Developing a Global Compendium on Water Quality Guidelines

IWRA

WORLD WATER COUNCIL

ONEMA
Office national de l'eau et des milieux aquatiques

Acknowledgements

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FOREWORD

PATRICK LAVARDE
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As the President of IWRA and the former Director General of the French National Office of Water and Aquatic Environments (ONEMA), I am thrilled to present *Developing a Global Compendium of Water Quality Guidelines*.

This report has been developed by IWRA, with the strong support of the World Water Council and French Biodiversity Agency (AFB – formerly ONEMA) over the past five years, and builds on IWRA's recent initiatives related to water quality on the international stage. This includes acting as the Coordinator and Thematic Champion for the Implementation Roadmap Thematic Process for "Ensuring Water Quality from Ridge to Reef" at the 7th World Water Forum in Daegu, Korea, in 2015. IWRA continued this initiative as the Topic Lead at the 8th World Water Forum in Brasilia, Brazil, in 2018. Water quality topics have also played a significant role in sessions at the two most recent IWRA World Water Congresses held in Edinburgh, Scotland, and in Cancun, Mexico.

These events helped develop ideas and themes used to finalise *Developing a Global Compendium of Water Quality Guidelines,* a report whose contents are important in addressing the lack of oversight and guidance in directing the appropriate water quality for various uses. As the world faces both water quantity and quality challenges, there is a need to match water fit for purpose to save higher quality source water and to reuse wastewater appropriately. However, to accomplish this requires clear guidance in specific sectors and at various geographic scales. This report is far from exhaustive but instead proposes content and structure for a comprehensive online compendium of water quality guidelines and regulations that would support this transition to meet water quality criteria and encourage alternative water use.

The development and publication of this report would not have been possible without the contributions, support and dedication of several organisations and people. This is a legacy report that results from the work of many IWRA staff, board members and volunteers since 2012 and I acknowledge and wholeheartedly thank these people for their contributions to the ideas and writing behind the report. Next, I would like to recognise the members of the IWRA Water Quality Task Force, who have spent the past year developing and editing elements of the report's chapters. The enthusiasm, efforts and diverse perspectives of all these people have enriched the content of the document.

Finally, this project was conducted in collaboration with two other organisations; the World Water Council and ONEMA/AFB. Their support in developing and finalising this document over the last five years was instrumental in its completion and on behalf of IWRA, I would like to express my gratitude to them for their contributions to this project.

Table of Contents

At the 2018 High Level Political Forum on Sustainable Development, Stefan Uhlenbrook (World Water Assessment Program of the UN Educational, Scientific and Cultural Organization (UNESCO)), discussed the current water quality problems: increases in freshwater pollution; climate change impacts; links between conflict and water-use; and the need for efficiencies in energy and agriculture, all contributing to his assessment that the world is not on track to achieve SDG 6 by 2030. Inadequate water resource management globally has come at a cost, particularly in relation to water quality. The way forward, addressing current challenges and building the foundation for a smarter and more sustainable approach to water resource management in the future, requires us to call into question current water governance paradigms and explore new pathways. This report provides an initial overview of one such management pathway.

Directing water of different qualities to their most appropriate use introduces greater efficiency and economy into the management of water resources across competing uses and aids in securing sustainability and security for future water use. It also reduces the extraction of new water which in turn increases environmental flows and the dilution effect, hence increasing water quality. As of 2018, there is no complete global overview of water quality guidelines from a user perspective to assess the usability of water of different qualities for various purposes. This report introduces the structure of a compendium providing a collection of concise but detailed information about existing water quality guidelines for several different uses, including a brief analysis and discussion.

About this report

This report, *Developing a Global Compendium on Water Quality Guidelines*, collects and examines examples of existing recommendations for influent water quality, as applied to various human and ecosystem uses. It provides examples and analysis of existing water quality guidelines, to demonstrate the type of content that should be included in a future larger online compendium. Building on the case studies, the report explores new perspectives, and raises pertinent questions for future work on the topic. Its primary objective is to lay the groundwork for an online compendium to improve access to examples of water quality guidelines and facilitate a better understanding of how water quality demand and supply can contribute to appropriate and economical multi-sectoral water resource management.

