Wastewater Pollution on Coral Reefs

Supporting Science Synthesis prepared by C_2O Consulting in cooperation with the United Nations Environment Programme

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Preface

This science synthesis has been prepared by C_2O (Coasts Climate Oceans) in collaboration with the United Nations Environment Programme through the Global Coral Reef Partnership and the Global Wastewater Initiative (GW2I, one of three global partnerships under the Global Programme of Action for the protection of the marine environment from land-based activities).

It provides a review of the science including sources of wastewater, their impacts on coral reefs including in the context of climate change, as well as management strategies, aimed at advisors, managers and other officials with technical roles in governments, regional environmental organizations, and conservation organizations. It constitutes the science-basis for “Wastewater Pollution on Coral Reefs: Science-to-Policy Brief on Managing Wastewater to Support Coral Reef Health and Resilience” (UNEP, 2017), which summarizes policy and management recommendations. The policy brief and the science-basis presented here can be read in conjunction with each other, or separately.

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Contents

Acronyms

DIN…………………………………… Dissolved inorganic nitrogen

EPA ………………………………… Environmental Protection Agency

GBR ………………………………… Great Barrier Reef

Gt …………………………………….. Gross tonnage

N……………………………………… Nitrogen

N_2 …………………………………… Nitrogen gas

N_2O ………………………………… Dinitrogen monoxide

NH_3 ……………………………….. Ammonia

NOx ………………………………… Nitrogen oxide

Nr …………………………………… Reactive nitrogen

P……………………………………... Phosphorus

PAH ………………………………… Polyaromatic hydrocarbon

PSII ………………………………… Photosystem II

SS…………………………………… Suspended sediment

Tg …………………………………… Teragram

Executive Summary

This report provides the supporting science for the UNEP Science-to-Policy brief (2017). It synthesizes the current science on wastewater pollution and coral reefs to inform decision-making and policy globally. This synthesis will support decision-making and capacity building efforts at a regional level under the Global Wastewater Initiative, initially in the Caribbean and Red Sea region, and later in the Pacific region; to strengthen monitoring of wastewater loading and impacts among key stakeholder groups; and to raise awareness through Regional Seas and other relevant mechanisms. The report also provides the foundation and key recommendations for linking wastewater monitoring explicitly to coral reef status and resilience assessments.

A wide range of wastewater compounds, including nutrients, pesticides, trace metals and petroleum hydrocarbons enter reef ecosystems through various pathways and affect reef species and/or life history stages. Many wastewater pollutants, including agricultural fertilizers, pesticides and organochlorine compounds, domestic and municipal wastes, trace metals and petroleum products are now recognized to have adverse effects on coral reefs, even when released at low levels (Haynes and Johnson 2000; Pinto et al. 2003). Understanding their impacts and the species that are sensitive to these pollutants is important for informing management and monitoring.

Key Messages

1. Coral reefs are important ecosystems that millions of people worldwide depend on for food security and livelihoods.
2. All types of wastewater pollution can impact on coral reefs, including sewage, industrial waste, agricultural nutrients, pesticides and other toxic chemicals.
3. Sources of wastewater pollution entering the marine environment are varied, ranging from urban wastewater, terrestrial river runoff, and industrial discharges. These sources can generate a range of pollutants including sediment, nutrients, pesticides, trace metals, hydrocarbons, industrial organochlorines and a range of emerging pollutants such as pharmaceuticals and microplastics.
4. The only documented examples of wastewater pollution having widespread and significant impacts on coral reefs are associated with nutrient and sediment inputs. Other pollutants may be significant at local scales.
5. Wastewater pollution exacerbates impacts on reef ecosystems already under pressure from overexploitation (mainly overfishing), climate change, ocean acidification and other anthropogenic threats.
6. In general, point source sewage or industrial discharges are easier to manage than diffuse agricultural or urban wastewater streams as technological options are available such as deep water disposal or treatment options, e.g. sewage treatment, which are not so easily applied to diffuse sources.
7. Policy solutions include: managing land-based activities that contribute to wastewater pollution, minimizing other pressures on reefs such as overfishing and habitat destruction, and establishing monitoring that can determine key sources of pollution for targeted management.
8. An integrated management approach across the catchment to reef continuum is required to address wastewater issues for coral reef ecosystems.

1. Introduction

Tropical coral reefs are located in shallow waters (< 50 m) in a zone centered along the equator between latitudes 30° N to 30° S due to their specific temperature, water clarity (and light availability) and ocean chemistry requirements (Figure 1). They occur in the Pacific, Atlantic and Indian Oceans, in over 100 countries. Coral reefs cover only 285,000 km^2 or less than 1% of the Earth's surface, yet they contain a disproportionate amount of marine biodiversity. Over 80% of the world's coral reefs are concentrated in Asia and Oceania. Their three-dimensional physical complexity provide habitat and nursery grounds that support high biodiversity and productivity. Reef structures support over 600 species of calcifying corals, 4,000 species of fish, as well as high diversity of invertebrates, macroalgae and marine megafauna (Wilkinson 2008). Coral reefs are not only biologically rich, they also have complex biogeochemical roles in producing sand and limestone substrates and protecting coastal shorelines from storms.

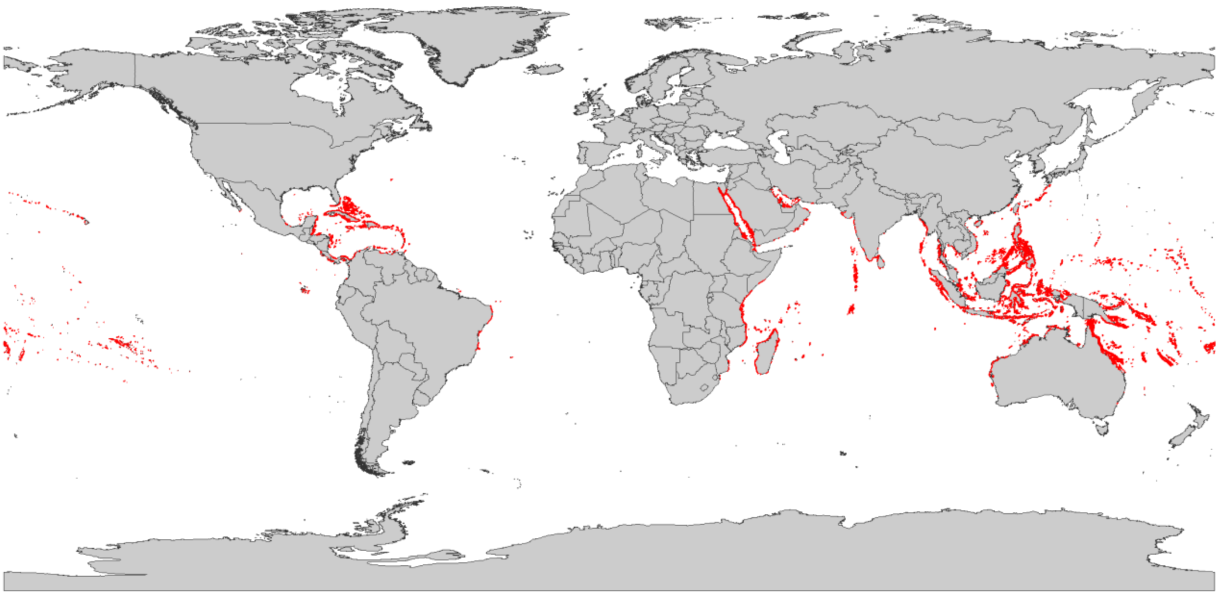

Figure 1. Map of global coral reef distribution. Coral reefs are defined in red. Source: UNEP-WCMC (http://datda.unep-wcmc.org).

More than 800 million people from 109 countries live within 100 km of coral reefs, which provide important sources of ecosystem goods and services for these communities (Donner and Potere 2007; World Resources Institute 2012). Many of these communities are in poor nations living in small islands or rural settings where they are directly dependent on reefs for livelihoods and food security. Reefs produce 10–12% of the fish caught in tropical nations and 20–25% of the fish caught by developing nations in the western Pacific, Indian Ocean, the seas of the Middle East, and the Caribbean (Garcia and Grainger 2005). Recent estimates are of 6 million reef fishers (including gleaners) in 99 nations worldwide, just over 25% of small-scale fishers fish on coral reefs, and 50% of all coral reef fishers are in Southeast Asia (Teh et al. 2013).

Approximately 500 million people depend on coral reefs for food, coastal protection, building materials and income from tourism and fisheries. This includes 30 million who are almost totally dependent on coral reefs for their livelihoods or for the land that they live on (i.e. atolls; Wilkinson 2008). For example, at least 94 nations benefit from reef-related tourism, and reef tourism contributes more than 15% of gross domestic product (GDP) in 23 of these nations (World Resources Institute 2012). Coral reefs therefore support the socioeconomic well-being of many coastal communities, and their ecosystem goods and services are estimated at between US$100,000 and US$600,000 per km^2 per year (UNEP 2006b).

With millions of people living near coral reefs, it's not surprising that human activities are taking their toll on marine environments. Human impacts have increased along with the rapid population growth, substantial developments in technology, and significant changes in land use. Approximately 75% of reefs around the world have been rated as threatened when local stressors (e.g. overfishing, pollution, habitat degradation, introduced species) are combined with thermal stress due to climate change (Carpenter et al. 2008; World Resources Institute 2012).

Declines in coral reef condition over the past few decades have implications for ecosystem structure and function as well as dependent communities. A global semi-quantitative assessment of social and economic vulnerability to coral reef decline found that greater than 33% of very highly vulnerable countries and territories are in the Caribbean, 20% are in east Africa and the western Indian Ocean, and smaller numbers are found in the Pacific, Southeast Asia, and south Asia. Among the 27 countries and territories rated as very highly vulnerable, the majority (19) are small island states (World Resources Institute 2012). Reducing local pressures on reefs, such as pollution, particularly in small island states is the most effective way to build reef resilience and support reefs in the face of warming seas and ocean acidification.

Areas of high marine species richness are disproportionately concentrated in regions with medium to higher human impacts (Tittensor et al. 2010). For example, approximately 70% of Southeast Asia's population lives in coastal areas and intensive farming and aquaculture, rapid urbanization and industrialization, greater shipping traffic and fishing effort, as well as widespread deforestation and near-shore development, are contributing towards pollution problems. Southeast Asia also encompasses approximately 34% of the world's coral reefs and includes the global hotspot of reef biodiversity – the Coral Triangle – formed by the six nations of Malaysia, the Philippines, Indonesia, Solomon Islands, Timor Leste and Papua New Guinea. The region is also a global hotspot in terms of local threats – overfishing, pollution and coastal development – with almost 95% of reefs assessed as threatened by a combination of impacts, and watershed-based pollution a key driver (World Resources Institute 2012). The need to reduce the impacts of marine pollution in this region is therefore critical (Todd et al. 2010).

The anthropogenic disturbance of the water cycle through reservoir construction, agriculture, deforestation, and urbanization has caused considerable changes in the fluxes of freshwater, sediment (e.g. Syvitski et al. 2005) and nutrients (e.g. Mackenzie et al. 2002) to coastal marine waters and the ocean. Catchment development has led to modification of flow regimes in tropical coastal catchments upstream from coral reefs (McCulloch et al. 2003; Prouty et al. 2009; Yamazaki et al. 2011) in both the Atlantic (Porter et al. 1999), Indo-Pacific (Pena-Arancibia et al. 2012) and South Pacific (Kroon et al. 2013; Waterhouse et al. 2016). The changes may be increases associated with increased erosion, or increased use of fertilizer or reductions due to increased number of dams and trapping of sediments and nutrients in the reservoirs. These changes have many geomorphological and ecological consequences for downstream environments. Increasing sediment and nutrient loads have been linked to, for example, decline in coral cover and seagrass abundance (e.g. Fabricius 2005; Restrepo et al. 2016; Brodie et al. 2011), while reductions in sediment and nutrient loads have caused coastal erosion and the collapse of inshore fisheries (reviewed in Syvitski et al. 2005). Models have predicted that 3 – 5 Gt of sediment is trapped by reservoirs annually compared to a total global sediment flux of 20 Gt per year (Syvitski et al. 2005).

It is evident that large increases or reductions in sediment and associated nutrient loads disturb the dynamic balance of coastlines and delicate ecosystems including coral reefs.

More than 25% of the world's coral reefs are affected by watershed-based pollution (including nutrient fertilizers, sediment, pesticides, and other polluted runoff from the land), with about 10% highly threatened. Southeast Asia surpasses all other regions with 45% of reefs influenced by pollution (World Resources Institute 2012). In comparison, marine-based pollution harms approximately 10% of coral reefs globally, with 1% at high threat. This pressure is widely dispersed around the globe, emanating from ports and widely distributed shipping lanes, and the Atlantic, Middle East, and Australia are the most impacted regions (World Resources Institute 2012). Thirty percent of the world's coral reefs have experienced an increase in threat from local and global stressors in the 10 years between Reefs at Risk analyses (1997 and 2007; World Resources Institute 2012) and this issue is expected to continue to increase in the future due to population pressures and climate change.

The sources of point source pollution are varied (see Section 2) and as these inputs are addressed globally (e.g. Kroon et al. 2014), the fraction of pollutant inputs reaching coral reef environments that are contributed by non-point sources becomes increasingly important. Regardless of the intention or delivery mechanism, all wastewater pollution has the potential to seriously damage marine habitats and organisms, particularly coral reefs that are adjacent to land-based sources of pollution (see Section 3). The additional implications of wastewater pollution in the context of climate change and ocean acidification effects, including the impact on reef resilience are also important considerations, particularly when identifying the implications of future threats for management (Section 4). Management options are considered, drawing on international experiences (Section 5), and examples of documented case studies are assessed in terms of management success (Section 6). Finally, recommendations for future management including monitoring requirements are discussed (Section 7).

