef ecosystems, with a major diversion of sewage from the reef to deeper waters contributing to a rarely seen recovery of a reef from algal domination to a coral dominated reef community (Bahr et al. 2015). More recent successes include coral reef ecosystems within Faga'alu Bay in American Samoa, where harmful runoff from the upstream Samoa Maritime Quarry was managed through the installation of drainage systems, alternative ground cover, and retention ponds (Vargas-Ángel and Huntington 2020). Both intervention strategies required large and costly monitoring efforts to observe success, and both observed set-backs in recovery trajectories due to external disturbances (e.g., storm waves and bleaching; Bahr et al. 2015; Richmond et al. 2019; Vargas-Ángel and Huntington 2020). High sediment loads were also successfully reduced in parts of Moloka`i, Hawai'i, by removing invasive goats and deer from areas that the animals had stripped of vegetation. The removal of these invasive ungulates with community, NGO, and government support resulted in revegetation of these areas and a 10-fold reduction in sediment load reaching coastal waters (State of Hawaii 2019).

Successful water quality management interventions are characterized by the deployment of an array of policy instruments and coordination across multiple sectors at multiple scales. This coordination between different independent authorities in this way is known as polycentric governance and often pioneers new and better regulated policies (Morisson 2017). These changes demand a substantial amount of political will, community and stakeholder buy-in (Jupiter et al. 2014), and investment over long time-scales required to measure impact (Meals et al. 2010).

Key Enabling Factors

CROSS-SECTORAL COORDINATION AND GOVERNANCE

Despite impacts of watershed-based pollutants, biodiversity protection targets may not be enough to compel governments to invest the required time and resources to achieve measurable recovery. Since several human activities in watersheds are known to negatively affect both human and downstream ecosystem health (Table 3), there is an opportunity to leverage the economic and social opportunity cost from both human and ecosystem health sectors as a catalyst for investment in strategic management interventions within watersheds.

Table 3. *Drivers of water quality that increase risks to coral reef ecosystem health and human health*

Overlapping Risk factor/ driver	Water Quality Threat	Direct impacts to humans	Key references
Deforestation and burning	Sediments	Increased cost and complexity of water treatment	Price et al. 2018; Albert et al. 2021
		Increased risk of water-related diseases	Herrera et al. 2017; Jenkins et al. 2016
Agriculture	Sediments	Increases cost and complexity of water treatment	Kabir et al. 2015; WHO 2016
	Agricultural chemicals	Accumulation in seafood	Portman 1975
Livestock and invasive ungulates	Pathogens	Increased risk of water-related diseases	Lau et al. 2010
	Personal care products and pharmaceuticals	Antibiotic resistant pathogens	WHO 2014
Aquaculture	Personal care products and pharmaceuticals	Antibiotic resistant pathogens	WHO 2014
Mining / Industry	Sediments	Increased cost and complexity of water treatment	Price et al. 2018; Albert et al. 2021
	Heavy metals, persistent organic pollutants	Severe health impacts and inhibition of biological sewage treatment	WHO 2016
Channel modification (e.g., road crossings, damming)	Sediments	Increased cost and complexity of water treatment	Price et al. 2018; Albert et al. 2021
		Increased risk of water-related diseases	Jenkins et al. 2016
	Water flow	Increased risk of water-related diseases	Sokolow et al. 2015
Wastewater and sewage	Sediments	Increases cost and complexity of water treatment	Jenkins et al. 2016; Rodríguez-Molina et al. 2019
	Heavy metals	Severe health impacts and inhibition of biological sewage treatment	WHO 2016; Müller et al. 2020
	Pathogens	Increased risk of water-related diseases	Sindermann 2005; Fleming et al. 2006; Lamb et al. 2017; WHO 2016
		Pathogens in seafood	Littman et al. 2020
	Persistent organic pollutants	Health impacts from endocrine disruptors	WHO 2016; Müller et al. 2020
	Personal care products and pharmaceuticals	Antibiotic resistant pathogens	WHO 2014
	Plastics and microdebris	Plastic in seafood	Littman et al. 2020

Traditional single sector approaches are unable to address the interrelated challenges of managing land-use and water quality to improve human and ecosystem health. Cross-sectoral collaborations can create a more holistic understanding of the watershed system and the breadth of its impacts across sectors. This holistic understanding can improve the efficiency of water quality projects by targeting multiple water quality problems at once, creating the potential for win-win scenarios for both coral reef ecosystem health and human health (Jupiter et al. 2014; Jenkins and Jupiter 2015). The success of this kind of cross-sectoral coordination and governance relies on careful engagement and integrated policy development and implementation. Decision making should be developed through engagement with a wide range of stakeholders and resource users at multiple scales to accurately capture land and water use practices, needs, goals and potential conflicts across sectors, ensuring that all involvement is participatory, transparent, accountable, and culturally appropriate (Jupiter et al. 2014; Richmond et al. 2019).