While there are many forms of regulatory requirements in the water sector and a number of reports that examine them, there are also water quality guideline documents that cover large geographical areas such as federal states, and international regions. These have not so far been well examined. Guidelines are tools that recommend a particular practice, allowing some discretion or leeway in its interpretation, implementation, or use. They can come in a variety of forms, ranging from strict guidance such as a directive that is not voluntary yet still needs to be transposed into a final product of regulation, to recommendations that are encouraged yet voluntary to the target audiences. Therefore, to avoid duplicating work already done, this report focuses on such guidelines.

Developing a Global Compendium
on Water Quality Guidelines

Objectives

As stated above, the main objective of this report is to provide the proposed framework and initial content to supply an online compendium on global water quality guidelines according to water use. The report aims to provide the justification and outline for such a compendium.

It is expected that the specific aims of the proposed compendium will include;

1. Reducing water demand conflicts by encouraging consideration of differences in water quality needs when allocating water resources.
2. Supporting decision-making by water management authorities who are concerned with managing different uses and different water qualities.
3. Contributing to improving awareness and access to information on existing water quality guidelines, to increase efficient water use and support further development of water quality guidelines.
4. Improving knowledge concerning certain water uses where international guidelines for water quality do not yet exist.
5. Enriching the debate on water quality, particularly in relation to multidisciplinary aspects (technical, economic, legal, institutional, and social) and across different geographic scales (international, regional, national).

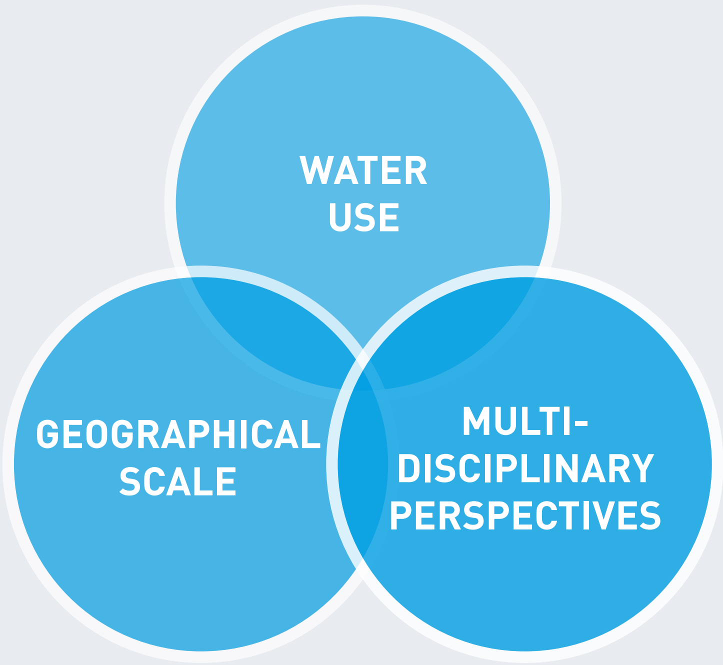
Target Audience

The primary intended audience for this report is national and international organisations working on water quality issues who wish to support water management decision/policy-makers, and regulators in both the public and private spheres. The audience of the future compendium would also include those who manage water in primary and secondary industries, as well as those monitoring and regulating drinking water and environmental water.

A wider audience in academia and water law may also find this report and proposed compendium useful, as well as students who wish to learn more on the subject of water quality guidelines that are fit for purpose.