2. Wastewater pollution and coral reefs: Primary sources

Global increases of nitrogen (N) and phosphorus (P) inputs to coastal waters have increased due to human activities (Cloern 2001; Galloway et al. 2008), with a doubling of riverine, reactive N and P in the preceding 150 years (Galloway et al. 2008; Mackenzie et al. 2002). Enriched signatures of N isotopes in coral cores and tissues indicate increased fluxes of terrestrial N to coral reefs from agricultural and sewage runoff since at least the 1970s (Jupiter et al. 2008; Marion et al. 2005; Yamazaki et al. 2011). Similarly, cores indicate an increase in terrestrial P to coral reefs in the 20th century, associated with soil erosion, sewage, aquaculture, agriculture, mining and port development (Chen and Yu 2011; Dodge et al. 1984; Harris et al. 2001; Mallela et al. 2013).

A summary of key pollutants in wastewater typically delivered to coral reef ecosystems and the broad land use classes that generate them is presented in Table 1 and discussed below. The potential impacts of wastewater pollution on coral reefs including case studies are included in Section 3.

Table 1. Key pollutants in wastewater and primary source land uses.

Pollutant	Description	Associated Land Use Types
Nutrients (nitrogen and phosphorus)	Generated from faecal material (sewage) and fertilizers, transported by surface rainfall runoff. Encourages algal growth and eutrophication.	Urban, Industrial, Intensive Agriculture
Suspended solids/ sediment	Generated when surface water flows collect and transport unsterilized soils and sediment. Can result in smothering of aquatic habitats and restriction of light penetration.	Urban (particularly construction), Intensive Agriculture, Rural
Herbicides	Applied to cropping to control weeds, transported aerially or by surface rainwater runoff. Can result in morbidity and mortality in freshwater, estuarine and marine species.	Intensive Agriculture, Urban
Insecticides	Applied to crops typically to control pests such as insects, transported aerially or by surface rainwater runoff. Can result in morbidity and mortality in freshwater, estuarine and marine species.	Intensive Agriculture, Urban
Trace Metals	Metals such as mercury, arsenic, lead, cadmium. Can result in morbidity and mortality in freshwater, estuarine and marine species (ecotoxicity).	Urban, Industrial
Hydrocarbons	Liquid fuels (diesel, petroleum, oil). Morbidity and mortality in freshwater, estuarine and marine species, and impact upon reproductive cycle.	Urban, Industrial – ports and shipping, Commercial
Tri-butyl Tin	Tri-butyl Tin (TBT) was a common antifouling additive used in paints applied to ship hulls. It is a contaminant that is commonly associated with sediments around ports and runoff from ship servicing facilities. TBT has now largely been replaced by copper-based and herbicidal based anti-foulants. Results in morbidity and mortality in freshwater, estuarine and marine species, and impacts upon reproductive cycle.	Industrial – ports and marinas

Source: Gunn and Barker (2009) Table 2.2, pp.5-6.

2.1 Urban

Wastewater from urban areas includes point sources such as discharges from wastewater collection systems, and where a treatment plant exists this would be treated effluent, and diffuse sources such as stormwater runoff. Hydrologic stress in urban settings results from increases in impervious cover due to the construction of roads, housing developments and community facilities, causing higher stormwater flow velocities and frequencies (Jacobson 2011); increasing erosion (in the construction phase), pollutant delivery and eutrophication in receiving environments (Taebi and Droste 2004).

Urban point source wastewater

The primary point source of pollution in a majority of urban areas is human sewage that reaches near-shore habitats through leaching of septic systems and point source discharges from centralised treatment systems. Sewage effluent contains a number of substances that may impact on the marine environment and coral reefs specifically (Wear and Vega Thurber 2015). These include organic matter, nutrients, suspended solids, and microorganisms (bacteria, viruses, fungi, protozoa, parasitic worms), some of which may be pathogenic. There may also be toxic trace metals, toxic synthetic organic substances such as pesticides and solvents; petroleum oil;

detergents; biologically active drug residues such as vitamins and steroids; and litter (Brodie 1995; Berry et al. 2013). In more industrialised areas, sewage can also contain elevated concentrations of heavy metals. Emerging pollutants such as phthalates, PCBs, PAHs, bisphenol A and pharmaceuticals used for human health as well as disinfectants and hormones are of increasing concern (Deblonde et al. 2011). The adverse impacts depend significantly upon the degree of treatment before reaching waterways.

In many countries, discharges of pollutants from point sources have decreased significantly over the past 30 years. The changes are mainly due to improved purification of urban wastewater and reduced industrial discharges. In western European countries, purification is now very effective and eastern European countries are following a similar process. In 2002, 90% of the EU-25 population was connected to sewage networks. However, some of this wastewater is discharged either raw or partially treated. Regional differences in sewage treatment exist. For example, in central European and Nordic countries more than 90% of the population is connected to tertiary treatment plants, while the percentage in southern Europe and new Member States varies between 50-80%. Some large cities discharge their wastewater nearly untreated, such as Cork, Barcelona, Brighton and Milan. However, this assessment was from 2004 and as of 2015 progress has been slow. A recent assessment states: *Perhaps first among the environmental problems of the Mediterranean region is the inadequate treatment of municipal wastewaters. Until today, a mere 55 per cent of coastal cities are served by treatment plants which means that a load of more than three billion m^3 of untreated water enters the Mediterranean Sea every year.*

Urban diffuse wastewater

Major diffuse sources of nutrients from urban settings include fertilized residential or commercial landscapes, pet wastes, septic systems and sewage leaks due to inadequate or aging infrastructure (e.g. Groffman et al. 2004; Burns et al. 2009), and stormwater (Collins et al. 2010). Stormwater runoff flows on the surface dissolving and collecting sediment and pollutants from urban environments that are ultimately discharged diffusely into receiving waters (Taebi and Droste 2004). Stormwater runoff is an important export vector for nutrients that have accumulated in urban environments (Davidson et al. 2009). Nitrogen loads in urban stormwater runoff are variable, but are greater than those found in runoff from undisturbed natural areas (e.g. Line et al. 2002; Groffman et al. 2004; Waters et al. 2014).

Urban stormwater runoff is being recognized as a major source of pollutants to receiving waters around the world (Davis et al. 2001) and many investigations have detected a range of pollutants in urban diffuse runoff including sediments, nutrients (principally N and P), oxygen demanding materials (biodegradable organic material), metals, toxic organic wastes (garden and household chemicals), pathogenic micro-organisms (bacteria, viruses etc.), hydrocarbons and litter (Chiew et al. 1997). Nutrient concentrations in urban stormwater are generally less than those from areas of intensive agriculture and significantly greater than from forested catchments (P is 2 – 10 times greater) or undeveloped catchments (N is 2 – 5 times greater) (Chiew et al. 1997).

Duncan (1999) synthesized information from around the world about urban stormwater quality and found that pollutant concentrations in urban stormwater are correlated with distance from the source. In some locations, stormwater runoff was more polluted than sewage wastewater (e.g. parts of Iran; Taebi and Droste 2004). The main process of stormwater contamination is from the accumulation of pollutant material on impervious surfaces during dry weather (build-up) including settling of fine particles from the atmosphere, accumulation of fine particles and gross pollutants from local sources and redistribution of surface pollutants by wind and traffic. Some contaminants can be carried relatively long distances by wind and rain before being deposited (distributed sources) while others have a local origin. Some of the more significant local sources of pollutants are associated with motor vehicles and roadways.

Coastal Development

As human populations increase worldwide, the need for housing, infrastructure and basic services has led to an acceleration of urban development in coastal areas. Coastal development generally results in clearing of native vegetation and forests to build housing, roads, water and sewage infrastructure, education and shopping precincts as well as tourist resorts. This clearing and construction can deliver sediments and associated pollutants, such as nutrients, hydrocarbons, and trace metals, into waterways and the adjacent marine environment.

2.2 Agriculture

Around the world intensive agriculture is affecting coasts and oceans, particularly estuaries and near-shore marine environments. Agricultural activities can be diffuse pollution sources – cropping, grazing, oil palm and forestry – or point source pollution – feedlots and aquaculture – and are often carried out in flood plains that drain directly into the marine environment.

River runoff transports agricultural pollutants to coastal reefs such as nutrients (Aronson et al. 2004, Brodie et al. 2011; Cooper et al. 2007; D'Angelo and Wiedenmann 2014; Devlin and Schaffelke 2009; Larsen and Webb 2009; McLaughlin et al. 2003; Restrepo et al. 2016; ; Wiedenmann et al. 2013); sediments (Bainbridge et al. 2012, 2014, 2016; Bartley et al. 2014; McLaughlin et al. 2003; Risk 2014) and pesticides (predominantly herbicides) into near-shore coral reef ecosystems (Du and Kunzmann 2015; Kennedy et al. 2012; Lewis et al. 2009; Royer et al. 2014; Shaw et al. 2012; Smith et al. 2012; Salvat et al. 2016; Brodie and Landos, 2019). All pollutants move and disperse during flood plumes, however due to variation in transport, uptake process, degradation (biotic and abiotic) and residence times, different constituents have discrete patterns of behaviour as they move through the estuary and onto coral reefs.

The impacts of nutrients and sediments on coral reef systems are similar to those noted above for point source pollution, although the influence may be acute rather than chronic. Unlike nutrients, sediments and metals, pesticides have no natural sources so their introduction has significant potential impacts. The use of herbicides, insecticides and fungicides on crops, vegetation and soils to eliminate pests, does not mean they remain in the soil but rather, pesticides find their way into waterways through leaching, surface run-off, spray drift, soil erosion and volatilization (Warren et al. 2003). A complex range of factors determines the fate of pesticides applied to agricultural soils including: method of application, active ingredients, weather conditions, land topography, soil type. These factors all influence the persistence and extent of contamination of non-target sites (Larson et al. 1995). Additionally, overuse of pesticides increases the probability of negative impacts on non-target organisms, such as aquatic biota (Tremolada et al. 2004). The transport, fate and toxicity of pesticides to aquatic environments is especially concerning in tropical areas where pesticide usage is generally much higher than in temperate areas (Ecobichon 2001), and where receiving reef environments are known to be sensitive (van Dam et al. 2011).

Global nitrogen fixation contributes 413 Tg (1 Tg is equal to one million tonnes) of reactive nitrogen (Nr) to terrestrial and marine ecosystems annually of which anthropogenic activities are responsible for half, 210 Tg N (Fowler et al. 2013). Leakages from the use of fertilizer Nr contribute to nitrate in drainage waters from agricultural land and emissions of trace Nr compounds to the atmosphere. Emissions, mainly of ammonia (NH_3) from land together with combustion related emissions of nitrogen oxides (NOx), contribute 100 Tg N /yr to the atmosphere. Leaching and riverine transport of nitrate contribute 40–70 Tg N /yr to coastal waters and the open ocean, which together with the 30

Tg input to oceans from atmospheric deposition combine with marine biological nitrogen fixation (140 Tg N /yr) to double the ocean processing of Nr. Some of the marine Nr is buried in sediments, the remainder being denitrified back to the atmosphere as gases (N_2 or N_2O). Thus globally, aquatic environments have received enhanced terrestrial inputs of bio-reactive P (~22 Tg P /yr) (Chen and Graedel 2012); and inorganic N (40 - 70 140 Tg N /yr) (Mackenzie et al. 2002; Fowler et al. 2013; Steffen et al. 2015). Sources of agricultural pollution vary, with different farming practices and intensity, producing and exporting a different suite of pollutants to reef environments.

2.3 Industrial pollution and mining

Industrial activities in watershed and coastal environments include: heavy manufacturing (e.g. paper mills, chemical plants, petroleum refineries), light manufacturing (e.g. printing and publishing, electronic and other electrical equipment manufacturing), coal and mineral mining, oil and gas processing, hazardous waste treatment, power generating plants, transport and storage facilities, scrap or recycling yards, shipping ports and dredging, and food processing (e.g. fish canneries). Although regulated in many nations, these activities can discharge a toxic cocktail of wastewater pollutants into near-shore ecosystems, including coral reefs; for example, heavy metals, fuels or petroleum hydrocarbons, carbon-based organic chemicals (e.g. halocarbons), polychlorinated biphenyls and dioxins (Torres et al. 2008). Ports and shipping activities can also directly deliver pollutants such as petroleum hydrocarbons and trace metals (e.g. tributyltin from anti-fouling paints) into marine waters and coral reefs (Loya and Rinkevich 1980; Negri and Marshall 2009).

The wastewater and associated contaminants generated by mining activities is generally in the form of concentrated tailings waste produced during ore processing (e.g. Powell and Powell 2001; Elberling et al. 2003), which contains high concentrations of toxic trace metals, or large volumes of excavated overburden which can change the sea floor and release heavy elements from the ore body (Brewer et al. 2007).

Industrial port areas and the dredging associated with providing access to ports are another source of pollutant inputs to coral reefs. Most ports are located in shallow inshore areas and have constructed channels, berths and swing basins to allow safe vessel access. Routine maintenance is often required to remove naturally accumulated marine sediments from these navigational areas. The removal and relocation of natural seabed to construct navigational areas for vessels is known as capital dredging, whereas the removal and relocation of mobile sediments that settle into previously constructed navigational areas is known as maintenance dredging. Both types of dredging generate elevated suspended sediments in adjacent environments for days to months, depending on the duration of the activity and environmental conditions (Schaffelke et al. 2016).

Disposal of the excavated material in unconfined ‘spoil grounds’ at sea is common during maintenance dredging. The coarse particles in relocated dredge material (gravels and sands) are rapidly deposited onto the seafloor, while finer sediments (silts and clay) can disperse many kilometres from the sites. Fine sediments at the relocation area can resuspend from the sea floor as a result of currents, tides and wave energy.

3. Wastewater pollution impacts on coral reef ecosystems

Many wastewater pollutants, including agricultural fertilizers, pesticides and organochlorine compounds, domestic and municipal wastes, trace metals and petroleum products are now recognized to have adverse effects on coral reefs, even when released at low levels (Haynes and Johnson 2000; Pinto et al. 2003; Risk 2014). Understanding their impacts and the species that are sensitive to these pollutants is important for informing management and monitoring of valuable environmental assets and ecosystem services.

This section provides an overview of documented impacts of wastewater pollution on coral reef ecosystems from a range of sources around the world.

