Diffuse Pollution, Degraded Waters
Emerging Policy Solutions

Annex 1.A1:
An overview of the main water pollutants in OECD countries

Excess nutrient losses

Globally, the most prevalent water quality challenge is eutrophication (UNESCO, 2009), a result of excess nutrient losses (primarily nitrogen and phosphorus) largely from intensive agriculture, and to a lesser extent from urban run-off and wastewater treatment plants. Furthermore, high nutrient loading not only causes eutrophication of lakes and rivers, but also excessive growth of aquatic weeds, algal blooms, hypoxia and declines in the ecosystem functioning of both freshwater and ocean environments.

There are health impacts associated with increasing nitrate toxicity in surface and groundwaters. Nitrate toxicity of drinking water can cause methemoglobinemia in infants (blue-baby syndrome) and other illnesses such as cancer[1]. Nitrates can accumulate in groundwater, particularly in confined aquifers and aquifers with very low recharge rates. It is costly for municipal utilities to invest in additional treatment of drinking water to remove nitrates. The health risk is particularly high in rural areas where untreated contaminated groundwater is abstracted for drinking water from private wells.

Harmful algal blooms are recognised as a global public health threat (Otten and Paerl, 2015). Algal blooms (cyanobacteria, green algae, diatoms) produce toxins which contaminate drinking water, cause acute poisoning, skin irritation and gastrointestinal illness, trigger livestock, fish and shellfish poisoning, and are costly to treat. Their toxicity, unattractive appearance and odour can cause lakeside or riverside property values to decline, and decrease the recreational use and aesthetical value of waters. Algal blooms can also block sunlight and reduce dissolved oxygen to levels that are lethal to aquatic fauna and flora, negatively impacting the food web and inducing fish kills. Algal blooms generally occur in nutrient-enriched waters coupled with low flow, and warm and sunny conditions. They are therefore likely to appear more frequently, and be present for longer, due to higher water temperatures and longer periods of low flows associated with climate change (Bates et al., 2008).

The extent and effects of high nutrient loading extends beyond the freshwater environment, to the development of eutrophic and hypoxic zones (also known as “dead zones”) in the oceans. Hypoxic zones have developed in continental seas, such as the Baltic, Kattegat, Black Sea, Gulf of Mexico, and the East China Sea, all of which are major fishery areas (Diaz and Rosenberg, 2008; Robertson and Vitousek, 2009). In total, more than 400 hypoxic dead zones have been identified, and their frequency has approximately doubled each decade since the 1960s (Diaz and Rosenberg, 2008; Robertson and Vitousek, 2009). This trend may continue with the occurrence, frequency, duration and extent of oxygen depletion and harmful algal blooms in coastal zones projected to increase as rivers discharge growing amounts of nutrients into the sea (OECD, 2012a).

A final consideration of nutrient loading in water bodies is the contribution from fallout of air pollutants: nitrogen oxides, sourced primarily from energy and transport emissions, and ammonia sourced primarily from agriculture (in particular, volatilisation of stock manure and effluent).

Microbial contamination

Microbial contamination (pathogenic bacteria and viruses) of water resources is a serious health risk, and is considered the most important pollutant affecting human health globally (Domingo et al., 2007; WWAP, 2009). Water bodies contaminated with pathogens are responsible for the spread of many contagious water-borne diseases (Chapra, 1997), such as cholera, giardiasis and other intestinal infections. This is particularly of concern where contaminated water resources are used for municipal water supply, crop irrigation, and for recreational purposes (Amirat et al., 2012; UK Environment Agency, 2003). Furthermore, microbial contaminants from wastewater can exacerbate biodiversity loss (European Commission, 2013).

Sources of pathogenic microorganisms originate from land application of animal manure, liquid slurry and human biosolids, direct defecation by livestock, leaking septic tanks, and discharges from insufficient wastewater treatment plants. Despite the investment in, and establishment of, wastewater treatment plants, many developed nations still suffer from microbial contamination due to sewage spills and diffuse agricultural pollution, particularly during high rainfall events when combined sewer overflows operate more frequently and runoff from agriculture is induced.