Integration of policy across sectors will also require the acknowledgement of the large time and spatial scales required to see recovery of coral reef ecosystems and effectively mitigate more diffuse water quality contaminants such as nonpoint source pollution. Post-project monitoring is essential to successfully measure the full scale of outcomes from interventions, yet currently such monitoring is rarely allocated by project funders. There are only a few cases of this integrated management method being applied to benefit both coastal ecosystems and human health, with most published examples from non-tropical regions in the northern hemisphere (Wang et al. 2016).

Critically, integrated policy needs to be developed based on a good understanding of the connections among systems so that evidence-based predictions and decisions can be made about how any interventions may influence outcomes in multiple sectors. It is essential to consider any potential trade-off scenarios wherein mutual benefits are not shared between sectors, or one sector may even be exposed to more harm (Agrawal and Redford 2006). For example, the construction or restoration of wetlands for improving water quality and ecosystem health may have unintended consequences for mosquito-borne disease risk (Malan et al. 2009; Finlayson and Horwitz 2015); and the installation of dams and weirs for improving water security and sediment pollution may have unintended consequences for freshwater ecosystems and fisheries (Kroon et al. 2014; Dudgeon 2005). Communities may also select to improve water infrastructure over sanitation infrastructure, assisting with issues relating to contaminated drinking water but not pollution. Having a wide range of informed stakeholders sharing resources and taking an integrated approach will assist in buffering this risk and create more effective and proactive governance wherein benefits across sectors are optimised.

Case Study 1 | **Watershed Interventions for Systems Health in Fiji**

Low coverage of improved drinking water and sanitation in remote areas of Fiji leaves rural communities heavily reliant on the safety and security of unprotected water sources and vulnerable to water-related diseases. Severe outbreaks of water-related infectious diseases are referred to by the Fijian government as the three plagues: leptospirosis, typhoid, and dengue (hereafter LTD). LTD cases and syndromes associated with these diseases are correlated with environmental conditions, with large outbreaks typically occurring following heavy rainfall events and flooding (Lau et al. 2010; Nelson et al. 2022), and being more severe in areas with degraded watersheds (Jenkins et al. 2016).

Coastal and freshwater ecosystems are also threatened by degraded watersheds in Fiji, with decreased fish and reduced coral cover and complexity seen downstream of cleared and developed watersheds due to the runoff of harmful pollutants (Jenkins et al. 2010; Brown et al. 2017). These ecosystems, particularly coral reefs, support the livelihoods, nutrition, and incomes of many rural communities.

The Watershed Interventions for Systems Health in Fiji (WISH Fiji) project is aimed at addressing these overlapping problems, and is a collaborative effort between the University of Sydney, Edith Cowan University, Fiji National University, the Wildlife Conservation Society, Fiji Ministry of Health and Medical Services, Water Authority of Fiji, Pacific Community, UNICEF and World Health Organization. Project collaborators are co-designing targeted upstream monitoring programs and intervention strategies with local communities to prevent, detect and respond to LTDs, as well as to mitigate degradation of downstream resources and ecosystems (McFarlane et al. 2019).

Management actions are implemented across nested scales, from policy change to landscape-scale forest protection and restoration to infrastructure improvements within residential settings and information campaigns targeting individual behaviors. In doing so, the WISH Fiji project aims to transform both environmental and public health action from reactive to preventative, and improve the overall health of the system to maintain integrity against LTD and natural disasters.

Case Study 2 | **Wastewater Management in Roatán, Honduras**

The island of Roatán in the Bay Islands of Honduras is bordered by clear waters and stunning coral reef ecosystems which attract over a million tourists into the region. The provisioning of safe and clear runoff from watersheds is essential to maintaining the health of these coral reef ecosystems, but also to protect the health of Roatán communities and tourists who use the water and have access to limited coverage of sanitation infrastructure on the island. However, limited wastewater treatment led to the discharge of untreated or inadequately treated wastewater to coral reef ecosystems. Local ecological knowledge links this wastewater runoff to outbreaks of water-related diseases in both humans and coral reefs in the region, and thus impacting tourism.