3.1 Urban

Urban point source wastewater

Human sewage inputs are one of the major causes of decreased dissolved oxygen and eutrophication in many coastal waters worldwide (Cloern 2001). For example, research in Chesapeake Bay has also shown that the depletion of oxygen as a result of organic enrichment in coastal environments is associated with fish kills, changes in benthic community structure, reduced densities of bottom fish, and altered nutrient cycling (Kemp et al. 1983). Organic enrichment via the disposal of sewage effluent has been documented in a range of marine communities including rocky shores (Fairweather 1990; Bickford 1996), coral reefs (Grigg 1994, Smith et al. 2002, Lapointe et al. 2005), kelp forests (Smith and Simpson 1992), and subtidal soft bottoms (Al-Ghadban et al. 2002).

As the focus of this policy brief is about wastewater and coral reefs, a range of examples of the documented impacts of nutrient enrichment on coral reefs are highlighted in Box 1 and summarised in Table 2.

BOX 1: Nutrients and coral reefs

Eutrophication is the result of a particular type of marine pollution caused by the release of excess nutrients (N and P) into coastal waters (Cloern 2001). Nutrient enrichment in coral reef systems can contribute to direct impacts such as loss of coral diversity, structure and function, including phase shifts to a macroalgae dominated system (Fabricius 2011) and/or indirect impacts such as increased coral disease (Sutherland et al. 2004, Vega Thurber et al. 2014) or reduced reproductive success (e.g. Gilmour, 1999).

High availability of dissolved inorganic nutrients can lead to significant physiological changes in corals, such as decreased calcification rates and higher concentrations of photopigments, but generally does not lead to mortality (reviewed in Fabricius 2005, 2011). Eutrophication has also been found to hamper coral gamete production, alter the timing of spawning and decrease fertilization success (Gilmour 1999; Loya et al. 2004), and can also decrease the survival of coral recruits (Gilmour 1999, Abelson et al. 2005).

The indirect effects of nutrient enrichment on corals can include enhanced macroalgal productivity and growth that compete with corals for substrate (Dunstan and Johnson 1998; Abelson et al. 2005), and increased phytoplankton productivity. Excessive phytoplankton productivity can result in extreme population increases that reduce benthic light availability for both corals and reef seagrasses (Diaz and Rosenberg 2008; McKenzie et al. 2014), or may lead to high organic matter concentrations in the water column and in sediments (as predicted in a recent study examining the loss of peat lands in Indonesia; Abrams et al. 2016). Corals in nutrient-enriched or turbid waters appear more vulnerable to temperature stress than those in low nutrient environments (Wooldridge and Done 2009).

A major long-term effect of increased loads of nutrients in coral reefs is postulated to be the triggering of outbreaks of the coral-eating crown-of-thorns starfish (*Acanthaster planci*), which kill significant areas of corals on reefs (Birkeland 1982; De'ath et al. 2012). Evidence suggests that the survival and growth of crown-of-thorns starfish larvae is enhanced by increasing concentrations of large phytoplankton that are dependent on the availability of terrestrially-derived nutrients (dissolved inorganic N and dissolved inorganic P) or naturally enriched nutrient conditions. Houk et al. (2007) linked the primary driver of outbreaks in the north Pacific to a natural transition zone chlorophyll front and a similar situation was found in Vanuatu (Houk and Raubani 2010). Present day outbreaks can also be influenced by other anthropogenic changes (Brodie et al. 2005; Fabricius et al. 2010), including removal of adult predators (Sweatman 2008), changes to population structures of predators on larval and juvenile stages (Randall 1972), destruction of larval predators (Chesher 1969) and larval food supply enhancement (Birkeland 1982, Brodie 1992).

Many studies have shown that increased nutrients from terrestrial sources can contribute to increased incidence of coral diseases (Antonius 1981; Al-Moghrabi 2001; Bruno et al. 2003; Furby et al. 2014; Haapkylä et al. 2011; Kuta and Richardson 2002; Lamb et al. 2016; Voss and Richardson 2006; Redding et al. 2013; Sato et al. 2016). Nutrient-rich terrestrial discharges from agricultural and urban lands can directly affect the microbial composition of reef environments (Kriwy and Uthicke 2011; Witt et al. 2012) and cause increased populations of potential pathogens on coral colonies (Garren et al. 2008; Jessen et al. 2013). Reducing nutrients derived from land-based sources is therefore a prime target to mitigate the impacts of coral disease.

Table 2. Summary of the documented effects of nutrient enrichment on coral reefs.

Issue	Process	Effect	Region	References
Macroalgal overgrowth	Nutrient enrichment leads to fast-growing macroalgae expansion	Macroalgae proliferates at the expense of coral	Global. However, in absence of grazing fish and invertebrates the problem may be more severe, e.g. the Caribbean.	De'ath and Fabricius (2010); D'Angelo and Wiedenmann (2014); Gavio and Mancera Pineda (2015); Hixon (2015); Jouffray et al. (2015); Lapointe et al. (2004, 2015); Rasher et al. (2012)
Increased turbidity	Increased sediment and nutrient inputs from rivers	Reduced light for coral growth	Global	Fabricius et al. (2014, 2016); Risk (2014); Lapointe et al. (2004, 2015)
Coral disease	Nutrient excess promotes certain coral diseases	Higher levels of coral disease in areas of poor water quality	Global	Bruno et al. (2003); Furby et al. (2014); Haapkylä et al. (2011); Lamb et al. (2016); Redding et al. (2013); Voss and Richardson (2006);
Crown-of-thorns starfish outbreaks	Enhanced survivorship of COTS larvae	Outbreak populations of COTS and large scale coral predation	Indo-Pacific	Brodie et al. (2005); Fabricius et al. (2010); Wolfe et al. (2015)
Increased bleaching susceptibility	Nutrient enrichment leads to lower bleaching thresholds in corals	Higher levels of bleaching when water quality is poor.	Global	Carilli et al. (2010); Fabricius et al. (2013); Vega Thurber et al. (2014); Wiedenmann et al. (2013); Wooldridge (2009); Wooldridge and Done (2009);

Issue	Process	Effect	Region	References
Bioerosion	Nutrient enrichment leads to increased populations of bioeroding organisms	Loss of coral framework	Global	DeCarlo et al. (2015); Glynn and Manzello (2015); Smith et al. (1981); Ward-Paige et al. (2005)
Nutrient enrichment exacerbating Ocean Acidification	Multiple stressors acting in additive or synergistic way	Reduced coral growth	Global	D'Angelo and Wiedenmann (2014); Vogel et al. (2015)

There are many examples around the world where sewage discharges have been shown to impact coral reef ecosystems. For example, macroalgal blooms on southeast Florida coral reefs have been attributed to sewage N (from septic tank leachate and ocean outfalls) (Lapointe et al. 2004; Lapointe et al. 2005). Prolonged discharge of primary treated effluent (1972 to 1992) at Green Island near Cairns on the Great Barrier Reef, Australia led to abnormal and luxuriant growth of seagrass in a bay where the hydrodynamic regime caused retention of the diluted effluent (van Woesik 1989). The best documented example of the effects of sewage on coral reefs is in Kaneohe Bay, Hawaii (Smith et al. 1981; Stimson 2015); see Box 2.

In Kuwait, the organic content of sewage discharged into coastal waters is high and regularly septic due to an overloaded system, long retention times, high ambient temperatures and low dissolved oxygen (Al-Ghadban et al. 2002). Kuwait marine waters have been subject to inputs from urban development, untreated sewage discharges and decreasing river flow from the Shatt al-Arab River (Devlin et al. 2015), which has increased phytoplankton biomass and changed the phytoplankton species composition.

In Mauritius, domestic sewage released to coastal waters from urban areas and poorly planned housing developments on reclaimed wetlands is a cause of eutrophication and algal blooms that have led to the smothering of nearby coral reefs (Botte 2001). Algal blooms are observed annually at Trou aux Biches and isolated cases have been reported at Bain des Dames near Port Louis. High levels of nitrate and phosphate and associated proliferation of algal growth have been recorded at both Belle Mare and Flic en Flac (Botte 2001). Nutrient enrichment of lagoon waters also caused increased algal overgrowth of corals, affecting the coral reef ecosystem (Botte 2001). In 1990, the coastal waters and ecosystems of Port Louis experienced severe impacts as a result of eutrophication due to nutrient-enriched runoff and sewage effluent (Ramessur 2002). Eutrophication, algal blooms and smothering of corals found in shallow lagoons in Mauritius are common, particularly in Port Louis, where coral mortality is prevalent (Ramessur 2002).

BOX 2: Sewage Case Study: Kaneohe Bay, Hawaii

Sewage discharges into Kaneohe Bay, Hawaii increased from the end of the Second World War to 1978 due to increasing population and urbanization up to 20 ML/day in 1977 (Viles and Spencer 2014). This chronic discharge into the lagoon introduced high levels of inorganic N and inorganic P, and southern lagoon waters become increasingly rich in phytoplankton (Clutter 1973).

Reefs closest to the outfall become overgrown by filter-feeding organisms, such as sponges, tube-worms and barnacles (Banner 1974). The abundance of the non-native rhodophyte *Acanthophora spicifera* increased with proximity to the sewage outfall (Soegiarto 1972). Reefs in the centre of the Bay further from the outfalls were overgrown by the indigenous green algae *Dictyosphaeria cavernosa* (Smith et al. 1981). After diversion of the outfall into the ocean in 1978, nearshore nutrient levels reduced (PO_4^{2-}, NO_3^- +NO_2^-, and NH_4^-), phyto- and zooplankton populations declined and *D. cavernosa* abundance declined to 25% of previous levels (Maragos et al. 1985). At the same time, increases in the abundance and distribution of coral species were reported, and the reefs slowly recovered (Evans et al. 1986).

Although extensive seasonal algal blooms of non-native species have continued in Kaneohe and other nearby urbanized bays (Smith et al. 2002), a drastic decline in previously dominant *D. cavernosa* occurred in 2006. This has been attributed to a gradual return to a coral-dominated state following relocation of the sewage outfall in 1978 that eliminated the nearshore sewage nutrient inputs, which drove the initial phase shift to macroalgae in the 1970s (Stimson 2015; Bahr et al. 2015). These results demonstrate that coral reefs can recover after sources of terrestrial pollution are removed from the local environment. However, full recovery to coral-dominated high diversity habitats with larger colonies requires several decades.

Other demonstrated effects of sewage wastewater discharge include (with a specific location in some cases):

- In general, poor water quality – low clarity and high nutrient status - is correlated with lower coral cover, higher macroalgal cover (Li et al. 2015 – in Hainan Island, China; Reopanichkul et al. 2010 – Phuket, Thailand; Lapointe et al. 2011 – Negril, Jamaica).
- Increased cover of opportunistic green algae, *Ulva lactuca* and *Enteromorpha intestinalis* (Fairweather 1990).
- High rates of organic matter deposition affecting biogeochemical processes in sediments (Bickford 1996).
- Eutrophication and sedimentation hinder coral gamete production, alter spawning timing and decrease fertilization success (Gilmour 1999; Loya et al. 2004).
- Changed microbial communities on coral reefs with implications for coral diseases (Ziegler et al. 2016; Redding et al. 2013; Sutherland et al. 2010; Kaczmarsky et al. 2005).
- Nutrient enrichment can slow the development and metamorphosis of larvae and decrease the survival of coral recruits (Gilmour 1999; Abelson et al. 2005).
- Eutrophication promotes the growth of potential space competitors of coral recruits (Dunstan and Johnson 1998; Abelson et al. 2005), particularly toxic cyanobacteria or macroalgae that inhibit coral larvae settlement (Kuffner and Paul 2004; Naumann et al. 2015 – Aqaba, Red Sea; Reopanichkul et al. 2009 – Surin Islands, Thailand; Reopanichkul et al. 2010 – Phuket, Thailand).
- Sedimentation hinders larvae settlement, smothers coral recruits and increases turbidity (Hodgson 1990), leading to coral losses (e.g. Sheppard 2015 – Persian Gulf).
- Significant changes to local fauna and flora communities including the bioaccumulation of trace contaminants by fish in the vicinity of inshore outfalls (Mann and Ajani 1991; McLean et al. 1991; Scanes 1992).
- Elevated levels of chloro-hydrocarbon, organochlorine compound and trace metal contaminants in sediment and fish around outfalls (Krogh and Scanes 1996).
- Changes in trace metal contamination in sediments around sewage outfalls (Gray 1996).
- Elevated concentrations of organochlorines in oysters (Scanes 1996), and in receiving marine biota in the Mediterranean Sea along with polychlorinated biphenyls (Syakti et al. 2012).

- Changes in fish and invertebrate communities, manifested as shifts in community structure and abundance (Grigg 1994; Otway 1995; Reopanichkul et al. 2009), reproductive impairment (Hose et al. 1989) and histo-pathological changes (Brown 1988).
- Sewage effluents increase growth anomalies in *Porites* corals in Hawaii (Yoshioka et al. 2016).

An important factor determining susceptibility of coastal ecosystems to the adverse effects from land-based pollutants is the amount of exchange between the water body and the open ocean. Long water residence times promote an increasing build-up of land-based pollutants, thus water bodies with low exchange rates with the open ocean seem to be particularly vulnerable to the effects of pollution (Brodie et al. 2012). Transport, dispersion, and ultimately biological effects of pollutants in marine systems depend on the persistence of these chemicals under tropical conditions and their bioaccumulation and biodegradation rates. Typically, pollutants with a higher solubility in surrounding waters will be transported further offshore, and the association of pollutants with particulate matter (sediment) may increase environmental persistence (van Dam et al. 2011). Biota carrying accumulated loads of persistent chemicals in their tissues can also transport pollutants between ecosystems and long distances from their discharge or deposition sites.

It is important to note that the impact of sewage discharge from marine outfalls is generally localized. For example, studies at Coffs Harbour, Australia showed that impacts are restricted to within approximately 300 metres of the outfall for most variables (e.g. algal species richness, changes to the structure of invertebrate communities living in kelp holdfasts). However, the green alga *Ulva lactuca* showed significantly greater cover than at reference sites for a distance of 500 metres from the point of discharge (Smith 1996). Similarly, Anderlini and Wear (1992) found that only benthic communities within a 500 metre radius of the outfall in Fitzroy Bay, Wellington, New Zealand, were affected by the discharge. However, for sewage discharge into enclosed bays, although impacts may be localized, they can be severe as demonstrated in the Kaneohe Bay case (see Box 2).