Outbreaks of water-related diseases from contaminated public water supply are not just limited to developing countries. While considerable advances in water supply and sanitation have occurred in OECD countries, pathogens can still enter water supply systems due to resistance to disinfection (e.g. *Giardia, Cryptosporidium*, and enteric viruses), treatment system deficiencies (e.g. inadequate disinfection), periodic treatment failures, or distribution system contamination.

Cases of waterborne disease outbreaks include the Walkerton outbreak of Ontario, Canada, in 2000, which resulted in seven fatalities and hundreds that fell ill as a result of *Escherichia coli O157:H7* infection from contaminated public water supply (Auld et al., 2004). Excessive rainfall and agriculture runoff was the cause of the contamination. In Europe, significant outbreaks of water-borne pathogenic organisms have occurred in Sweden (Widerström et al., 2014; Rehn et al., 2015), Norway (Robertson et al., 2009), Finland (Laine et al., 2011), and throughout England and Wales (Furtado et al., 1998; Smith et al., 2006; Nichols et al., 2009). In New Zealand, the town of Havelock North in the farming region of Hawke's Bay, suffered from a large-scale campylobacter outbreak as recently as August 2016. Over 5 000 people became sick – more than one-third of the town's 14 000 population, causing temporary closure of schools and businesses.

There is also growing evidence of microbial contamination of groundwater, which is often used as an untreated private water supply by many communities, particularly in rural regions (Kay et al., 2007; Feighery et al., 2013). For example, in 2014, 13% of 6 200 private water supplies surveyed in England tested positive *E. coli* (DWI, 2015).

Acidification

Acidification of surface water is particularly acute where there is a strong source of acid, such as downwind of atmospheric pollutants (acid deposition), particularly where soils have a low buffering capacity, and downstream of mining areas (acid mine drainage). A reduction in sulphur pollutants through control measures at power plants has reduced the impact and occurrence of acid deposition. However, nitrogen oxides (NO_x) (largely from combustion processes thermal and fossil fuel), and ammonia (NH_3) (largely from livestock manure and urine, synthetic nitrogen fertilisers and the cultivation of legumes and other crops), are still prominent sources of atmospheric pollutants that cause acid deposition, eutrophication, contribute indirectly to climate change, and reduce visibility (acid aerosols/smog).

Acid mine drainage (AMD) (also known as acid rock drainage) is often considered one of the main pollutants of water in countries that have historic or current mining activities (Simate and Ndlovu, 2014). AMD is a strong acid wastewater, rich in high concentrations of dissolved heavy metals. It most commonly originates from operating and abandoned polymetallic sulphide mining sites, where exposure of sulphide minerals to oxygen, water and microorganisms triggers chemical, biological, and electrochemical reactions that promote the creation of sulphuric acid, which subsequently promotes the release of heavy metals (Egiebor and Oni, 2007; Jennings et al., 2008; Simate and Ndlovu, 2014).

The acidification and mobilisation of heavy metals in water bodies has severe impacts on human and aquatic species health, can contaminate groundwater, raise water treatment costs, impact commercial fisheries, and cause corrosion of concrete and metal infrastructure. Impacts to aquatic species include fish kill, stunted growth, reduced reproduction, deformities, and disruption of the aquatic food chain (Jennings et al., 2008). Impacts to human health include disruption of metabolic functions; liver, kidney, and gastrointestinal damage; damage to the nervous system; and other health effects (Simate and Ndlovu, 2014).