To combat both the human health and ecosystem impacts of untreated wastewater discharge, a collaboration between government, conservation groups (Coral Reef Alliance, Bay Islands Conservation Association-Roatán, Mesoamerican Reef Fund), and water associations (Polo's Water Association Waterboard) identified the need for a community wastewater treatment plant and water quality program in West End, Roatán. The West End wastewater treatment plant (WWTP) was then built in 2011, and has since been connected to 99% of accessible homes and businesses in the area.

Critically, a water quality laboratory led by the Bay Islands Conservation Association was also built as part of this collaboration to enable testing of marine water downstream of the WWTP. Significant improvements in water quality were able to be observed through the laboratory. Within seven years of the WWTP installation, the public beach in the West End passed the United States EPA safe swimming standards for *Enterococcus*, a bacteria which can cause a variety of infections and is associated with fecal contamination. The beach has since been awarded an Ecological Blue Flag certification that validates the areas as safe for tourists. Improved metrics for coral reef ecosystem health were also observed, likely as a result of improved water quality, with monitoring finding that fleshy macroalgae decreased from 27% to 24% (McField et al. 2020).

Sustainable Financing

One of the major roadblocks to implementing upstream interventions for improving water quality is that they are expensive and require sustained investment (Muchapondwa et al. 2018). Large lags between implementing interventions and observed improvements in coral reef ecosystem health mean that interventions must be long-term to see results, and their success can be negated or obscured in the short-term by other disturbances such as cyclones and coral bleaching (Richmond et al. 2019). The short-term nature of funding cycles and input from key personnel often results in the discontinuity of environmental management projects and reduces their effectiveness (Jupiter et al. 2014; Muchapondwa et al. 2018).

Water and watershed funds are a common financing tool that has been used within other systems to help combat these issues and ensure a sustained source of funding (TNC and Goldman 2009; Kauffman 2014; EPA 2021; Claudet et al. 2021). Water and watershed funds are often resourced through voluntary contributions of donors and water users such as utility companies and farmers, which are then used to pay for and support upstream strategies to conserve the quality and security of water sources. Linking the needs of downstream water users with upstream communities and land users allows water and watershed funds to provide a low-cost and sustainable financing method of maintaining clean and regular water supply (TNC and Goldman 2009; TNC 2018). In some coral reef areas, payment for ecosystem services schemes have also been proposed as a way for downstream resource users to incentivize upstream resources users to manage water quality (Goldman-Benner et al. 2012; Peng and Oleson 2017).

Examples of successful water funds are mainly from temperate regions or exclude marine ecosystems, such as the Latin American Water Funds Partnership (LAWFP). LAWFP is an agreement between a consortium of international NGOs to enhance and preserve water security in Latin America, and currently supports 25 water funds across nine countries with varying water management goals and local funding bodies (Bremer et al. 2016, LAWFP n.d.). In total, LAWFP supported water and watershed funds are managing over 227,000 hectares of land, potentially benefiting 89 million people, and have leveraged over $205 million USD in resources (LAWFP 2020). However, as with many watershed funds (and conservation efforts), there have been limited measurements of the outcomes or baselines to fully perceive the benefits of these funds (Bremer et al. 2016).

By leveraging the wide-ranging value of clean and reliable water, watershed funds are often cross-sectoral organizations with donors and boards made up of public, private, and community stakeholders, all contributing to any investments and expenditure of the fund. Boards may invest the funding directly or use grants to identify and develop critical intervention strategies (TNC and Goldman 2009; TNC 2018). Many watershed funds prioritize not only water management for humans, but also the use of nature-based solutions and sustainable watershed management as a means to preserve the health of aquatic ecosystems (Kauffman 2014; NFWF 2021). There is an opportunity for coastal water quality to be managed and funded sustainably through similar practices.

The availability of local sources of funding for the sustainable financing of a watershed fund will vary from region to region as beneficiaries of the fund vary. Not all communities and industries pay for water use: under these circumstances, it may be feasible to develop business cases for investment based on foregone healthcare and productivity costs if watershed improvements prevent people from getting sick. Key to developing these business plans is first assessing how much disease risk can be reduced by a portfolio of management interventions and balancing the wide range of savings in foregone costs (healthcare, missed work and education, tourism impacts) against annual investment needs. Considerations also need to be taken for the potential benefits from buffering against the influence of climate change on disease. More information on sustainable financing is available here.

What Is Success?

Success in managing water quality impacts on coral reef ecosystems requires effective, cost efficient, measurable and culturally appropriate intervention strategies that result in the improved health of both coral reef ecosystems and the surrounding communities. To be able to detect improvements in health of either system, the monitoring of outcomes and/or water quality is key using clear, measurable indicators and targets. Improved understanding of stressor-response relationships, with consideration of the impacts of future climate change, is also critical for determining robust thresholds for water quality which can be used by managers and policy makers to effectively monitor and mitigate threats.