The direct discharge of sewage also introduces human pathogens, such as bacteria and viruses, which contaminate seafood and diminish the recreational attractiveness of the area. Introduced human pathogens also have potential consequences for bacteria/virus-host interactions, which can increase the impact of bacterial or viral infections in marine biota, and potential synergistic effects in the receiving environment.

Urban diffuse wastewater

Diffuse wastewater pollution delivered from urban environments has similar impacts on receiving environments as point-source pollutants. In urban centers, stormwater overflows may deliver raw sewage where combined stormwater and sewer systems or illegal connections of sewer lines to stormwater systems, which can impact the receiving environment more significantly than either discharge alone (e.g. in Korea, Lee and Bang 2000; in Kuwait, Lyons et al. 2015). In coral reefs, elevated nutrient concentrations from urban diffuse sources have been shown to trigger harmful algal blooms (Lapointe and Bedford 2010; see Florida Keys case study in Box 3), sediment can increase turbidity (Fabricius et al. 2014, 2016) and smother corals (e.g. in the Western Gulf of Thailand, Yeemin et al. 2013), and toxic contaminants, such as metals, pathogens and hydrocarbons can bioaccumulate in aquatic organisms causing sub-lethal effects and a reduction in organism fitness (Mearns et al. 2012). Diffuse pollution from Jakarta has caused extensive damage to the marine environment as far as the extensive coral reefs of the Thousand Islands region, which is up to 100 km from the city (Dsikowitzky et al. 2016; Baum et al. 2015).

BOX 3: Diffuse Urban Pollution Case Study: Florida Keys, U.S.A.

Coral reefs in southeast Florida have experienced an unprecedented succession of macroalgal blooms and invasions by native and non-native chlorophytes since the late 1980s (Lapointe and Bedford 2010). Extensive blooms of unattached *Codium isthmocladum* first grew during summer in 1989 and 1990 on deep reefs (24–43 metres) off southern Palm Beach and northern Broward county (Lapointe 1997). These initial blooms were followed by blooms of attached *C. isthmocladum* and two Caulerpa species in the late 1990s on reefs off north Palm Beach (Lapointe et al. 2005). Documented blooms in 2001 were the first reports of two green algal species in Florida's coastal waters. These unprecedented macroalgal blooms have been attributed to increasing land-based nutrient inputs (Lapointe and Bedford 2010).

Recent studies demonstrate that the invasion of coral reefs in southeast Florida by non-native macroalgae can be attributed to stormwater, as the sites most directly impacted and the seasonality both correlate with stormwater runoff (Lapointe and Bedford 2010).

Coastal development

The implication of poorly managed coastal development on coral reefs are similar to those observed for urban areas described above, but new development is often associated with sediment runoff and soil erosion due to land clearing in coastal areas.

Coral reef ecosystems are directly and negatively affected by sediment inputs that increase turbidity (reducing light penetration) and sedimentation of fine particles and organic rich flocs (muddy marine snow). The potential impacts of sediment runoff on coral reefs are summarised in Box 4.

BOX 4: Sediment and coral reefs

Turbidity and light effects

Pulses of suspended sediments from river runoff increase turbidity and reduce the levels of light reaching corals and seagrass, reducing adult photosynthesis and production (Fabricius et al. 2013, 2014, 2016; Restrepo et al. 2016). While corals can occur across a broad range of light conditions due to their physiological (Titlyanov 1991; Anthony and Fabricius 2000) and morphological (Anthony et al. 2005; Todd 2008) plasticity, some corals are vulnerable to reduced light levels, leading to critical metabolic deficits and reduced growth (Cooper et al. 2008). Prolonged or excessive sediment exposure can also result in coral disease (Sutherland et al. 2004) and ultimately mortality (Victor et al. 2006). Similar effects occur when corals are exposed to suspended sediment pulses from dredging and spoil dumping activities (McCook et al. 2015) including increased incidence of coral diseases (Pollock et al. 2014).

Sedimentation

Corals vary greatly in their tolerance to sediment deposition, with some of this variation due to differences in colony morphologies (Erftemeijer et al. 2012; Flores et al. 2012; Junjie et al. 2014). Tolerance can also be considered in terms of the energetic cost to the colony. The energy required to shed sediments varies between species due to differences in the efficiencies of passive (largely dependent on growth form) or active (such as cilia or tentacle manipulation or mucus production) strategies for sediment removal (Rogers 1990; Sofonia and Anthony 2008; Stafford-Smith and Ormond 1992). Compounding the energy cost of removal is the reduction of photosynthesis by sediments that shade the coral (Weber et al. 2012).

Early life-history stages of corals are particularly susceptible to sedimentation. Following high river flows and associated increases in sediment and nutrient loads, the densities of juvenile corals on reefs prone to sediment accumulation have been shown to markedly decline on the Great Barrier Reef (Thompson et al. 2013). Sedimentation is known to hamper larvae settlement and to smother coral recruits (Hodgson 1990). Sediment accumulation reduces coral settlement by physically blocking access to suitable substrate (Birrell et al. 2005; Dikou and van Woesik 2006) and also alters benthic microbial communities and so disrupting critical chemical cues for settlement and metamorphosis (Negri et al. 2002; Webster et al. 2004). Once settled, survival depends in part on water quality (Abelson et al. 2005) with juveniles highly vulnerable to sedimentation due to their small size, which precludes passive shedding, and small energy reserves limiting the scope for active removal or tolerance of intermittent shading (Fabricius and Wolanski 2000).

There are several examples of the impacts of coastal development on coral reef ecosystems. For example, in Langkawi Island, Malaysia, some fringing coral reefs around the island have high coral cover while others have low coral cover. High sedimentation rates are the main driver of declines in fringing reefs, associated with intense coastal development (Abdulla et al. 2002; Abdulla and Yasin 2002). Post-tsunami surveys carried out in the Langkawi archipelago in January 2005 showed that corals did not suffer any significant structural damage as a result of the tsunami. Therefore, recent coral mortality has been attributed primarily to high sedimentation and turbid water due to poorly regulated coastal development (Abdulla et al. 2002; Abdulla and Yasin 2002; Lee et al. 2005; Praveena et al. 2012).

In the Thousand Islands, off Jakarta in Indonesia, one of the largest megacities worldwide, coral reefs are depauperate in normally dominant coral reef species close to Jakarta, but return to more usual reef species community composition the greater the distance offshore (Cleary et al. 2016). This apparent degradation of the inshore reefs is believed to be associated with land-based pollution from Jakarta and western Java (Baum et al. 2015) and reef species composition is strongly correlated to water quality variables, especially water clarity (Cleary et al. 2016).

In many cases, the combined influence of coastal development including urban wastewater can be significant, as demonstrated in Sulawesi, Indonesia (Box 5).

BOX 5: Coastal development Case Study: Sulawesi, Indonesia

The Spermonde Archipelago in southwest Sulawesi supports high diversity coral reefs located in the centre of the Coral Triangle (Veron 1993), however, is one of the most vulnerable reef regions globally. Coral reefs in the archipelago are exposed to land runoff (causing eutrophication and sedimentation) as well as other pressures (destructive fishing and overfishing) that have collectively impacted on reef structure and function (Edinger et al. 1998). Reefs exposed to land-based pollution (sediment and nutrient loads from agricultural as well as urban wastewater) had 30-50% lower diversity at 3 metres, and 40-60% lower diversity at 10 metres depth relative to unpolluted reefs. Temporal comparison of the results with surveys 15 years earlier documented a 25% decrease in coral generic diversity on reefs that were resampled (Edinger et al. 1998). Recent studies found that strongly eutrophic near-shore reefs had low juvenile coral diversity, high abundance of potential space competitors, such as filamentous algae and filter feeders, and low live hard coral cover (Sawall et al. 2013). This raises concerns for recovery and resilience of near-shore reefs to future impacts. Management actions have focused on controlling sources of land-based pollution (agricultural, land clearing and urban sources) to address this declining coral reef condition.

3.2 Agriculture

As described in Section 2.1, agricultural development can generate a range of pollutants including sediments, nutrients and pesticides. The impacts of nutrients and sediments on coral reef systems are similar to those noted above for point source pollution, although the influence may be acute rather than chronic. The potential impacts of pesticides are described in Box 6.

BOX 6: Pesticides and coral reefs

The connectivity of catchment, estuarine and inshore reef ecosystems, the high sensitivity of foundation species (e.g. corals and seagrasses) to pesticides, and evidence that pesticides increase the vulnerability of reef species to the negative effects of thermal stress support efforts to significantly reduce pesticide contamination (Negri et al. 2011). A number of studies have documented the impacts of pesticides on reefs, including on reef-building corals, marine sediment and biota in the Florida Keys (Glynn et al. 1984, 1989, 1995), on coral photosynthesis in Bermuda (Owen et al. 2002) and the GBR (Cantin et al. 2007), on coral metabolism in the Philippines (Råberg et al. 2003) and causing sub-lethal effects on coral life stages in the GBR (Lewis et al. 2009; Markey et al. 2007; Negri et al. 2005).

Organophosphorus insecticides such as chlorpyrifos, or herbicides such as glyphosate; triazine herbicides such as atrazine, simazine, ametryn and Irgarol 1051; and urea herbicides such as diuron and tebuthiuron are some of the key pesticides that affect coral reef biota (Haynes and Johnson 2000; Lewis et al. 2009; Mitchell et al. 2005;). The most commonly detected herbicides on coral reefs are photosystem II (PSII) herbicides (e.g. diuron, atrazine, simazine, Irgarol 1051), which inhibit electron transport through the photosystem and inhibit photosynthesis in coral symbionts – zooxanthellae (Cantin et al. 2007) – and other marine biota (e.g. macroalgae, Magnusson et al. 2008; crustose coralline algae, Harrington et al. 2005). The effects of PSII herbicides on zooxanthellae have flow-on effects to the animal host, which suffers a proportional decrease in energy transfer (Cantin et al. 2009), which can lead to a long-term reduction in reproductive output (Cantin et al. 2007).

Short-term exposure to low insecticide concentrations can also affect different coral life history stages, with endosulfan, chlorpyrifos and profenofos found to impact photosynthetic performance and/or the density of zooxanthellae within adult corals at higher concentrations (Markey et al. 2007). Pesticides have also been shown to accumulate in coral tissue (Olafson 1978), inhibit larval metamorphosis (Markey et al. 2007), and cause coral bleaching (Jones 1997; Jones 2004; Negri et al. 2005), which is considered a sub-lethal stress response (and secondary effect) to the oxidative stress in zooxanthellae as a result of chronic photoinhibition (van Dam et al. 2011).

A key concern in relation to persistent pesticides is due to their bioaccumulation in food webs and their potential impacts on top predators. There is increasing evidence of widespread relatively low-level exposure of inshore reefs to these chemicals during high flow flood events at concentrations sufficiently high to cause effects on biota (diuron 0.1-1.0 µg/L) (for example on Australia's Great Barrier Reef; Lewis et al. 2009). As multiple factors potentially interfere with the same physiological mechanism (e.g. PSII herbicides), additive or even synergistic toxic effects may occur (Bengtson-Nash et al. 2005). Herbicide-induced interference with primary production may exert a bottom-up pressure on the ecosystem, potentially decreasing reef resilience to other environmental stressors, such as increased sea temperatures and ocean acidification (van Dam et al. 2011).

There are well documented examples of the impacts of agricultural runoff on coral reef systems. In many cases, these impacts are combined with influences of urban areas and coastal development but the agricultural land uses often dominate wastewater discharges. For example, in Puerto Rico (Box 7) and the Great Barrier Reef Australia (Box 8).

BOX 7: Agricultural Wastewater Case Study: Puerto Rico

Documented land cover changes in a Puerto Rico watershed between 1936 and 2004 due to reforestation and urbanization resulted in the predominantly sugarcane fields being replaced by twice as much forest cover and 10-times more urban areas. Expected sediment yield improvements to near-shore coral reefs were not realized, with sediment and nutrient loads remaining high and at potentially threatening levels for adjacent coral reefs. The simultaneous reduction in live coral cover that accompanied reforestation and urbanization since the 1970s could be attributed to: (a) alternative yet highly influential sources of sediment; (b) the potentially secondary role of cropland and forest cover changes in influencing near-shore coral reef conditions relative to other types of stressors, such as climate change; and (c) the potentially dominant role that urban pollution may have had in affecting marine water quality to the extent of reducing live coral cover (Ramos-Scharron et al. 2015). There are also possible exacerbating influences on coral reefs that are impacted by both terrestrial runoff and reduced herbivory (Jackson et al. 2014). The results highlight the complex nature of marine water quality management, and the importance of a portfolio of actions to address the range of land-based pollutants impacting near-shore coral reefs.

BOX 8: Agricultural Wastewater Case Study: Great Barrier Reef, Australia

The Great Barrier Reef (GBR) is a World Heritage Area and contains extensive areas of coral reef, seagrass meadows and fisheries resources. It is estimated that the GBR is worth A$15-20 billion per year to the Australian economy and provides approximately 64,000 full time jobs (Brodie and Pearson 2016). Many of the species and ecosystems of the GBR are in poor condition and continue to decline. The principal causes of the decline are catchment pollutant runoff associated with agricultural and urban land uses, climate change impacts and coral predation by crown-of-thorns starfish outbreaks.

Numerous rivers in adjacent catchments discharge pollutants from agricultural, urban, mining and industrial activity. Pollutant sources have been identified and include suspended sediment from erosion in cattle grazing areas; nitrate from fertiliser application on croplands; and herbicides from various land uses (Brodie et al. 2013; Waters et al. 2014). Modelling predictions estimate that each year almost 19,000 tonnes of P and 141,000 tonnes of N are discharged to rivers flowing to the coast (Kroon et al. 2013), ultimately ending up on near-shore habitats, including coral reefs. Modelled estimates of the total load of photosystem II (PSII) inhibiting herbicides entering the Great Barrier Reef annually range from 15,700 kg per year (Lewis et al. 2011) to 30,000 kg per year (Kroon et al. 2013).