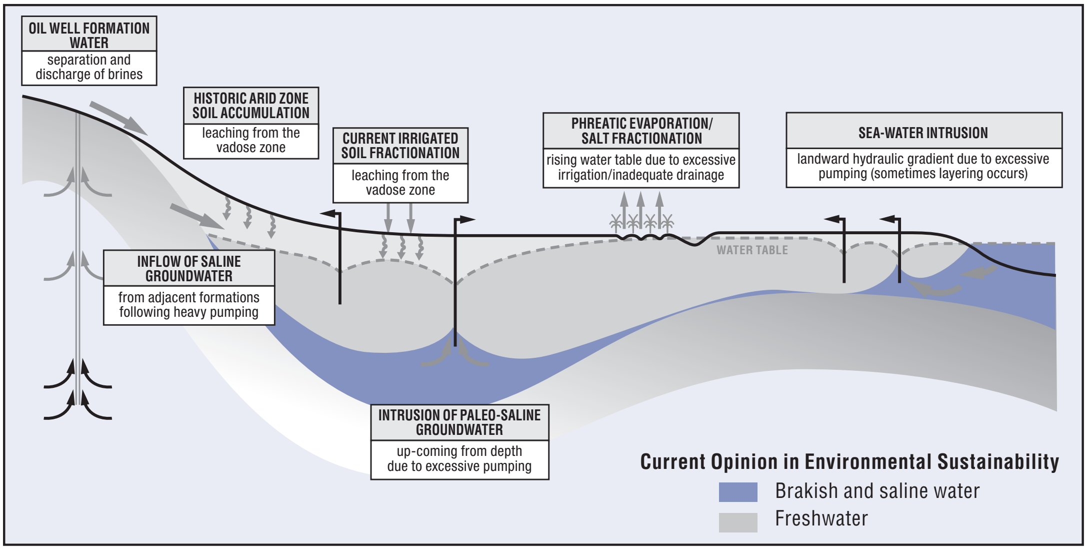
Despite efforts to prevent, mitigate and control AMD using the best available technologies, AMD production can be sustained for hundreds of years and remains the greatest environmental liability associated with mining (Egiebor and Oni, 2007; Jennings et al., 2008).

Salinity

Salinity is the primary threshold that limits water use and availability. Groundwater quality deterioration is of concern particularly in coastal regions, and in semi-arid regions with salinised soils. Clearing of perennial vegetation and irrigation of salt-affected soils leads to leaching of salts and increasing groundwater salinity (OECD, 2012b). In addition, rising water tables of high salinity can lead to salinisation of soils and cause a positive feedback mechanism for further increasing salinity of groundwater. In coastal areas, over-abstraction of groundwater, and sea level rise associated with climate change, contributes to salt water intrusion into aquifers. The application of salt for anti-icing and de-icing of roads can also enter surface water bodies. The principle processes causing groundwater salinity are illustrated in Figure A1 below.

Groundwater salinity and soil salinisation are largely irreversible and have impacts on irrigation, and domestic and industry water use, as well as long term effects on agricultural land and aquatic life (Bennett et al., 2009). The effects, and the continued considerable threat, of salt water intrusion on the global scale is well documented (e.g. OECD, 2015; Werner et al., 2013). A number of OECD countries are especially concerned with seawater intrusion to aquifers in coastal areas, such as Greece, Italy, Spain, the Netherlands, Australia, New Zealand, Mexico and parts of the United States (OECD, 2015).

Figure A1. **The principle processes causing groundwater salinisation**



Source: Foster et al. (2013).

Sedimentation and organic materials

Sedimentation and the release of organic matter (dissolved organic carbon [DOC]), particularly during storm events and sediment release from dams, can cause turbidity and deoxygenation of water bodies. Deoxygenation of water causes loss of aquatic life. Sedimentation and turbidity blocks light and inhibits aquatic plant growth, reduces die-off of pathogens, clogs the gills of fish and smothers benthic invertebrates and fish eggs. It effects water transportation systems, prevents effective treatment of drinking water and wastewater, and produces carcinogenic compounds (such as chloroform) when water with high levels of DOC is disinfected with chlorine.

Sediment particles can also carry heavy metals, pathogens, pesticides and other toxic organic compounds as attachments. In the United Kingdom, DOC concentrations in 22 upland catchments increased by an average of 91% between 1988 and 2003 (Evans et al., 2004). Here, the increase in DOC has significantly affected other chemical variables, in particular, an increase in metal transport (organic Al and Fe). In England and Wales, past and present mining, processing and utilisation of base metals have polluted sediments with heavy metals in rivers, lakes and estuaries. Such sediments are likely to be causing ecological damage; the re-suspension of these sediments during floods has the potential to cause additional harm to aquatic life and contaminate floodplain soils used for agriculture, and this has implications for delivering the Water Framework Directive (UK Environment Agency, 2008; DEFRA, 2003). Increases in DOC have also occurred elsewhere in Europe and North America (Evans et al., 2004).