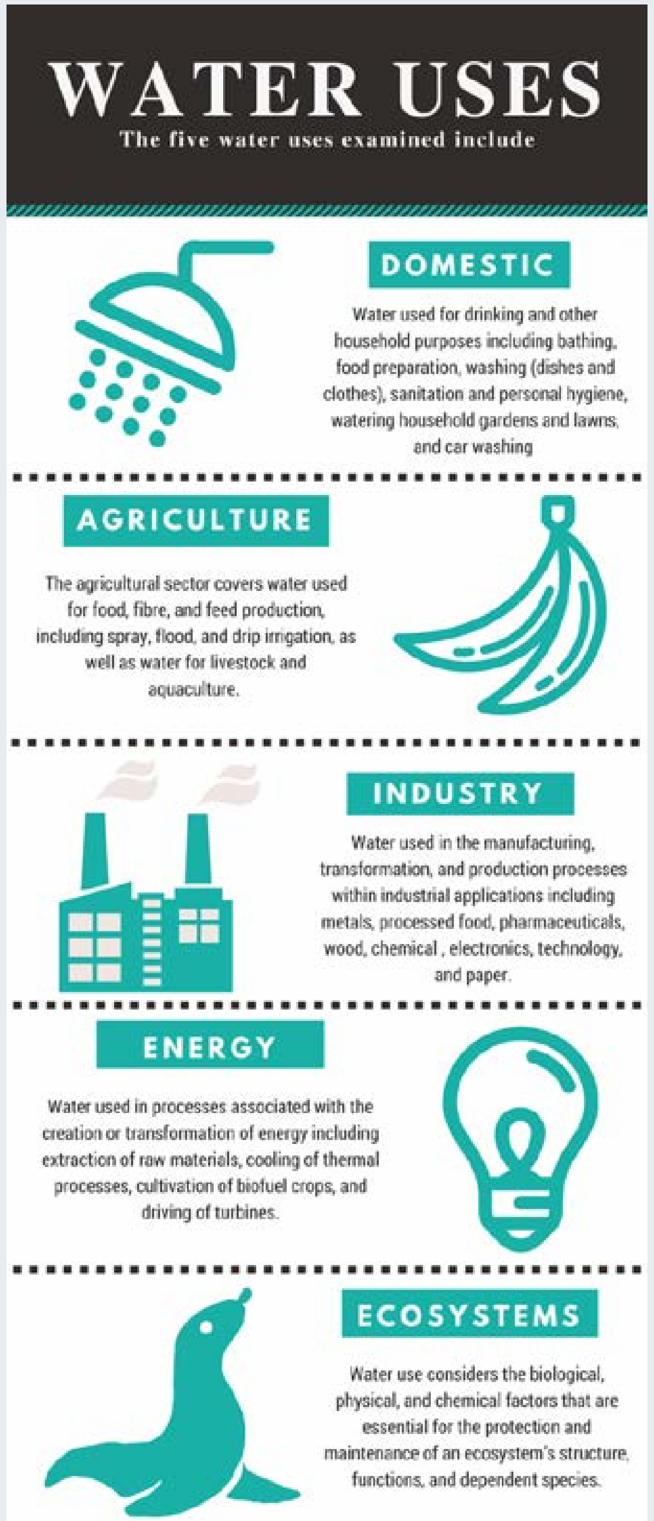
Structure

The contents and outputs of this report will be oriented around three overlapping domains: water use, geographical scale, and multi-disciplinary perspectives. It is important to realise that this report does not seek to create new guidelines, but to provide a reference on existing guidelines in alignment with these three domains.



Water Uses

Due to the nature of the resource, there are few water quality guidelines that address the full range of uses. This report is no exception, but focuses on five main categories of water use: domestic, agriculture, industry, energy, and ecosystems (it is noted that this is not an exhaustive list of all available water uses). These five sectors were chosen based on existing categories within water quality and management reports from international organisations including the United Nations (UN) and the European Environment Agency (EEA), offering a comprehensive range of sectors that are considered as essential when considering water quality applications.