Long-term delivery of terrestrial pollutants since the 1850s, when land use changes to agriculture began, has driven declines in near-shore reefs, with a 50% reduction in coral cover documented in the last 27 years on the Great Barrier Reef (De'ath et al. 2012), and seagrass and dugongs have been affected (Brodie and Waterhouse 2012), especially over the last 30 years.

3.3 Industrial pollution and mining

As identified in Section 2.3, industrial and mining activities can discharge a mix of wastewater pollutants including trace metals, fuels or petroleum hydrocarbons, carbon-based organic chemicals (e.g. halocarbons), polychlorinated biphenyls.

Following industrialization, unnatural quantities of metals such as arsenic, cadmium, copper, mercury, lead, nickel and zinc have been released, and continue to be released into the aquatic environment through stormwater and industrial wastewater discharges. Arsenic, cadmium, copper, mercury and zinc are the five metals with most potential impact that enter the marine environment in elevated concentrations as a consequence of agricultural activity (Haynes and Johnson 2000).

The potential impacts of trace metals on coral reefs are summarised in Box 9.

BOX 9: Trace metals and coral reefs

Bioavailability, physiological effects and fate of trace metals are highly dependent on the chemical form and oxidation state in which metals exist, as reflected by their toxicity (van Dam et al. 2011). Once introduced in a biotic matrix, trace metals have the potential to affect nutrient cycling, cell growth and regeneration, as well as reproductive cycles and photosynthetic potential (Peters et al. 1997; Haynes and Johnson 2000). Elevated levels of copper, zinc and tin in the effluent of a tin smelter in Thailand caused reduced growth and calcification rates in branching corals (Howard and Brown 1987). Exposure to some trace metals has also been shown to cause coral bleaching (e.g. iron - Harland and Brown 1989; copper - Jones 2004; mercury - Markey et al. 2007). Exposure of corals to trace metals can also lead to sub-lethal effects, such as decreased photosynthetic efficiency, inhibition of gamete fertilization and larval metamorphosis (mercury - Markey et al. 2007; copper - Negri and Heyward 2001) and detrimental effects on the metabolism of both branching – *Pocillopora damicornis* – and massive – *Porites lutea* – corals (copper - Alutoin et al. 2001; Nyström et al. 1997).

Some impacts from trace metals may not be immediately obvious, for example, toxic metals (e.g. mercury) can bioaccumulate in the tissues of marine organisms, increasing in concentration at each successive trophic level in the food web. These sub-lethal affects can have implications for species' reproductive success and along with the known lethal effects of wastewater pollutants, raises significant concerns for reef habitats and biota. Of particular concern is the extra stress that metal bioaccumulation places on higher tropical level organisms that are already threatened or endangered, such as migratory cetaceans and turtles, and on ecosystem resilience to other pressures, such as climate change driven thermal stress.

Around the world, concentrated tailings and excavated overburden from mining activities are disposed of into marine environments with the main ecological effects being: (i) uptake of bioavailable trace metals into tissues of marine organisms; (ii) bioaccumulation of heavy metals in food webs (e.g. Wang and Rainbow 2008; Ratte 1999;) and ultimately into seafood consumed by people; and (iii) reduction in biodiversity and abundance of receiving marine communities, due to direct smothering or sub-lethal effects from the contamination of benthic communities (Kline and Sketoll 2001; Ellis 2003), or indirectly to loss of habitat.

The delivery volumes and contaminant loads in mine tailings, overburden and leachate to coral reefs, and local hydrology influence the impacts on marine habitats and organisms. For example, only very localized impacts on lower trophic level groups (e.g. zooplankton) were documented near the Lihir gold mine on Niolam Island, Papua New Guinea, but not in higher organisms (e.g. micronekton, baitfish or pelagic fish) (Brewer et al. 2012). This lead to the conclusion that the impacts of the mine wastewater discharge were locally confined to the influence of the tailings slurry on trace metal accumulation in small, less mobile species, with little effect on the abundance and biodiversity of the broader reef habitat or food web.

An example of the impact of discharged mine tailings is provided in Box 10 for the Panguna copper mine in Bougainville.

BOX 10: Mining Case Study: Panguna Copper Mine, Bougainville, Western Pacific

The Panguna copper mine on Bougainville Island operated from 1969–1990 and discharged mine tailings into the Kawerong and upper Jaba rivers to be ultimately transported and deposited in the adjacent tropical marine environment. It was intended that tailings reaching the near-shore marine environment would be removed by ocean currents (AGA 1989). The copper concentrator in the mine processed 130,000 tons of ore daily, which discharged dissolved copper, residual lime, aluminium, heavy metals such as mercury, cadmium, lead, zinc, and arsenic, xanthate, methyl isobutyl carbinol and polyacrylamide monomer into waterways and ultimately the near-shore marine environment (Gillespie 1996).

A large portion of the tailings discharged into the Kawerong-Jaba river system stayed in the system (40%), with the remaining 60% entrained in the delta at the mouth of the Jaba River in Empress Augusta Bay. Due to low water exchange rates with the open ocean, very little material was transported away from Empress Augusta Bay by currents (AGA 1989). The impacts of this toxic cocktail of contaminants were observed locally in the waterways and near-shore environment (e.g. alkaline waters, loss of wetland and soil productivity, plant and fish kills, geological and hydrological changes to Empress Augusta Bay) as well as by local people (e.g. skin and eye irritations, poisoning) (Gillespie 1996). Critically, all plant and animal life in the Kawerong and Jaba rivers died, and significant declines in marine fish and shellfish food resources were observed (Gillespie 1996).

Decades after the mine closed the river, wetland and near-shore marine environments have not fully recovered.

Dredging impacts on coral reefs can be categorised into physical impacts such as changing bathymetry, smothering, current velocity and wave conditions, and environmental impacts such as increased water turbidity, sedimentation and habitat removal or damage (Jensen and Morgensen 2000). Sediment plumes formed by the release and dispersal of material during dredging, transport or disposal of dredge spoil decrease light penetration through the water column. The attenuation of light directly impacts corals and their algal symbionts, which have minimum light requirements for photosynthesis ranging from <1% to 60% of surface irradiance (Erftemeijer et al. 2012). Tolerance to reduced light below 10% of surface radiance is rare, and most fast growing reef-building corals (e.g. branching *Acropora*) requiring at least 60% of surface radiance to survive (Japp and Hallock 1990). Decrease light results in decreased algal symbiont productivity leading to a decline in coral nutrition, growth, reproduction, and calcification rate and depth distribution, eventually result in coral starvation (Richmond 1993).

Direct deposition of solid waste also occurs around the world, as demonstrated at an industrial complex in the Red Sea, Jordan (Box 11).

BOX 11: Industrial Case Study: Industrial Complex, Red Sea, Jordan

On the southern section of the Jordanian Gulf of Aqaba in the Red Sea is a coastal industrial complex with a fertilizer plant, thermal power station and chemical storage facilities in close proximity to fringing coral reefs. The reef flat and reef front at this location support hard and soft corals to a depth of more than 40 metres. Improper planning of the construction and operation of the coastal industrial site has led to degradation of the adjacent coral reef ecosystem (Al-Zibdah et al. 2008).

Three years of reef surveys documented benthic communities close to the industrial jetty characterized by low diversity and soft coral dominance (16–30% cover). Reef front sites (12 m) had higher hard coral cover (30–35%) than reef flat sites (5–12%) but lower than unpolluted reef sites along the Jordan coast (50-65%). Species richness for corals and other macrobenthos increased with greater distance from the industrial jetty, and there was a higher abundance of hard coral competitors (e.g. macroalgae and corallimorphs) at sites closer to the industrial complex (Al-Zibdah et al. 2008). The rate of death of the scleractinian coral *Stylophora pistillata* was 4–5 times greater at the polluted site near the phosphate plant compared with a healthy reef in the south (Walker and Ormond 1982).

These impacts have been attributed to the deposition of solid waste in the shallow water of the industrial complex and the use of ineffective waste handling and disposal facilities.

Hydrocarbons can be introduced into marine environments through oil and fuel spills, which can occur more frequently in areas associated with industrial or port activities. The potential impacts of hydrocarbons on coral reefs are summarised in Box 12.

BOX 12: Hydrocarbons and coral reefs

Direct contact with oil or sediment contaminated by hydrocarbons can kill adult corals or cause sub-lethal impacts, such as decreased growth, metabolic aberrations or nutritional abnormalities (Jackson et al. 1989; Raimondi et al. 1997; White et al. 1985). Sessile or low mobility filter feeders and benthic organisms typically bioaccumulate toxic hydrocarbon compounds or show genetic mutations and metabolic disorders in their tissues (van Dam et al. 2011). Corals exposed to hydrocarbons often respond by expelling their zooxanthellae (bleaching; Jones and Heyward 2003), having impaired reproduction or tissue damage (Jackson et al. 1989). Chronic exposure of coral reefs to refinery petroleum in the Caribbean resulted in decreased coral cover, diversity and local recruitment (Bak 1994), and comparable detrimental impacts on reefs were observed after an acute major oil spill in Panama (Guzmán et al. 1994). Aromatic hydrocarbons have been shown to decrease photosynthetic performance of zooxanthellae in some corals (Cook and Knap 1983; Neff and Anderson 1981) and cause tissue retraction after exposure to low concentrations but normal tissue expansion recovered within a week (Knap et al. 1983).

Decreased reproductive success of both brooding and broadcasting corals after oil exposure has been observed due to impaired gonadal development (Peters et al. 1981; Guzmán and Holst 1993), and infertility and decreased egg size up to five years after exposure to a major oil spill (Guzmán and Holst 1993). In annual mass spawning events like those that occur in the Indo-West Pacific or South Pacific, broadcast spawning coral gametes are released in the water during brief synchronized events. If the spawning event coincides with an oil spill, an entire year of reproductive effort is threatened due to the implications for larval settlement and parent colonies. If exposure to oil and/or dispersant endures, impacts include inhibition of fertilization, metamorphosis and settlement of broadcast spawning scleractinian corals (Harrison 1994, 1999; Mercurio et al. 2004; Negri and Heyward 2000).

Chlorinated organic compounds (or organochlorines) are organic (carbon based) chemicals that contain bound chlorine mainly residual from historic use. A majority of these compounds are artificial and enter the environment through human activities, such as byproducts of combustion and industrial processes, or specifically manufactured as pharmaceuticals, plastics, and solvents (Haynes and Johnson 2000). Organochlorines include polychlorinated dibenzodioxins, dibenzofurans and biphenyls (PCBs) and are ubiquitous contaminants that are extremely toxic and persistent in marine environments, and have a tendency to bioaccumulate in tissue (van Dam et al. 2011). The potential impacts of industrial organochlorines on coral reefs are summarised in Box 13.

BOX 13: Industrial organochlorines and coral reefs

Organochlorines have been implicated in reproductive and immunological abnormalities observed in top predators, such as birds and marine mammals, and their effects on tropical marine species including mammals (Buckland et al. 1990; Haynes et al. 1999; Jarman et al. 1996;), fish (Lobel and Davis 2002; Matthews et al. 2008) and invertebrates (Matthews et al. 2008). However, there is limited data on concentrations in tropical waters or on coral reefs and their effects on reef-building corals. These substances bind to the aryl hydrocarbon receptor in vertebrates and invertebrates, resulting in interference with a broad range of cellular processes and the most significant known impacts are due to bioaccumulation in organisms at the top of the food web (van Dam et al. 2011).

An example of the impact of a range of industrial pollutants on coral reef communities is provided in Box 14 for a tuna cannery in Pago Pago, American Samoa.

Box 14: Industrial Case Study: Tuna Cannery, Pago Pago, American Samoa

In 1917, diverse coral communities occurred on the reef flat at Aua village in Pago Pago Harbour, American Samoa. Between the 1950s and 1980s, this area was seriously degraded by chronic pollution from two tuna canneries, fuel spills in the inner harbour and coastal development. By the 1970s, coral communities had declined substantially (Dahl and Lamberts 1977). In 1992, a pipe was installed to export wastewater from the tuna canneries to the harbour mouth. In addition, management of coastal development and fuel spills had improved by the early 1990s. Recent studies (Birkeland et al. 2013) have found that since the 1990s, there has been significant recovery of coral communities on the reef crest and outer reef flat where there is consolidated reef substratum (up to 30 m behind the reef crest). In contrast, it was found that recovery has been substantially slower or absent behind the reef crest, where the substratum is primarily loose rubble.

3.4 Emerging contaminants

In recent years, there has been increasing concern over the environmental risks of “emerging contaminants" or chemicals that were not previously detected in marine waters. These chemicals originate from a variety of products including human pharmaceuticals, veterinary medicines, nanomaterials, personal care products, paints and coatings. Some emerging contaminants, such as natural products and transformation products of synthetic chemicals may be formed in the environment by biochemical processes in animals, plants and microbes (Boxall 2012). The risk these chemicals pose to human health and the marine environment is largely unknown, and methods to detect them in natural environments are often not well-developed.

These chemicals enter the marine environment through different pathways (Berry et al. 2013), for example, directly from veterinary medicines that are used to treat animals at pasture, or indirectly during the application of manure, biosolids or other solid waste materials to soil. Once in soil, emerging contaminants may be transported to water bodies by leaching, runoff and drainage processes. They can also enter the marine environment via humans directly entering the water (sunblock chemicals, Downs et al. 2016), sewage discharges (O’Brien et al. 2014), urban stormwater, septic tanks, and intensive animal production (Ellis 2006). They are generally associated with health effects including endocrine disruption, interference with normal disease resistance, and altered reproductive cycles in aquatic organisms.

3.5 Conclusions

The only examples of coral reef communities that have been severely damaged from wastewater pollution are those where the primary pollutant was sediment or nutrients, or a toxic combination of pollutants. While pesticides, metals, hydrocarbons, and industrial organochlorines may cause sub-lethal and localized effects on reefs, no severe or extensive damage to reef communities has been documented. This is also the case for emerging pollutants such as pharmaceuticals, microplastics, nano materials and endocrine disrupting substances. A summary of documented impacts of wastewater pollution on coral reefs is provided in Table 3.