Human-induced sources of DOC and sediment in surface water bodies include food processing waste, manure spreading on livestock farms, sediment release from dams, and erosion of topsoil and peatlands due to poor farming, construction, and forestry (including deforestation) practices (Neal and Hill, 1994). Dams retain sediment the majority of the time and regulate flow regimes. This alters the timing and intensity of river discharge, causing downstream riverbed and delta erosion and affecting the natural imbalance of sediment, nutrients and organic matter to flood plains used for agricultural production and coastal marine ecosystems (e.g. Renshaw et al., 2014; Yang et al., 2014). Such imbalances can also increase the risk of harmful algal blooms (OECD, 2012a).

Toxic contaminants

Toxic contaminants include pesticides, heavy metals, chlorinated solvents, and persistent organic pollutants (POPs).

Pesticides (which include herbicides, insecticides, fungicides and other chemical agents) are introduced to surface and groundwater from their use for plant and animal protection in agriculture. In nearly half of OECD countries, nutrient and pesticide concentrations in surface and groundwater in agricultural areas exceed national recommended limits for drinking water standards (OECD, 2012a). Furthermore, pest species can become resistant to the harmful effects of pesticides over time through genetic adaptation (Becker and Liess, 2015). For example, genetic resistance to herbicides has been recorded in 210 weed species (Bourguet et al., 2013). Similarly, genetic resistance has been recorded against 300 insecticide compounds in over 500 pest species, and 30 fungicides in 250 species of phytopathogenic fungi. This adaptive evolution reduces the efficacy of conventional control strategies and requires the development of new pesticides (which is costly and time consuming) in order to keep up with increasing resistance. However, interspecific competition and predation can delay genetic adaptation to pesticides, supporting the importance of biodiversity for effective pest management (Becker and Liess, 2015). Other factors that can potentially delay the onset of pesticide resistance include the deployment of biopesticides (e.g. bio-based products); implementation of integrated pest management (IPM) programme; use of genetically engineered crops; adoption of sensitivity monitoring for pesticide resistance; and use of pest forecasting advisory systems.

Land application of sewage sludge, urban stormwater runoff, corroding water supply infrastructure, and industrial waste are sources of heavy metal pollution to water resources. Furthermore, soil and water acidification (such as acid mine drainage) and flooding events can exacerbate these issues, mobilising heavy metal contaminants in sediment and rock. Some regions of the world suffer from naturally elevated levels of heavy metals (such as arsenic and chromium) in groundwater due to the local geology. Natural arsenic pollution of drinking water is now considered a global threat with as many as 140 million people affected in 70 countries on all continents (UNESCO, 2009). For example, well-known areas with high arsenic concentrations include Argentina, Chile, Mexico, China and Hungary, and more recently in West Bengal (India), Bangladesh and Vietnam. In such areas, more than 10% of wells may be "affected" (defined as those exceeding 50 µg/L) and in the worst cases, this figure may exceed 90% (Smedley and Kinniburgh, 2002).

The contamination of water bodies with chlorinated solvents (e.g. petrol and aviation fuel) originates from transport, industrial spills, leaking underground storage tanks, hydraulic fracking, and urban stormwater runoff. For example, hydraulic fracturing involves the injection of fluids under pressures great enough to fracture oil- and gas-producing formations (U.S. EPA, 2015a). The fluid generally consists of water, chemicals, and proppant (commonly sand). Concerns have risen regarding not only competition for the large quantities of water used, but also regarding groundwater and surface water quality (Ground Water Protection Council, 2009; Verrastro and Branch, 2010; Grubert and Kitase, 2010; Center for Biological Diversity, 2014).

Three potential pathways for water contamination have been identified through the hydraulic fracking process: (1) the contamination of shallow aquifers with fugitive hydrocarbon gases (i.e., stray gas contamination), which can also potentially lead to the salinisation of shallow groundwater through leaking natural gas wells and subsurface flow; (2) the contamination of surface water and shallow groundwater from spills, leaks, and/or the disposal of inadequately treated wastewater; and (3) the accumulation of toxic and radioactive elements in soil or stream sediments near disposal or spill sites (Rozell and Reaven, 2012; Vengosh et al., 2014; Vengosh et al., 2013; Vidic et al., 2013). In the United States, oil and gas production via hydraulic fracturing in shales, tight formations and coalbeds occurs in close proximity (within 1 mile) of approximately 6 800 public water supply sources (U.S. EPA, 2015a). Although the number of identified cases where drinking water resources have been impacted are small relative to the number of hydraulically fractured wells, the risk is significant with such public water supply sources serving more than 8.6 million people. In recognition of the risks of water pollution from hydraulic fracturing, the United States EPA is improving the scientific understanding of contamination and its effects, and providing guidance for its management (U.S. EPA, 2015b).