Developing a Global Compendium
on Water Quality Guidelines

List of Selected Guidelines

DOMESTIC WATER QUALITY GUIDELINES			
Scale	Name	Date	Location
International	WHO Guidelines for Drinking Water Quality (GDWQ) - fourth edition incorporating the first addendum	2017	All
International	Global Drinking Water Quality Index (GDWQI)	2007	All
International	RAIN Water Quality Guidelines: Guidelines and Practical Tools on Rainwater Quality	2008	All
Regional	EU Drinking Water Directive (with latest amendments)	2015	European Union
Regional	UNECE Protocol on Water and Health	2005	Europe
	Taking policy action to improve small-scale water supply and sanitation systems. Tools and good practices from the pan-European Region	2016	
	Guidelines on the Setting of Targets, Evaluation of Progress and Reporting	2010	
National	Guidelines for Canadian Drinking Water Quality (GCDWQ) (updated version)	2017	Canada
National	Code of Practice on Piped Drinking Water Sampling and Safety Plans	2008	Singapore
National	Australian Drinking Water Guidelines (ADWG)	2011	Australia
AGRICULTURAL WATER QUALITY GUIDELINES			
Scale	Name	Date	Location
International	FAO Water Quality for Agriculture	1994	All
International	WHO-FAO Guidelines for the Safe Use of Wastewater, Excreta and Greywater Volume 2: Wastewater use in Agriculture	2006	All
International	ISO Guidelines for Treated Wastewater use for Irrigation Projects	2015	All
International	Codex Alimentarius Code of Hygiene Practice for Fresh Fruits and Vegetables	2003	All
National	Guidelines for Water Reuse	2012	U.S.A.
National	Canadian Water Quality Guidelines for the Protection of Agricultural Water Uses	1999	Canada
	Protocols for Deriving Water Quality Guidelines for the Protection of Agricultural Water Uses (Irrigation and Livestock Water)		
National	Guidelines on the Procedures and Technical Requirements for the Issuance of a Certification allowing the Safe Re-Use of Wastewater for Purposes of Irrigation and Other Agricultural Uses	2007	Philippines
INDUSTRIAL WATER QUALITY GUIDELINES			
Scale	Name	Date	Location
International	WHO-FAO General Principles of Food Hygiene	2009	All
International	WHO Good Manufacturing Practices: Water for Pharmaceutical Use	2012	All
Regional	Water Quality Demands in Paper, Chemical, Food and Textile Companies	2010	EU
National	South African Water Quality Guidelines Volume 3	1996	South Africa
National	Canadian Water Quality Guidelines (Chapter 5)	1987	Canada
ENERGY WATER QUALITY GUIDELINES			
Scale	Name	Date	Location
International	Efficient Water Management in Water Cooled Reactors	2012	All
National	Cooling Water Options for the New Generation of Nuclear Power Stations in the UK	2010	United Kingdom
ENVIRONMENTAL WATER QUALITY GUIDELINES			
Scale	Name	Date	Location
International	UNEP International Water Quality Guidelines for Ecosystems (IWQGES)	2016	All
Regional	EU Water Framework Directive	2000	European Union
National	Australian and New Zealand Guidelines for Fresh and Marine Water Quality	2000	Australia, New Zealand
National	Canadian Water Quality Guidelines for the Protection of Aquatic Life (CWQG-PAL)	1999	Canada
National	South African Water Quality Guidelines for Aquatic Ecosystems	1996	South Africa

Key Findings

- Water quality guidelines in reference to the domestic sector (specifically for drinking water and other household uses) are well established internationally by the World Health Organisation (WHO), and case studies provided in this review indicate the existence of comprehensive drinking water quality guidelines on both regional and national levels.
- Most guidance for water used in the agriculture sector is directed at safe wastewater reuse, especially for irrigation practices.
- There is a distinct difference between agricultural water use between developed and developing countries, with developed countries requiring guidelines to encourage the use of reclaimed water, and developing countries requiring guidelines to assist in making their practices of unplanned water reuse safer.
- Defined water quality guidelines for the total industrial sector are not available.
- International guidelines on water inputs for secondary industries are aimed primarily at food processing, pharmaceuticals and high-tech industries, all of which require sophisticated water treatment facilities.
- Few international or national guidelines on energy water uses currently exist.
- Most water quality guidelines currently omit mention of emerging pollutants including pharmaceuticals, personal care products and disinfection by-products.
- The usefulness and success of guidelines developed for water quality recommendations could be reflected by the number of regulatory bodies which uptake the content during the creation of binding policies.