Additionally, different wastewater pollutants may trigger similar responses in reef species through alternate pathways. For example, exposure to metals (Harland and Brown 1989; Jones 1997), cyanide (Jones and Steven 1997), herbicides (Negri et al. 2005), elevated temperature (Hoegh-Guldberg et al. 2007a) and freshwater (Jones and Berkelmans 2014) can all induce coral bleaching. It is also possible that a single stressor induces a variety of responses including metabolic and reproductive sub-lethal responses when exposed to thermal stress (Downs et al. 2000). Flow-on effects to marine organisms that depend on coral reef habitats have also been documented as a result of exposure to wastewater pollutants. Fish assemblages have been shown to change across water quality gradients (Fabricius 2005) and in response to loss of coral habitat (Halford et al. 2004; Wilson et al. 2009; Yahya et al. 2011).

Table 3. Summary of impacts of specific wastewater pollutants on coral reef functional groups.

POLLUTANT	Representative compounds	Structural/reef matrix (corals, CCA)	Primary producers (seagrass, algae, phytoplankton)	Planktivores (reef fish, COTs)	Herbivores/grazers (reef fish, invertebrates)	Predators (fish, sharks, seabirds)
Nutrients	Dissolved inorganic nitrogen (DIN), dissolved inorganic phosphorus (DIP)	Hinders coral gamete production (Loya et al. 2004), alters spawning timing; decreases fertilization (Gilmour 1999), impacts larval metamorphosis and settlement (Gilmour 1999;); enhances substrate competition (Dunstan and Johnson 1998; Abelson et al. 2005), phase shifts (Fabricius 2011); increased coral disease (Sutherland et al. 2004, Vega Thurber et al. 2014)	Enhances growth (Dunstan and Johnson 1998; Abelson et al. 2005); population booms that reduce benthic light (Diaz and Rosenberg 2008; McKenzie et al. 2014); hypoxia (Al-Ghadban et al. 2002)	Enhances growth; potential population explosions (Birkeland 1982; De'ath et al. 2012)	Increases availability of algal food sources	
Sediment	Suspended sediment	Sedimentation/ burial; inhibits photosynthesis (Erftemeijer et al. 2012); hinders larval settlement; smothers coral recruits (Hodgson 1990); inhibits recovery	Inhibits photosynthesis due to turbidity (Fabricius et al. 2013, 2014, 2016; Restrepo et al. 2016); alters benthic microbial communities (Negri et al. 2002; Webster et al. 2004).			

POLLUTANT	Representative compounds	Structural/reef matrix (corals, CCA)	Primary producers (seagrass, algae, phytoplankton)	Planktivores (reef fish, COTs)	Herbivores/grazers (reef fish, invertebrates)	Predators (fish, sharks, seabirds)
Pesticides	Herbicides (diuron, atrazine, hexazinone, glyphosate); Insecticides (dieldrin, chlorpyrifos, DDT)	Inhibits reproduction; inhibits larval metamorphosis (Markey et al. 2007); genetic effects; herbicides inhibit photosynthesis (Owen et al. 2002) and the GBR (Cantin et al. 2007), & calcification	Inhibition of growth and photosynthesis	Herbicides can inhibit calcification	Bioaccumulation of persistent pesticides	Bioaccumulation of persistent pesticides
Trace Metals	Copper, zinc, arsenic, mercury, cadmium	Toxic sub-lethal effects on metabolism (Alutoin et al. 2001; Nyström et al. 1997), cell growth and regeneration; inhibits gamete fertilization and larval metamorphosis (Markey et al. 2007; Negri and Heyward 2001); affects photosynthetic potential (Peters et al. 1997; Haynes and Johnson 2000); coral bleaching (Harland and Brown 1989; Jones 2004; Markey et al. 2007)	Inhibition of growth and photosynthesis	Bioaccumulation (Wang and Rainbow 2008; Ratte 1999)	Bioaccumulation (Wang and Rainbow 2008; Ratte 1999)	Bioaccumulation (Wang and Rainbow 2008; Ratte 1999) & bio-magnification of toxicity

POLLUTANT	Representative compounds	Structural/reef matrix (corals, CCA)	Primary producers (seagrass, algae, phytoplankton)	Planktivores (reef fish, COTs)	Herbivores/grazers (reef fish, invertebrates)	Predators (fish, sharks, seabirds)
Hydrocarbons	Crude oil and other oil products; polycyclic aromatic hydrocarbons	Toxic sub-lethal growth reduction, metabolic and nutritional impacts (Jackson et al. 1989; Raimondi et al. 1997; White et al. 1985); inhibits reproduction; tissue damage (Jackson et al. 1989)	Inhibition of growth and photosynthesis (Cook and Knap 1983; Neff and Anderson 1981); bioaccumulation (van Dam et al. 2011)	Bioaccumulation (van Dam et al. 2011)	Bioaccumulation (van Dam et al. 2011)	Bioaccumulation (van Dam et al. 2011) & bio-magnification of toxicity
Industrial organochlorines	Dioxins, PCBs, furans	Toxic sub-lethal metabolism and genetic effects	Toxic sub-lethal metabolism and genetic effects	Bioaccumulation (van Dam et al. 2011)	Bioaccumulation (van Dam et al. 2011)	Bioaccumulation (van Dam et al. 2011); reproductive and immunological abnormalities
Emerging contaminants	Human and veterinary pharmaceuticals, nanomaterials, personal care products, paints, coatings	Endocrine disruption; interfere with normal disease resistance; altered reproductive cycles		Endocrine disruption; interfere with normal disease resistance; altered reproductive cycles	Endocrine disruption; interfere with normal disease resistance; altered reproductive cycles	Endocrine disruption; interfere with normal disease resistance; altered reproductive cycles

4. Wastewater pollution on reefs in the context of climate change

The combination of local threats and global threats from ocean warming and acidification leads to increasingly degraded coral reefs. Impacts include reduced areas of living coral, increased macroalgal cover, compromised reef structure, reduced species diversity, and lower fish abundance. Degradation of coral reefs is often accelerated by other local impacts from storms, pest infestations, and diseases (World Resources Institute 2012).

The “Reefs at Risk” program spatially analyzed the main risks to coral reefs from local and global stressors, at a global scale (Burke et al. 2011), and for the Coral Triangle region (Burke 2012). Coral reefs were classified using an estimate of present threat from local human activities, using an integrated index that considers the combined threat from activities at local and global scales, and identified the following cumulative pressures and impacts:

Local threats:

- Coastal development, including coastal engineering, runoff from coastal construction, sewage discharge, and impacts from unsustainable tourism.
- Watershed-based pollution, focusing on erosion and nutrient fertilizer runoff from agriculture delivered to coastal waters from rivers.
- Marine-based pollution and damage, including solid waste, nutrients, toxins from oil and gas installations and shipping, and physical damage from anchors and ship groundings.
- Overfishing and destructive fishing, including unsustainable harvesting of fish or invertebrates, and damaging fishing practices such as the use of explosives or poisons.

Global threats:

- Thermal stress, including warming sea temperatures, which can induce widespread or “mass” coral bleaching.
- Ocean acidification driven by increased CO_2 concentrations, which can reduce coral growth rates and decrease skeletal density.

Anthropogenic climate change (ocean warming and acidification) will exacerbate chronic local pressures, such as wastewater pollution, and the impacts on coral reefs are expected to magnify as sea surface temperatures, ocean chemistry, ocean circulation, sea level, rainfall and storm patterns continue to change this century. Although predicting the overall impacts of climate change on marine ecosystems is difficult, scientists agree that climate change has the potential to seriously affect marine habitats and species, decrease marine biodiversity, cause species distributional changes and reduce ocean productivity (IPCC 2014).

Interactions between climate and localized stressors such as pollution are expected to create particularly damaging synergies, adding to concerns about coral reefs globally. For example, corals exposed to nutrients, turbidity, sedimentation, or pathogens have been shown to be more susceptible to bleaching, or less able to survive a bleaching episode (Hoegh-Guldberg et al. 2007a; Wiedenmann et al. 2013). Furthermore, chronic local stressors, such as poor water quality, can affect the recovery potential of reef communities (Hoegh-Guldberg et al. 2007b). This is because fertilization and larval recruitment in corals are particularly sensitive to environmental conditions (Lam et al. 2015), and because macroalgal growth rates increase in nutrient-rich waters thus outcompeting corals (McCook 1999).

Recent research has demonstrated that the combination of ocean acidification (low aragonite saturation) and nutrient loading is ten times more effective at driving coral macrobioerosion than ocean acidification alone (DeCarlo et al. 2015). This has significant implications for coral reefs since declines in aragonite saturation will affect calcifying organisms, such as corals, resulting in slower growth rates and compromised reef structures. The best available modelling suggests that by 2050, only about 15% of coral reefs around the world will be in areas where aragonite levels are 'adequate' for sustainable coral growth (World Resource Institute 2012). Some reef species will also be directly affected by ocean acidification (e.g. shellfish), as well as indirectly through declines in the structural integrity of coral reef habitats. Even the present-day aragonite saturation level is close to the point where calcareous organisms may already be experiencing a weakening in their skeletons and shells. In this state, reef systems will be far more susceptible to other pressures including eutrophication, coral disease, storms and bleaching, which are also projected to increase in frequency due to climate change (e.g. Meissner et al. 2012; van Hooidonk et al. 2014).

Multiple stressors can influence coral reef ecosystems simultaneously. For example, low salinity, high nutrients and the presence of other pollutants such as pesticides are all experienced during flood events and can impact on coral reef health (Fabricius 2005, 2011; Jones and Kerswell 2003). Extreme flood events are also predicted to be more frequent due to climate change, increasing the delivery of terrestrial pollutants to coral reefs in some locations. Stress-resistance of communities, however, depends on the sensitivity of the resident species and further on the combined effect of the above-mentioned stressors (Coles and Jokiel 1978; Faxneld et al. 2011). This can lead to medium- and long-term impacts like reduced densities of juvenile corals (Thompson et al. 2011), subsequent changes in community composition (Smith et al. 2005; Thompson et al. 2011;), decreased species richness and shifts to communities that are dominated by more resilient coral species and macroalgae (DeVantier et al. 2006; Hughes et al. 2011;). These chronic environmental pressures – changes in terrestrial fluxes of freshwater, sediment, and nutrients (De'ath and Fabricius 2010; Dubinsky and Stambler 1996; Fabricius 2011) – reduce reef resilience by decreasing the threshold at which the coral-dominated state shifts into a different state. A return to the more desirable coral-dominated state by reducing chronic drivers of change such as land-based wastewater pollution may be difficult to achieve due to the inherent stability of the degraded state (Mumby and Steneck 2011). However, reducing pollution will generally have positive benefits for coral reefs even if the reef doesn't return to its original condition.

BOX 15: Case Study: Great Barrier Reef Resilience

The resilience of the Great Barrier Reef is challenged by a suite of stressors acting separately and in combination, both temporally and spatially. A key regional or local-scale driver of resilience on the Great Barrier Reef is water quality, specifically the consequences of land-based pollutants – nutrients, turbidity and sedimentation – on coral reefs (Fabricius 2011). There are several lines of evidence on the Great Barrier Reef demonstrating that elevated nutrients enhance macroalgal overgrowth of corals (Schaffelke 1999), and high turbidity as an acute stressor has a negative impact on herbivore abundance (Cheal et al. 2010; Wolanski et al. 2003). Reduced water quality is therefore likely to lower reef resilience through three mechanisms: (1) bottom-up enhancement of macroalgal growth (Schaffelke 1999), (2) negative impacts on coral physiology (Fabricius et al. 2013), and (3) loss of top-down control of macroalgal abundance through loss or displacement of herbivores.

5. Managing wastewater pollution to minimize impacts on coral reefs

In a number of locations, regulatory controls have been effective in reducing wastewater discharges to coral reefs, see examples for Kaneohe Bay (Box 2), Pago Pago Harbour (Box 14), and Great Barrier Reef point source sewage (Waterhouse and Johnson 2002). The Kaneohe Bay example in particular is a rare example of a reverse phase shift from algal domination after massive sewage pollution, to a coral dominated reef community (Stimson and Conklin 2008; Stimson 2015). Today Kaneohe Bay stands out as among the better reef sites across the Hawaiian Islands in terms of reef condition (Ku'ulei et al. 2015; Bahr et al. 2015). The spatial scale of these pollution solutions and the resources involved demonstrate how resource-intensive this issue can be, and ecological improvements to date have remained small-scale.

Successfully addressing wastewater impacts on coral reefs requires an approach that promotes integrated management at ecosystem scales, recognizing the connectivity between ecosystems and the catchment-coastal-marine continuum (Brodie and Waterhouse 2012; Waterhouse et al. 2016; Kroon et al. 2016). A large range of management approaches have been developed around the world including Integrated Coastal Zone Management (ICZM), Ecosystem Based Management (EBM), Marine Protected Areas (MPAs) and Integrated Marine (and Spatial) Planning (IMP).

Land-based sources of wastewater pollution are traditionally managed through wastewater treatment standards and regulations, coastal zone planning and policy, and integrated catchment management to reduce sediment and nutrient runoff from agriculture and urban centers (e.g. Brodie and Waterhouse 2012; Richmond et al. 2007; Wilkinson and Brodie 2011). Reducing diffuse source loads becomes increasingly important where point source discharges comprise only a small percentage of the total N and P loads, such as in the Great Barrier Reef (Waterhouse et al. 2012; Waters et al. 2014). Particularly as some point source treatment technologies can be excessively expensive. Globally, substantial effort is going into restoration of more natural flow regimes to coastal marine waters through, for example, removal of large dams, buying back irrigation water (Pincock 2010) or agricultural land (Stokstad 2008), and restoration of coastal floodplains (Buijse et al. 2002). Some effort is also focusing on decentralizing wastewater treatment, and promoting recycling and reuse of treated wastewater (Li et al., 2009, Hai et al., 2018).