Persistent organic pollutants (POPs) are organic chemical substances that are resistant to biodegradation and have been linked to bioaccumulation in the food web, declines in a number of bird species, and poor human and environmental health (U.S. EPA, 2009). The use of chemicals and synthetic pesticides with POPs has largely been phased out in developed countries due to the signing of the Stockholm Convention 2001, in which countries agreed to reduce or eliminate the production, use, and/or release of 12 key POPs (e.g. DDT, dioxins, and PCBs[2]). However, due to their long life-time, the ban on POPs may not necessarily lead to a sharp reduction in their occurrence (Lohmann et al., 2007).

Thermal pollution

Thermal pollution results in a change in the physical properties of water. Causes of thermal pollution are most commonly associated with power plants and industrial manufacturers who use water as a coolant before discharging it back to the environment. Urban runoff may also elevate the temperature of surface waters. Elevated water temperatures decrease oxygen levels, which can kill fish, alter food chain composition, reduce species biodiversity, and foster invasion by new thermophilic species (e.g. Teixeira et al., 2009; Chuang et al., 2009). Thermal pollution can also be caused by the release of very cold water from the base of reservoirs into warmer rivers (Langford, 2001). The global extent of thermal pollution is not well-documented, and limited research has been undertaken on its impact to freshwater ecosystems (most are marine studies).

Plastic particle pollution

Pollution of water bodies with plastic (micro-plastic and macro-plastic) and other solid waste is a significant problem, caused by illegal and accidental rubbish dumping by individuals, the plastic production industry, recreational and commercial fishers, and urban stormwater runoff. Beaches and oceans act as a sink, and since plastic is also buoyant, an increasing load of plastic debris is being dispersed over long distances. When the debris does finally settle in sediments, it may persist for centuries (Derraik, 2002).

Plastic particle pollution disrupts the marine food chain, causes physiological damage to marine organisms through ingestion and entanglement, and releases POPs (such as PCBs) into the surrounding waters. Plastic particle pollution is an increasing problem, and it is reported that 88% of reported incidents between organisms and total marine debris was associated with plastic, 11% of which was with microplastics (GEF, 2012). For instance, surveys carried out in the western North Atlantic Ocean show significant increases in plastic particle density from 1991 to 2007 (Morét-Ferguson et al., 2010). A series of surveys in coastal Australia, Bay of Bengal and the Mediterranean Sea estimates that a minimum of 5.25 trillion plastic particles weighing over 260 000 tons are afloat at sea in the world's oceans (Eriksen et al., 2014). In the Mediterranean Sea, plastic debris has been found in the stomachs of 18% of swordfish, bluefin tuna and albacore (Romeo et al., 2015). Due to their small size, microplastics may be ingested by low trophic fauna, with uncertain consequences for the health of organisms (Wright et al., 2013). There is concern that the POPs in plastic can have additional toxic effects on fish (such as reproductive changes) and impacts on human health from the transfer of these chemicals via consumption of fish. Further research is required regarding these ecological and human health effects.

Contaminants of emerging concern

Contaminants of emerging concern (CECs) comprise a vast array of contaminants that have only recently appeared in water, or that are of recent concern because they have been detected at concentrations significantly higher than expected, and/or their risk to human and environmental health may not be fully understood. Examples include pharmaceuticals, hormones, industrial chemicals, personal care products, perfluorinated compounds, flame retardants, plasticizers, detergent compounds, caffeine, fragrances, cyanotoxins, engineered nanomaterials (such as carbon nanotubes or nano-scale particulate titanium dioxide), anti-microbial cleaning agents and their transformation products[3]. The number of CECs is continuously evolving as new chemical compounds are produced, and improvements in science and monitoring increase our understanding of the effects of current and past contaminants on human and environmental health (Sauvé and Desrosiers, 2014). Despite the increasing number of published studies covering CECs, very little is known about the effects of their transformation products and/or metabolites (Lambropoulou and Nollet, 2014).