Recommendations

- Define water quality requirements based on both application and geographical setting allows water resources to be applied more effectively.
- Encourage refining the quality of outflow from treatment facilities to match the needs of uses such as agriculture, landscapes, recreational areas and sports grounds.
- Given the innovations and requirements for the energy sector in biofuel, tidal power generation, hydropower, nuclear, solar and wind, as well as the continued use of non-renewable sources, develop guidelines for water quality used for these purposes.
- This is a sectoral analysis of water qualities; however, it is clear that a nexus exists between water and all the main sectors explored. Decision-makers must collaborate with other sectors for an integrated and broader approach.
- Water inflow into ecosystems consists increasingly of water discharges from the four other water uses examined in this report. Water is cyclical so a cross-sectoral perspective including water discharges from domestic, agriculture and industry sectors needs to be considered to safeguard environmental systems.
- As the global community works towards meeting the Sustainable Development Goals for 2030, further widespread use of the guidelines compiled within this report will contribute to meeting the key performance indicators:
  - 6.3.2 Proportion of bodies of water with good ambient water quality
  - 6.4.1 Change in water-use efficiency over time
  - 6.4.2 Level of water stress: freshwater withdrawal as a proportion of available freshwater resources
  - 6.5.1 Degree of integrated water resources management implementation
  - 6.6.1 Change in the extent of water-related ecosystems over time.

Developing a Global Compendium
on Water Quality Guidelines

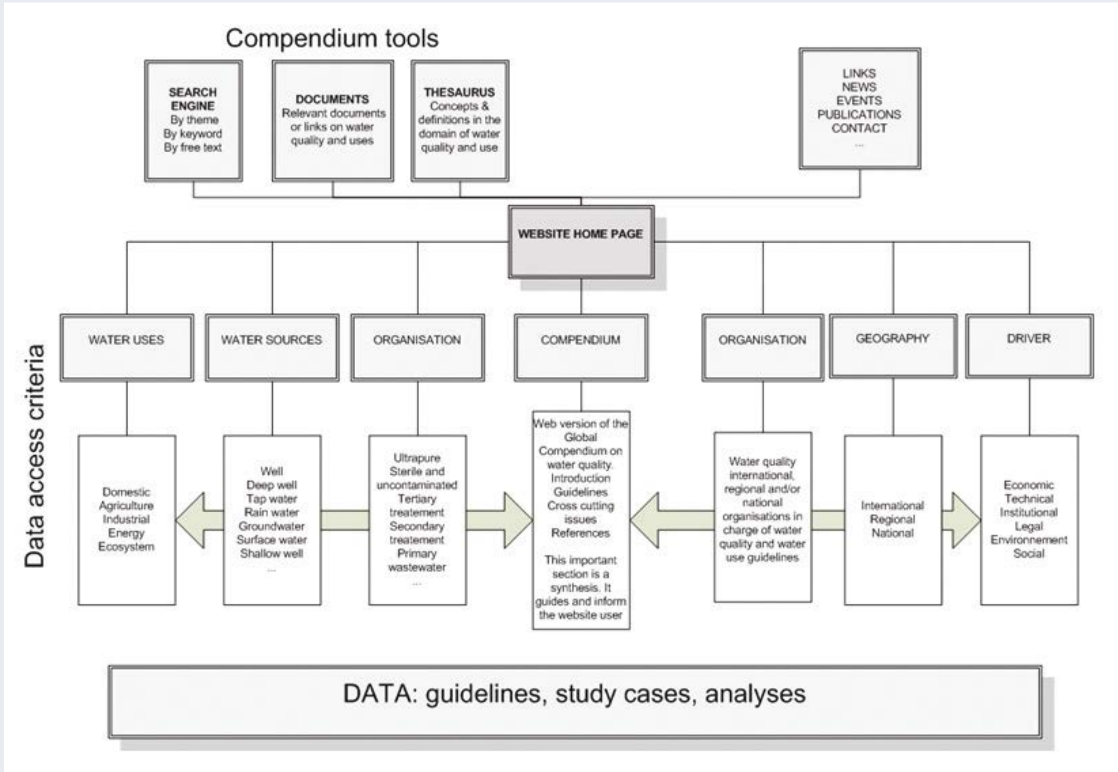
Proposed Database Structure

The first part of the report outlines a selection of water quality guidelines according to water use; however it is acknowledged that there are many more available guidelines and regulatory frameworks for directing management behaviour according to water quality. A compilation of the provided material, as well as a more comprehensive list or database would provide a complete picture of the water quality guidelines available at national, regional and international scales. The full compendium would also include regulations as an additional category of content. It is proposed that this information be stored and available on an online website, in a format that is user-friendly and easily accessible. The added benefit of an online compendium is the ease of access of information and analysis. This will contribute to increased access and sharing of data and tools, which in turn helps lead to sustainable development.