5.1 Regulation and standards

Managing for reductions in land-based inputs of nutrient pollutants from point source discharges such as sewage treatment plants and phosphate mines (Cloern 2001) through regulation and standards is solvable using technology and proven practices and has been implemented for decades around the world, with relative success. For example, regulation has reduced the contributions from wastewater treatment plants and industrial discharges to total annual average N and P loads to the Danish coast from 50% to <10%, and from 59% to 20%, respectively, over 14 years (Carstensen et al. 2006). Subsequent declines in nutrient concentrations and phytoplankton biomass have been reported in the Western Dutch Wadden Sea (Duarte et al. 2009), the Danish straits (Carstensen et al. 2006; Duarte et al. 2009), and the Danish straits have shown some associated changes in flora and fauna. However, reducing sediment and nutrient inputs to coastal marine ecosystems by addressing agricultural sources at local and regional scales is infinitely more challenging (Cloern 2001), including those bordering coral reefs (Brodie et al. 2012).

UNEP (2015) has recently released the book "*Good Practices for Regulating Wastewater Treatment: Legislation, Policies and Standards*". While many useful recommendations are made as to the policy and legislative regimes needed to regulate wastewater, most of the case studies are from temperate regions and do not address marine pollution specifically. Established standards and technology exist to address some sources of terrestrial wastewater, such as the ANZECC Water Quality Guidelines, WHO Water Sanitation Health Standards, as well as standards specific to coral reefs such as the GBR Water Quality Guidelines 2010 (Great Barrier Reef Marine Park Authority 2010) and the ASEAN Marine Water Quality Management Guidelines and Monitoring Manual (Brodie et al. 2008) and ASEAN Marine Water Quality Criteria (AMWQC) (2002)[1].

5.2 Regulatory reform

The following conclusions on the need for a strong and coordinated regulatory regime to protect coral reefs comes from the GLOBE Action Plan for Coral Reefs (GLOBE 2010):

- *"Legislation must be reformed and rationalized for effective management of coral reefs. Lack of communication between government departments and a fragmented approach to policy-making for the coastal zone have led to both gaps and overlaps in legislation, inefficiencies and conflicting priorities. For example, in some cases, fishing licenses are granted at the national level that allows fishing in community based marine reserves which are covered by local legislation. A more integrated approach to coastal zone management is required which will establish robust and ambitious policies and rationalize existing and new legislation.*
- *Coral reef ecosystem-based management must be a top priority within government. At present the real social and economic value of coral reef ecosystems is not adequately integrated into government decision-making procedures meaning that there is often a perceived conflict between development needs and sustainable ecosystems management. Ecosystem-based management of coral reefs and closely associated ecosystems must be made a higher priority within government, and funding for sustainable, reef resilience-boosting measures for coral reefs must be dramatically increased.*
- *Swift strategic political action is urgently required at all levels of government. National parliaments must act now to introduce legislation that fills existing gaps in coral reef management requirements and to ensure that government implementation of existing legislation is effective and comprehensive. Governments should also recognise that they may not initially have the human capacity required for comprehensive implementation and a more strategic and integrated management approach may be necessary according to national coral reef priorities.*
- *A strong mandate for reform and greater scrutiny of government implementation is required. Many coral reef countries will require significant investment to build capacity and improve governance in order to ensure that legislation on specific coral reef management issues is effectively implemented. It is the responsibility of legislators to provide government agencies with the mandate and the resources to protect coral reef ecosystems within their jurisdiction and the communities which depend on them.*
- *Greater cooperation is required between coral reef nations to build capacity and coordinate effective and efficient management. International collaboration between coral reef nations, neighbouring countries, and the international community is essential for funding, capacity building, knowledge dissemination and coordination of management activities. Parliaments must ratify and adopt robust implementing legislation for all international and regional*

[1] http://environment.asean.org/46-2/

agreements relating to coral reef ecosystem conservation and management and hold governments to account for international commitments.

- *Legislators must provide the political leadership necessary for coral reefs and support governments in taking ambitious action to ensure ecological and social resilience for the future. Policymakers must begin planning now for social adaptation to climate change, particularly through win-win measures that reduce both human dependence and impacts on coral reef ecosystems. Our planet is on an irreversible path to a high level of climate change impacts on coral reefs which will have serious consequences for the ecosystem and the services it provides for humanity, irrespective of future emission levels. The full socioeconomic consequences of these impacts (e.g. health, food security, poverty and migration) will need further consideration and fall outside of the remit of this initiative. However, we can ensure that coral reefs are in the healthiest, most resilient condition possible to face the effects of climate change by following the course of action laid out in this document.*
- *An increase in policymakers', engagement and support for effective coral reef conservation and management will be critical for financing and implementing the measures required to save coral reefs. Legislators have a key role in supporting and expanding efforts to reduce direct human impacts on coral reefs to make them – and humanity – more resilient to the impacts of global climate change."*

The specific recommendations for the water quality objective in the GLOBE report (2010) titled "*Manage Watersheds, Water Quality and Reduce Pollution*" are as follows:

Objective 2:

Target: *Comprehensive watershed and coastal water quality management plans that reduce pollution to half of 2010 levels by 2019 are implemented for all major pollutants, especially those that cause eutrophication, have sublethal effects on corals (e.g. affect reproduction), lower seawater pH or have other negative impacts (including Persistent Organic Pollutants).*

5.3 Policy Recommendations

Phase 1:

1. *For all major watersheds linked to coral reefs identify the level of management required to draw up integrated watershed management policies;*
2. *Identify natural and legal watershed boundaries and determine what nations, sectors or communities have legal jurisdiction over these areas;*
3. *Identify the main point and diffuse sources of all pollutants on coral reefs;*
4. *Develop legislation to reduce the levels of all major pollutants to at least half of 2010 levels by 2019;*
5. *Set up comprehensive national monitoring programmes for riverine and coastal water quality;*
6. *Redefine international shipping lanes to avoid coral reef areas and improve the monitoring of merchant vessels in national waters;*
7. *Develop national management strategies for large-scale marine pollution incidents such as oil leaks;*
8. *Support the establishment and implementation of polluter pays legislation for coral reefs;*
9. *Establish best practice standards for mariculture operations conducted in or adjacent to coral reefs;*

10. *Ratify and adopt robust implementing legislation for the Stockholm Convention on Persistent Organic Pollutants, the Global Program of Action for the Protection of the Marine Environment from Landbased Activities (non-binding global agreement), and the International Convention for the Prevention of Marine Pollution from Ships (MARPOL);*
11. *Ratify regional Conventions and Protocols for the protection of the marine environment against landbased pollution.*

Phase 2:

12. *Implement watershed management policies involving afforestation, runoff-reduction, sustainable agriculture methods, reduction of pesticide, herbicide, fertiliser and other agrochemical use;*
13. *Set up trans-boundary watershed management bodies;*
14. *Declare, through the International Maritime Organisation, coral reef regions of outstanding ecological value as Specially Sensitive Areas, prohibiting transport of hazardous cargo through these waters;*
15. *Encourage all coral reef states to ratify and implement the IMO Ballast Water Convention with support from the GloBallast Partnership;*
16. *Implement national management strategies for large-scale marine pollution incidents;*
17. *Implement best practice standards for mariculture operations conducted in coral reef or adjacent environments;*
18. *Ensure that water quality control and coastal zone building and industry regulation are integral parts of sustainable coastal planning legislation both locally and nationally that require Environmental Impact Assessments (EIAs) which are:*

    a. *Conducted for all coastal development with a full peer-review;*

    b. *Followed through so that all development projects identified by EIAs to have a negative impact on coral reefs are refused planning permission, relocated, or provide sufficient mitigation for any environmental damage caused.*

5.4 Integrated coastal zone planning and policy based on ecological principles

Since the United Nations Conference on Environment and Development in Rio de Janeiro in 1992, the Integrated Coastal Zone Management (ICZM; also called Integrated Coastal Management ICM) concept has been used by many nations and states as the basis for effectively and sustainably managing coastal areas. Most environmental management concentrates on improving integration in catchments (through Integrated Catchment Management) and in coastal areas (through ICZM) but there is often little coordination between these two programs. Integration of catchment and coastal management is necessary to avoid duplication between management objectives or critical issues being missed, and to set out clear responsibilities for all authorities. Integrated catchment and coastal management can avoid duplication between management objectives and ensure the most appropriate planning tool is adopted to achieve better environmental outcomes and more effective management of natural resources. ICZM is a management process that acknowledges the connectivity and relationships between catchment, coastal, and marine environments (Wilkinson and Brodie 2011; Ban et al. 2012) and the central role of wastewater management (Corcoran et al. 2010).

6. Summary of pollutant-reduction management and effectiveness

This section provides a summary of the different impacts of wastewater pollution on coral reefs and management responses around the world. Importantly, it highlights examples of management efforts to address wastewater pollution and their effectiveness. Table 4 presents a summary and description of selected examples of wastewater pollution, the documented effects on coral reef ecosystems and an assessment of management effectiveness. These examples demonstrate that addressing the impacts of wastewater pollution associated with point-source sewage and industrial sources are manageable by improving treatment standards and/or relocating coastal outfalls into deep well-flushed locations. Although relocating discharges into the deep ocean does not remove the pollutants from the marine environment, the greater mixing and dilution significantly reduces the potential impacts. Despite these successes with reducing point-source pollution, it is evident that there are very few cases in the world where diffuse agricultural wastewater pollution discharges and their subsequent impacts on coral reefs have been managed successfully.

Table 4 Summary of selected examples of wastewater pollution, primary issues, effects on coral, where management has been implemented and an assessment of management effectiveness.

Location	Description	Primary issues	Effects on coral	Management	Effectiveness of management	Relevant references
Sewage management						
Kaneohe Bay, Hawaii	25 year history of direct discharge of primary / secondary treated sewage into an enclosed bay with coral reef ecosystems.	Nutrient and organic matter enrichment. Limited flushing.	Proliferation of phytoplankton, macroalgae and filter feeding organisms and associated large scale coral mortality.	Relocation of sewage outfalls from inside the Bay to deep-water ocean location with high water flushing in 1978.	*Successful in the long term (20+ years)* Reductions in the abundance of macroalgae and increases in the distribution and abundance of coral species and the reefs slowly recovered.	Stimson (2015) Evans et al. (1986) Smith et al. (1981)
Suva Lagoon, Fiji	40 year history of direct discharge of secondary treated sewage into shallow	Excessive nutrient and organic matter enrichment. Limited flushing.	Phytoplankton blooms and excess macroalgal growth on coral reefs. Chronic crown-of-thorns starfish population possibly	Prior to 1978 raw sewage was discharged from Suva city into adjoining Suva Harbour. The	*Limited success for ecological outcomes* Management addressed public health concerns but management	Morrison et al. (2013) Zann et al. (1987)

Location	Description	Primary issues	Effects on coral	Management	Effectiveness of management	Relevant references
	enclosed Laucala Bay.		linked to the nutrient enrichment.	management response was to improve treatment to secondary standard and discharge into Laucala Bay.	has had limited documented benefit for ecological outcomes.	
Dragon Bay, Jamaica	Sewage effluent entering bay	Nutrient enrichment	Weedy algae smothering coral	Sewage effluent recycled for irrigation on land in 1996	Weedy algae smothering reef began to die back in weeks and were gone in 2 months. 13 years later this reef was still free of high nutrient-indicating algal species and the corals are recovering.	Goreau et al. (2003) in DeGeorges et al. (2010) p2925
Barbados	Sewage and other chronic pollution	Nutrient enrichment / eutrophication	Overgrowth of the reef by turf algae (beyond the capacity of grazing organisms (such as parrot fish and sea urchins to control by grazing), and finally cyanobacteria which grazing organisms will not eat.	Improved sewage treatment standards	Cyanobacteria replaced by algal growth which can be grazed.	DeGeorges et al. (2010) p2926
Jakarta, Thousand Islands		Sewage, urban stormwater, industrial wastewater, agricultural wastewater discharges from	Gradient of reef degradation across the Thousand Island reefs decreasing the further from Jakarta	Plans to treat sewage effluents better	Ineffective so far.	Cleary et al. (2014, 2016); Baum et al. (2015)

Location	Description	Primary issues	Effects on coral	Management	Effectiveness of management	Relevant references
		the megacity of Jakarta				
Turks and Caicos					All development treated to minimum secondary standard	Goreau et al. (2008)
Mamala Bay, Oahu, Hawaii	Discharge of raw sewage			1977 treatment upgraded to advanced primary levels and outfalls extended to deep-water (>65m)	Successful Impacts to coral reefs no longer significant.	Grigg (1995)
Industrial / Mining / Agriculture						
Pago Pago Harbour, American Samoa	Discharge from multiple tuna canneries into highly enclosed bay	Nutrient and organic matter enrichment in poorly flushed harbour	Chronic phytoplankton blooms and macroalgal growth at the expense of coral ecosystems.	Installed large pipe in 1992 to export waste from tuna canneries from the harbour to outside the harbour mouth.	Repeated surveys have shown that significant recovery of coral reef communities on reef slope and coral reef flat. Substantially slower or absent recovery behind the reef crest where the substratum is primarily a loose rubble.	Birkeland et al. (2013)
Great Barrier Reef, Australia	River discharge of agricultural pollutants	Increased turbidity, eutrophication effects.	Loss of light for benthic communities, COTS outbreaks, coral disease	Reduced pollutant loads through improved practices in farming.	Some success in reducing loads but GBR corals still in decline	Bainbridge et al. 2012, 2014, 2016; Brodie et al. (2013)
Florida, USA						

Location	Description	Primary issues	Effects on coral	Management	Effectiveness of management	Relevant references
Hawaii	Runoff of fertilizers from pineapple plantations	Fertilizer (nitrate) and pesticide runoff entering groundwater and waterways discharging into receiving coral reef communities.	Massive filamentous algal growth. Potential connection to fibropapiloma virus in green turtles.	Fertiliser management	Limited	Claar and Takabayashi (2016)

7. Recommendations and conclusions

Globally the only successful mitigation programs for land-based pollution discharge to the ocean involved regulation (see Kroon et al. 2014, 2016) and have been few in number. In addition, the only successful wastewater pollution management programs that have led to effective coral reef recovery were specifically addressing point source discharges, e.g. Kaneohe Bay, Hawaii (see Box 2) and Pago Pago Harbour, American Samoa (see Box 14). There is no documented evidence of successful programs of agricultural wastewater management that have actually led to coral reef recovery, even in developed countries where significant funding has been allocated to this purpose (e.g. the Great Barrier Reef, Australia – Box 8 and Florida Keys, USA – Box 3). However, it is now well recognized that critically important to the success of wastewater pollution management is a focus on managing multiple stressors (Ateweberhan et al. 2013) and building resilience of the ecosystem (Wilkinson and Brodie 2011) (see also Box 15).