CECs are derived from a variety of municipal, domestic, agricultural, and industrial waste sources. Complex mixtures of CECs have been documented in plant and animal tissue, groundwater and drinking water (Khan et al., 2016; Pal et al., 2014). There is also growing concern that CECs may be bioactive and interactive (e.g. with additive, synergistic and/or antagonistic effects) (Bhandari et al., 2009). Large CEC concentrations have been identified in a variety of sources such as septic systems, landfills, animal manure and sewage sludge (Pal et al., 2014).

Endocrine disruptors affect the reproductive systems of fish and humans, with some documented cases of fish and other freshwater and marine organisms changing sex (Porte et al., 2006; Velasco-Santamaría et al., 2011; Vos et al., 2000). But perhaps the CEC of most worry is excess use of antibiotics and the health implications of increasing resistance to antibiotics.

Antibiotic resistance is now considered by authorities in the United States, United Kingdom and by international experts to be one of the paramount public health challenges of our time (Centers for Disease Control and Prevention, 2013; UK Department of Health, 2013; WHO, 2014). Antibiotics kill good bacteria in rivers which naturally treat pollution, and build human resistance to antibiotics.

Antibiotics residues, and antibiotic resistant bacteria and genes, from the intentional use of antibiotics (for human and animal health) can enter the environment (water and soil) through wastewater systems (Proia et al., 2016), direct livestock excretion, and land application of biosolids and effluent (Williams-Nguyen et al., 2016). They then have the potential to impact on human health, ecosystem functioning and agricultural productivity (although research on the pathways of exposure is premature). For example, a study by Khan et al. (2016) discovered the occurrence of antibiotic resistant bacteria exist at the consumers' end of the drinking water distribution system in Glasgow, Scotland, some of which also contain integrase genes, which can aid in the dispersion of resistance genes.

The current additional economic costs of antimicrobial resistance is considered to be relatively small, as mitigating action (switching prescribing to other antibiotics) can be taken. However, when this is coupled with growing rates of resistant organisms and a declining number of new antibiotics in development, the potential future health costs are very high (Smith and Coast, 2012).

Other factors that contribute to degradation of water quality

Other factors that contribute to degradation of freshwater ecosystems, and thus their ability to process contaminants, include the introduction of invasive alien species and anthropogenic modifications to river systems. According to the IUCN, invasive alien species constitute the second most severe threat to freshwater fish species (William et al., 2009), and the spread of invasive alien species is projected to increase due to a combination of increasing trade and climate change (Death et al., 2015; Rabitsch et al., 2016; Walther et al., 2009). Changes in the natural morphology of water bodies (e.g. channelized rivers, dams, canals) can also affect the ability of ecosystems to process and retain pollutants (Wagenschein and Rode, 2008).

The deterioration of water quality also has subsequent knock-on impacts on the functioning of in-stream invertebrates, fish, and aquatic plant communities (Doledec et al., 2006; Ling, 2010), which causes negative feedbacks, particularly the ability of ecosystems to process contaminants, thereby causing pollutants to accumulate in the environment and cause further damage.

Notes

1. High nitrate levels in drinking water can lead to infant methaemoglobinaemia (blue-baby syndrome), gastric cancer goiter, metabolic disorder, birth malformations, hypertension and livestock poisoning (Khandare, 2013). This is of particular concern in private groundwater wells located in agricultural regions with overlying permeable soils. The US Environmental Protection Agency requires that public water systems not exceed a nitrate concentration of 10 mg/L, because nitrate above this level, causes infant methaemoglobinaemia.
2. DDT: dichlorodiphenyltrichloroethane, a synthesised organochloride known for its insecticidal properties; PCBs: Polychlorinated biphenyls, a synthetic organic chemical compound that was widely used as electrical insulators, coolant fluid, flame retardants, and plasticisers in paints and cements, amongst other uses.
3. Transformation products and metabolites of man-made chemicals that are produced from biological, chemical and physical breakdown reactions.

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