Key considerations for the proposed database development and structure are presented here, to encourage and assist in its development. While there are several possible ways to create and structure an online database, this proposal has been identified by IWRA as one structure that would be able to meet the set outcomes for ease of information retrieval.

As a minimum functionality, the online database of water quality guidelines and regulatory frameworks should include an appropriate, current and comprehensive content base covering each water use sector, and a broad range of geographical regions. Further to the listing the guidelines themselves, there should be brief summaries of each document as well as sector analysis, such as the example key findings and recommendations given in this report. The inclusion of a glossary of key terms, news, events and contact information would add value to the online platform. Key functional requirements for the public interface include convenient search tools to find the content needed, a responsive website (display adapts to different supports: screens, mobile phones), and various paths to obtain data from the system. Figure 1 outlines this structure.

One must acknowledge key challenges that should be addressed in order to overcome potential limitations to an online database. First, funding arrangements need to be made for the creation and upkeep of the proposed database, either through the public sector, grants or from users of the database through subscription. Proper maintenance is essential for any database to remain relevant and classified as a "living document". As such, it is recommended that the database be managed on a regular basis (at least annually) through review of previous examples and hyperlinks to ensure they are still accurate and up-to-date, followed by scanning for new guidelines and regulations, and subsequently adding commentary. A further challenge is ensuring the available guidelines and analysis cover more than the Anglo-saxon region. While this report uses mostly English guidelines, it is acknowledged that a compendium of water quality guidelines should include a broader scope of regulations and guidance from other languages.



The proposed water quality compendium structure of content for an online database.

Conclusion

Water quality remains a key consideration for global water management, not only for addressing low quality discharges that affect other uses and have environmental impacts, but also for examining the most efficient water quality for a specific purpose. The expansion of water quality criteria and references to more adequately consider five central applications of domestic, ecosystem, agriculture, energy and industry water uses has been reviewed and identified as an essential component of future management practices. This report identifies a number of existing guidelines directing water quality on an international, regional and national scale. The report also sets the structure for a more comprehensive online compendium of water quality guidance according to water use. Promoting the integrated use of these guidelines, while acknowledging the water cycle as a whole and that all outputs are eventually released to the environment, will contribute to smarter water management. This will help relieve stress on water scarce resources and ensure adequate water quality inputs to various applications, with the end goal of contributing to water security.

Web Links

The full document Developing a Global Compendium on Water Quality Guidelines and related materials will be published in 2018 on the IWRA website, and a link will be added to the project webpage. For more information on any of these water quality activities that IWRA is involved in, please visit the Water Quality Projects page on the IWRA website: www.iwra.org/waterquality.

CHAPTER 1

Introduction

CHAPTER 1
Introduction

Introduction

Human well-being and environmental sustainability depend on access not only to sufficient water but also to water of appropriate quality. Access to safe drinking water, the highest priority, remains a significant global challenge (WHO, UNICEF 2017). Simultaneously, there is need for water of adequate quality in other domains, such as agriculture, ecosystems and industry of various types, including power generation. Water quality is an important determinant of water scarcity, which occurs when "the aggregate impact of all users impinges on the supply or quality of water, to the extent that demand by all sectors, including the environment, cannot be satisfied fully" (UN Water, 2006). As not all uses of water require the same quality, a finer-grained approach to water management recognizes that variations in quality criteria for different purposes can help mitigate potential conflicts and reduce water scarcity.