7.1 Adopting a holistic management approach

As most coral reef ecosystems are located in coastal areas and subject to multiple stressors, an integrated and holistic approach to management is essential to ensure their future sustainability (Aswani and Ruddle 2013; Brodie and Pearson 2016; Aswani et al. 2015; Sale et al. 2014; Waterhouse et al. 2016). Such approaches must address land-based pollutant sources, as well as other local and global pressures, such as marine-based pollution, overfishing, destructive and illegal fishing practices and shipping impacts (e.g. grounding and oil/chemical spills). Ultimately, reducing the multiple pressures on coral reefs that are amenable to management (such as wastewater pollution) will enhance their resilience to future changes, such as ocean warming and acidification.

It is evident that additional measures, such as maintenance and restoration of coastal ecosystems and regeneration of system functions, must also be considered where land-based influences are a significant source of impacts on coral reefs. In most places around the world, current understanding of the linkages between coastal ecosystem functions and water quality outcomes is conceptual, and is yet to be quantified. However, it is probable that activities that restore ecological functions, such as hydrological connectivity and retention of water in the floodplain, will have downstream water quality benefits, at least in moderate flow events (there is limited retention time in the floodplain in high flow events), as well as more substantial benefits for system functions such as productivity and connectivity (Wolanski 2007; Wolanski et al. 2004). Importantly, both direct action on wastewater pollution sources and indirect action on restoring ecological function will be required to reduce land-based influences on coral reefs and build their resilience to other pressures, such as climate change (Waterhouse et al. 2016).

7.2 Recommended management options

A number of steps are recommended for managing agricultural and land based pollution:

1. ***Define management objectives***: the desired outcomes of managing agricultural pollution for coral reef ecosystems need to be clearly defined. The outcomes should be underpinned by knowledge of the processes that determine the trajectories of ecosystem recovery. The substantial large-scale and long-term decline in coral reef condition over recent decades (Bruno and Selig 2007; De'ath et al. 2012; Gardner et al. 2003) has, in part, been linked to agricultural pollution. Attempts to reverse this decline, however, are generally constrained to improving agricultural and land-based pollution per se (Brodie et al. 2013; Richmond et al. 2007) without the consideration of the effort required to achieve desired outcomes for coral

reefs. Consequently, many management efforts are not targeting the critical sources and ecological processes that underpin the pollution problem being remedied.

2. ***Portfolio of regulatory and voluntary mechanisms***: management approaches that have successfully reduced agricultural pollution to coastal ecosystems have all been non-voluntary (Chu et al. 2009; Cloern 2001; Pastuszak et al. 2012; Stålnacke et al. 2003; Windolf et al. 2012), indicating that voluntary approaches alone may not be sufficient to achieve improvements. These reductions were achieved through legislation and regulation supported by long-term political commitment (e.g. China, Denmark) (Shi and Shao 2000; Windolf et al. 2012) or declining economic subsidies, fertilizer use and livestock numbers following the collapse of the Soviet Union (eastern Europe) (Jankowiak et al. 2003; Pastuszak et al. 2012; Stålnacke et al. 2003). While specific details may differ in tropical countries, the examples from China and Europe indicate that targeted regulatory policy approaches can greatly enhance the protection of downstream coral reef ecosystems from land-based pollution.

3. ***Spatially extensive and long-term effort***: management efforts to control agricultural pollution need to be at relevant spatio-temporal scales to achieve desired ecological outcomes for downstream coral reefs. Management effort over large spatial areas and long periods is required to obtain significant pollution reductions, as demonstrated in non-tropical systems, including: (i) (unintended) large cuts in pollutant sources (e.g. 95% cut in fertilizer use and 70% drop in livestock numbers in Latvian rivers (Stålnacke et al. 2003), (ii) application at large spatial scales (e.g. 84,000 km^2 of land terracing, tree and grass planting, and construction of sediment trapping dams in China (Chu et al. 2009), and (iii) adaptive implementation over decadal time frames (e.g. >25 years in Denmark (Windolf et al. 2012). Longer and upscaled management efforts in agricultural systems will improve the condition of coral reef ecosystems, whilst also preventing further detrimental impacts from predicted increases in sediment and nutrient fluxes in the next 35 years.

At all scales, there needs to be political will and economic commitment to reduce local pressures on reefs and promote reef resilience in the face of a changing climate. Improved overall governance, policies and management of our oceans at all scales, from individual sites, to regional, national and multinational levels balancing development and conservation needs. There is value in replicating successful local and national approaches and working internationally using tools such as transboundary collaboration and regional agreements to address land-based and marine pollution. All levels of government (local, provincial, state, national) may have a role in wastewater management but the on-ground situation with respect to governance varies greatly depending on governance structure, resourcing and technological capability. In this regard, multidisciplinary work across sectors, such as the collaboration between health and conservation organisations would be beneficial (Wear 2019). Management also needs to be integrated across the land-sea boundary and include multiple jurisdictions across this continuum. Management suitable to the scale of the issue and local conditions should be integrated additionally. In the section below, we describe practice management techniques that are suitable for small island situations.

An excellent analysis of wastewater treatment options is given in DeGeorges et al. (2010). In our opinion this is the most realistic analysis of sewage treatment options for developing countries and small island states. They examine the various options with respect to discharge standard needs under the following headings with their conclusions following enclosed in the Box:

Sewage Pollution & Treatment, Lessons from the Caribbean

1. Inadequacy of Secondary Sewage Treatment in Tropical Waters

Their conclusions are: In watersheds with significant human populations, wherever quantitative nutrient data exists, coral reef degradation has been closely linked to inappropriate sewage treatment and disposal. In the case of tourist resorts, most developers use prefabricated —package plants, or septic tank systems, both designed to attain secondary levels of treatment. In many cases these systems malfunction, failing to attain the design-level of treatment. Regardless of operating performance, the effluent is discharged close to shore and/or enters into the nearshore waters indirectly through drainage ditches or through groundwater percolation. Regardless, secondary treatment, without a long outfall, fails to meet both ecological (significant elimination of nutrients) and public health (significant elimination of viruses) objectives. Secondary treatment removes only a small portion of the nitrogen and phosphorus nutrients which over-fertilize coastal waters, causing harmful algae blooms that smother coral reefs and destroy fisheries habitat. Septic tanks in coastal areas with high groundwater tables often malfunction during heavy rain events, flushing huge quantities of untreated effluent into coastal waters. In addition, if chlorination to kill bacteria/viruses in secondary treatment is undertaken improperly, high residual chlorine levels in the effluent can be extremely toxic to aquatic life.

2. A Solution to Pollution Is Dilution for Sewage Disposal, Lessons from the Caribbean.

Their conclusions are: Thus, to protect coral reefs, grassbeds (seagrass) and people, land-sourced pollutants should either not be discharged from land or should be discharged far enough offshore that they are not a threat to nearshore waters.

3. Land Disposal of Sewage, Lessons from the Caribbean

The advantages of land disposal of secondarily treated sewage effluent are that advanced (tertiary) waste treatment is attained, and nutrients are recycled to land vegetation, which is usually nutrient-starved. This can vary from 82–99% removal of BOD, 92–98% removal of suspended solids, 0–90% removal of nitrogen, 60–95% removal of phosphorus, 50–95% removal of metals and up to 98% of micro-organisms by the soil/plant system depending on the land application; sprinkler irrigation being most efficient, overland flow intermediate and infiltration-inflow being the least effective in removing pollutants. Wastewater and nutrients should be used productively, and little or nothing should flow into nearshore waters.

7.3 The role of monitoring

Monitoring and assessing coral reefs usually consist of measuring coral cover and species diversity and there are often differential sensitivities of organisms to a given pollutant. These data are useful in providing a snapshot of the reef but cannot provide predictive data in a timely fashion for decision-making (McKenna et al. 2001). Similarly, monitoring can track the effects of pressures and responses of coral reefs but often impacts are irreversible by the time they are detected. Techniques to detect stress before mortality and with predictive value are needed to monitor pollution impacts on coral reefs (Brown 1988). Typically, data are lacking for periods prior to wastewater discharge (both point source and non-point source), making application of any Before-After-Control-Impact-Paired design impossible (Stewart-Oaten et. al. 1986). Relaxation experiments are an alternative, if it is possible to stop the discharge (e.g. sewage effluent) and use the 'affected' observations as the baseline as in the Kaneohe Bay, Hawaii Sewage Case Study (Smith et al.

1981, Evans et al. 1986). However, as this is rarely possible in most cases, it is still possible to obtain meaningful data by using a variety of physiological and ecological tests on selected appropriate species (McKenna et al. 2001). For example, techniques that use survivorship, growth, fecundity and other population parameters to quantify the sub-lethal effects of sewage stress in corals have been used in the Pacific (McKenna et al. 2001) and for measuring chronic water quality stress in the Great Barrier Reef (Thompson et al. 2013).

Other bioindicator species have been used to measure organic and inorganic pollutants in receiving environments, such as marine microalgae that are a particularly promising species since they are typically the most abundant life forms in aquatic environments and occupy the base of the food chain (Torres et al. 2008). Many other aquatic organisms have also been used as bioindicator tools in environmental programs, e.g. bivalve molluscs in the Asia Pacific region (Tanabe 1994; Haynes and Kwan, 2001; O'Brien et al. 2014), mangrove mussels in Brazil (Torres et al. 2002), crabs in South Africa (Thawley et al. 2004), and fish in Australia, Asia, and the USA (Edwards et al. 2001; Ueno et al. 2005; Carrasco-Letelier et al. 2006 respectively).

In order to assess the risks of contaminants to organisms and to classify the environmental quality of ecosystems, at least five environmental monitoring methods can be performed which represent nested scales of effect: (i) chemical monitoring at the pollutant source, (ii) bioaccumulation monitoring at the source and distal sites, (iii) biological effect monitoring for species in receiving environments, (iv) health monitoring in receiving environments, and (v) ecosystem monitoring at a wider scale (Torres et al. 2008). The primary principles for monitoring the long-term effects of persistent pollutants on reef ecosystems and their bio-accumulation at higher trophic levels include:

- Monitor the pollutant source as the first priority (i.e. as it comes out of the river or pipe).
- Combined approach of monitoring and modelling delivery and transport of pollutants.
- Use of bioindicators to assess impacts on reef organisms.
- Use a system approach at multiple scales with nesting at in spatial and temporal dimensions.

Sustained monitoring at appropriate spatio-temporal scales is required to ascertain whether wastewater management results in desired improvements of downstream coral reef ecosystems. Importantly, these monitoring programs should be driven by the development of critical questions and objectives, a conceptual understanding of linkages between desired outcomes and land-based pollution (Bartley et al. 2014), robust statistical design, and adaptive review cycles (Lindenmayer and Likens 2009). In complex systems such as coral reefs, this would maximize the probability of detecting trends following management intervention, which could take years to decades to detect (Darnell et al. 2012). Importantly, consideration of desired outcomes for coral reefs in monitoring programs will focus efforts towards detecting change in relevant metrics. For example, specific biological indicators, for example, coral colour, have been identified that link changes in marine water quality to changes in coral reef ecosystem condition (Cooper and Fabricius 2012). These can easily be adapted for other reef situations.

7.4 Conclusions

The scientific consensus for coral reefs globally is that they are in decline and local pressures are a key driver, exacerbated by rising sea temperatures and ocean acidification. Marine water quality continues to be negatively affected by the discharge of land-based wastewater, particularly excess nutrients, sediments and pesticides from urban and agricultural activities, as well as heavy metals, hydrocarbons, organochlorines and emerging contaminants from industry, mining and other wastewater sources. These contaminants are either artificially concentrated or synthesized or both, and can persist within marine ecosystems for decades, bioaccumulating in marine organisms and causing environmental impacts on marine biota and humans. The sources of these pollutants are often cryptic and difficult to trace, as are their fates once in the marine environment. Wastewater pollution of coral reefs is therefore a major cause for concern, and one that must be addressed to conserve important coral reef ecosystems. However, a whole of system approach is required to ensure that ecological, social and economic values of coral reefs and associated ecosystems are sustained into the future.

There are few examples of highly successful management of wastewater pollution which has been shown to cause severe damage to a coral reef system, but in two well established cases – Kaneohe Bay, Hawaii (see Box 2) and Pago Pago Harbor, American Samoa (see Box 14), the fairly simple solutions of diverting the waste stream to outside of the enclosed water body and hence into a situation of high dispersion and dilution was highly effective. This solution is also available in many other situations for point source discharges where a deep water discharge option is available nearby. In general point source sewage or industrial discharges are easier to manage than diffuse agricultural or urban wastewater streams as technological options are available such as deep water disposal or treatment options e.g. sewage treatment, which are not so easily applied to diffuse sources.

A global review by Kroon et al. (2014) demonstrates that transformative change in agricultural management for coastal ecosystem outcomes is necessary and achievable. For coral reef ecosystems, future protection demands policy focused on: (1) desired ecosystem outcomes, (2) targeted regulatory approaches, (3) upscaling of watershed management, and (4) long-term scientifically robust monitoring programs linked to adaptive management. Additionally, the often additive or synergistic deleterious impacts of wastewater contaminants delivered to coral reefs requires an integrated approach that addresses multiple pollutant sources. Implementing these recommendations will increase the resilience of desired, coral-dominated states within a timeframe (years to decades) where more extreme perturbations associated with climate change are expected.

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