Detailed analytical assessments of stressors and their thresholds for harm on coral reef ecosystems are rare, with limited research into the cumulative effects that specific stressors may have on different coral organisms at different life stages or how these may be altered under future climate change. Turbidity has an estimated long-term threshold of 5 nephelometric turbidity units (NTU) before severe stress impacts on some coral species (Cooper et al. 2008; Hawaii WQ guidelines). A recent chemical pollutant meta-analysis by Nalley et al. 2021 was only able to develop robust analytical thresholds for two pollutants, copper and diuron, which were 44.8 – 365.3 µg L^{-1} and 43.7 µg L^{-1}, respectively. Other thresholds have been developed through field observation without the development of explicit stressor-response curves, such as a macro-bioeroder density threshold of 50 m^2. General guidelines for a variety of stressors have been developed for broad marine regions, however, no thresholds or guidelines exist for pathogen loads (DEHP 2013; ANZECC & ARMCANZ 2021). Indicators used to monitor the impacts of human activities within watersheds on water quality parameters within coral reef ecosystems are summarized within the Appendix.

Water quality standards for humans are much more vigorously tested, with different thresholds sometimes developed for different water uses (e.g., drinking water or recreational use) and for different kinds of exposure (chronic or acute) (e.g., DEHP 2013; WHO 2017, 2021). Higher standards are also typically used to protect human safety, with conservative guidelines and thresholds used particularly when there is uncertainty surrounding the impacts of the contaminant. Turbidity guidelines for drinking water are 1 NTU, which is much more sensitive than the thresholds for coral (5 NTU) (WHO 2017). However higher levels of many other contaminants are acceptable within drinking water, such as 2,000 µg L^{-1} copper guidelines for drinking water and 40,000 µg L^{-1} for recreational water use (WHO 2017, 2021).

Collaboration in monitoring across conservation, WASH, industries (logging, mining, food production), and public health sectors can provide additional evidence of the success of any intervention strategies. Improvements in the function of marine protected areas and that include the protection of forests and coastal ecosystems from clearing will not only also lead to gains towards protected area targets and will sequester/avoid substantial CO2 emissions.

Future Recommendations: Incentivizing Integrated Watershed Approaches

The latest science makes it clear that unplanned development, poor land use and agricultural practices, and poor wastewater management within watersheds are significant threats to coral reef ecosystems, yet incentivizing the development of watershed management for the sake of improving water quality on coral reefs has remained a challenge.

In the future, it is recommended that policies and management are designed using systems health approaches that aim to restore water quality for multiple benefits within human health and coral reef ecosystem health while facilitating sustainable social and economic development.

Actionable recommendations:

1. **Undertake** risk assessments to identify main sources of land-based impacts to coral reef ecosystems, and consider where these risks overlap with risks to public health, especially in the context of future climate change scenarios.
2. **Ensure** engagement of the full range of actors, landowners, and beneficiaries within watershed boundaries and provide platforms for transparent, participatory planning, and decision-making.
3. **Develop** guidance materials to integrate coral reef ecosystem health into integrated watershed management, public health, and WASH planning.
4. **Engage** and/or establish multi-sector management authorities (e.g., watershed commissions) with the mandate and resources to coordinate action across marine resource users/managers, logging, mining, agricultural, public health, and WASH sectors.
5. **Undertake** policy gap analysis to improve implementation of existing policies and identify opportunities to strengthen best-practice management guidelines for land use including logging, mining, food production, and wastewater treatment to properly account for downstream human and ecosystem health impacts.
6. **Conduct** research and synthesis to improve the quantity and quality of data available on thresholds and indicators of water quality and impacts on coral reef ecosystems, and make the information easily accessible (i.e., through an open-source water quality database) to support monitoring and assessment programs.
7. **Develop/enhance** sustainable and innovative financing mechanisms, through impact investment and private sector engagement, business case studies and integrated resource mobilization strategies, to provide the resources required to implement phased, integrated watershed management interventions across nested scales.
8. **Advocate** for integrated watershed management in places where pollution is likely to undermine other conservation interventions being implemented (e.g., within marine protected areas).
9. **Document** the process of developing and implementing integrated watershed management strategies in order to create communication materials for the broader conservation, WASH and public health communities on lessons learned.