Recognising that quality requirements vary by use can have several important benefits. Primarily, it can help improve water security, increasing "the availability of an acceptable quantity and quality of water for health, livelihoods, ecosystems and production" (Grey & Sadoff, 2007). Water security means adequate provision of safe drinking water as well as sustained flows of 'good enough' quality water to agriculture, industry and ecosystems. But what is 'good enough' quality? This is one of the most important questions facing water managers, particularly when considered in the context of wastewater reuse and water treatment demands. Furthermore, this improved water security will reduce both the capital and operational costs of providing potable water and wastewater treatment as it will reduce the pressure on existing infrastructure and delay the need for new investments.

It has long been acknowledged that water quality requirements are variable across a broad range of uses. This variability offers the potential to put waters of different qualities to their most beneficial uses (Enderlein, Enderlein & Williams, 1997) with higher quality water reserved for human consumption and allocations of poorer quality water given to less sensitive uses (Medgal, 2012; Molle et al. 2012). Yet, tools and criteria for specifying water quality targets are not readily defined or globally accessible for the full range of water use applications (Biswas & Tortajada, 2009) and there remains a critical need for a more nuanced approach to water quality management (Molle et al. 2012, Cross & Latorre, 2015). Until decision-makers have better guidance on the water quality requirements of particular uses, water resources will continue to be governed sub-optimally.

In preparation for the 6th World Water Forum, a stock-taking report by AFEID (French National Committee of the International Commission on Irrigation and Drainage), supported by several other French organisations (Académie de l'eau, SHF, ASTEE, ONEMA), outlined a starting point for global guidance of water quality for different uses, particularly for alternative water sources (AFEID, 2012). The International Water Association (IWA) and UN-Water have also developed a compendium that compiles and analyses global instruments and policies regulating water quality for different uses (UN-Water, 2015). This IWRA report supplements the regulatory instruments explored in that compendium by focusing on guidelines - not mandatory regulatory limits, but recommended water quality targets. Management of water quality has traditionally focused on a) requirements for human health, for example requirements for human consumption and domestic use, following guidance from the World Health Organisation (WHO) (Meybeck & Helmer, 1996; WHO, 2017), and b) standards for discharged wastewater/effluent, typically following guidance from national environmental agencies. Since influent water quality guidelines are less well-documented (WWAP, 2012), this report focuses is on the input side for economic, human and environmental use.

1.1 What is Water Quality?

Water quality- the physical, chemical, and biological characteristics of water- is a key determinant of a resources' suitability relative to a use or species requirements (WWAP, 2012). It has numerous influences including climatic, geomorphological, geochemical and biological factors inherent to the hydrological cycle, as well as anthropogenic influences operating from the global to local scale (UNEP, 2010; WWAP, 2012). Human influences impact water quality via waste discharge, land use alterations, and structural interventions (leading to changes in infiltration, runoff, and hydrodynamics), as well as the introduction of exotic and invasive species (Meybeck & Helmer, 1996; Lundqvist, 1998; Meybeck, 2004; WWAP, 2012). The interplay of these factors results in water quality characteristics specific to geographic locations and temporal cycles (Meybeck & Helmer, 1996). By defining limits on anthropogenic pollutants as well as naturally occurring water impurities, we hope to regulate the spread of pollution and disease and protect the short- and long-term interests of users and receiving environments.

Translation into Guidelines

The above-mentioned attributes can be measured and translated into water quality criteria; specific parameters of water used as tools to describe its various properties. Quality, in this setting, becomes a relative term: related either to a natural baseline level, or a level deemed acceptable for a particular use. Characterisation of water using quality criteria can be broken down into two groupings:

1. **physico-chemical parameters** - (e.g. temperature; electrical conductivity; total dissolved and suspended solids; organic compounds; and major trace and radioactive elements)
2. **biological parameters** - (e.g. microbial organisms; primary production; oxygen demand; and organism assemblages)

Table 1 provides an example of a more detailed classification of water quality parameters.

Water quality criteria have two main functions: to provide information on the effects of certain parameters on specific uses, and to detail threshold values to safeguard and sustain water quality for particular applications (Enderlein, Enderlein & Williams, 1997; Carr & Neary, 2008). Criteria are set according to the intended use of the water and are usually presented as quantifiable limits on chemical, physical, and biological parameters. These objective-driven criteria may be used in the design of monitoring, management, and policy directed at identifying, using, restoring, and protecting water resources (Enderlein, Enderlein & Williams, 1997; Carr & Neary, 2008).