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Appendix 1 Monitoring indicators for coral reef ecosystem health outcomes and water quality processes

Response variable	Indicator	Options for measurement	Implementation Requirements	Time required to observe response[1]	Key References
Outcome variables					
Overall coral reef ecosystem health	Coral cover	Benthic surveys	*In situ*	MEDIUM	Graham et al. 2011, Vercelloni et al. 2020
	Coral diversity	Benthic surveys	*In situ*	MEDIUM	Maynard et al. 2017
	Coral recruitment rate	Benthic surveys	*In situ*	MEDIUM	Maynard et al. 2017
	Coral disease	Coral colony surveys	*In situ*	FAST	Lamb et al. 2015, Lamb et al. 2016; Lamb et al. 2018
	Macroalgal cover	Benthic surveys	*In situ*	FAST	Flower et al. 2017
	Functional groups of benthic primary producers	Benthic surveys	*In situ*	FAST	Littler and Littler 2007
	Sediment necrosis	Coral colony surveys	*In situ*	FAST	Pollock et al. 2014
Sedimentation stress	Coral growth rate	Coral core collection & X-radiograph	Specialized equipment, fridge storage, & lab	SLOW	Flower et al. 2017
	Mucous sheet production	Coral colony surveys	*In situ*	FAST	Bessell-Browne et al. 2017a
	Massive coral partial mortality	Coral colony surveys	*In situ*	MEDIUM	Nugues and Roberts 2003
Process variables					
Water quality & nutrient enrichment	Proximal flooding or landslide	Information obtained from local knowledge	N/A	FAST	N/A
	Turbidity (NTU)	Secchi disk, turbidity meter, OR calibrated multi-parameter water quality meter (sonde)	*In situ*	FAST	Cooper 2008, Hawaii WQ guidelines, WHO 2017
	Sedimentation	Total suspended sediment, sediment traps, SedPods, electronic sediment vacuum	Fridge storage & lab	FAST	Rogers 1990, De'ath and Fabricius 2008, GBRMPA 2010
	Copper	Water sample processed at lab facility	Fridge storage & lab	FAST	Nalley et al. 2021, WHO 2017
	Dissolved oxygen	Calibrated multi-parameter water quality meter (sonde)	*In situ*	FAST	Haas et al. 2014, Johnson et al. 2021
	Salinity	Refractometer OR calibrated multi-parameter water quality meter (sonde)	*In situ*	FAST	WHO 2017
	Particulate nitrogen	Water sample processed at lab facility	Fridge storage & lab	FAST	GBRMPA 2010
	Dissolved nitrogen	Water sample processed at lab facility	Fridge storage & lab	FAST	Zhao et al. 2021, WHO 2017
	Particulate phosphorous	Water sample processed at lab facility	Fridge storage & lab	FAST	GBRMPA 2010
	Trace elements (e.g., Ba) within coral skeletons	Coral core sample processed at lab facility	Coring machinery, fridge storage, & lab	SLOW	Risk and Edinger 2011
	Macro-bioeroder density	Coral colony surveys	*In situ*	MEDIUM	Cooper et al. 2008, Le Grand and Fabricius 2011
	Macroalgae cover	Benthic surveys	*In situ*	MEDIUM	Flower et al. 2017
	Sponge overgrowth of corals	Benthic surveys	*In situ*	MEDIUM	Lamb et al. 2014
	Enterococcus (marine fecal indicators)	Water sample processed at lab facility	Fridge storage & lab	FAST	Lamb et al. 2017
	Changes in microbial community	Microbiome sample processed at lab facility	Fridge storage & lab	FAST	Glasl et al. 2019
Herbivory	Turf algae height	Benthic surveys	*In situ*	MEDIUM	Flower et al. 2017
	Grazing rates & algal removal	Benthic video deployment or turd macroalgal assays	*In situ*	FAST	Goatley et al. 2016
	Biomass & functional groups of herbivorous fish^	Fish surveys	*In situ*	MEDIUM	Littler and Littler 2007, Green and Bellwood 2009
Primary productivity	Chlorophyll-a	Water sample processed at lab facility OR calibrated multi-parameter water quality meter (sonde)	Fridge storage & lab OR *in situ*	FAST	GBRMPA 2010

*[1] Fast = weeks – months, Medium = months – years, Slow = decades | * Caribbean coral growth rates see https://geography.exeter.ac.uk/reefbudget/caribbean/; Indo-Pacific growth rates see collated data and references in (Kubicek et al. 2012; Ortiz et al. 2014a suppl. info.)*

^ Grazing rates and algal removal offer a more sensitive indicator, as biomass and functional groups of herbivorous fish can remain unchanged under poor water quality in some contexts (Goatley et al. 2016)