Water quality criteria and corresponding guidelines are variable depending on whether water is used in a domestic setting, agricultural application, for the protection of ecosystem values, for an industrial process, or within the energy sector. This report aims to distinguish between these various applications to assess differences and integration of water quality guidelines. Table 2 provides a simplified summary of the various water quality parameters, for which criteria exist, based on anthropogenic pressures, however it should be noted that there are also naturally occurring water quality challenges that are not addressed.

Table 1: Categories of broad classifications for water quality parameters. Source: WMO, 2013.

Categories of WQ parameters
• Basic parameters, e.g. water temperature, pH, conductivity, DO and discharge, used for a general characterization of WQ
• Suspended particulate matter, e.g. suspended solids, turbidity and organic matter (total organic carbon (TOC), BOD and COD
• Indicators of pollution with oxygen-consuming substances e.g. DO, BOD, COD and ammonium
• Indicators of pollution with nutrients and eutrophication effects, e.g. nitrogen and phosphorus, and various biological effect variables, e.g. chlorophyll and Secchi-disc transparency
• Indicators of retention time in a slow-changing water body (lakes, reservoirs, impoundments)
• Indicators of acidification, e.g. pH, alkalinity, conductivity, sulphate, nitrate, aluminium, phytoplankton and diatom sampling
• Indicators for forecasting the future eutrophication state of water bodies
• Specific major ions, e.g. chloride, sulphate, sodium, potassium, calcium and magnesium: these are essential factors in determining the suitability of water for most uses, such as public water supply, livestock watering and crop irrigation
• Specific minor ions, e.g. arsenic and fluoride: above certain concentrations, these ions are toxic to human health
• Metals, e.g. cadmium, mercury, copper and zinc
• Organic micropollutants, such as pesticides and the numerous chemical substances used in industrial processes, products and households
• Indicators of radioactivity, e.g. total alpha and beta activity, 137Cs, 90Sr
• Microbiological indicator organisms e.g. total coliforms, faecal coliforms and faecal streptococci bacteria
• Biological indicators of the ecological quality, e.g. phytoplankton, zooplankton, zoobenthos, fish and macrophytes

Table 2: Drivers, pressures and water quality parameters measured for different water uses. Source: WMO, 2013.

Service and use (drivers)	Human health, drinking-water	Agriculture	Municipal/ industrial, energy	Ecosystem stability, structure and health	Tourism and recreation
Pressures	Pollution	Runoff, pollution from fertilizer and pesticide use	Pollution from effluents, construction and other supporting infrastructural impacts	Human activities; climate change and variability	Pollution
Parameter	Total coliform	Salinity	Nutrients	Temperature	Parasites
State	Faecal coliform	Nutrients	Temperature	pH	Pathogens
	Pathogens	Chlorophyll a	DO	Conductivity	Chlorophyll a
	POPs	Pathogens	Pathogens	Major ions	Nutrients
	DOC	Pesticides	Organic contaminants	DO	
	Chlorophyll a	Suspended solids	Other contaminants such as metals	Nitrogen	
	Turbidity	Trace metals	BOD and COD	Phosphorus	
			Heavy metals (particularly in sediment), radioactivity, acid mine drainage	Suspended solids	

1.2 Current Water Quality Context

Globally we are facing both water quantity and quality challenges (WWAP, 2012). In 2016, the World Economic Forum identified water crises as the global risk of highest concern over the next decade (WEF, 2016; WWAP, 2012). This scenario of scarcity has the potential to lead to severe water shortages, conflicts between uses as well as users, and severely undermines global stability and sustainability. Additionally, projections from the European Environment Agency (EEA) show that gains derived from traditional efficiency and productivity measures will be insufficient to meet growing water demands internationally. Projections of demand for raw water by 2030 reveal a 60% disparity between supply and demand on a business-as-usual scenario, even with the incorporation of historical improvements in water productivity (Figure 1) (EEA, 2010). Such scenarios highlight the urgent need for new approaches to water governance that introduce innovative methods to meet current challenges.

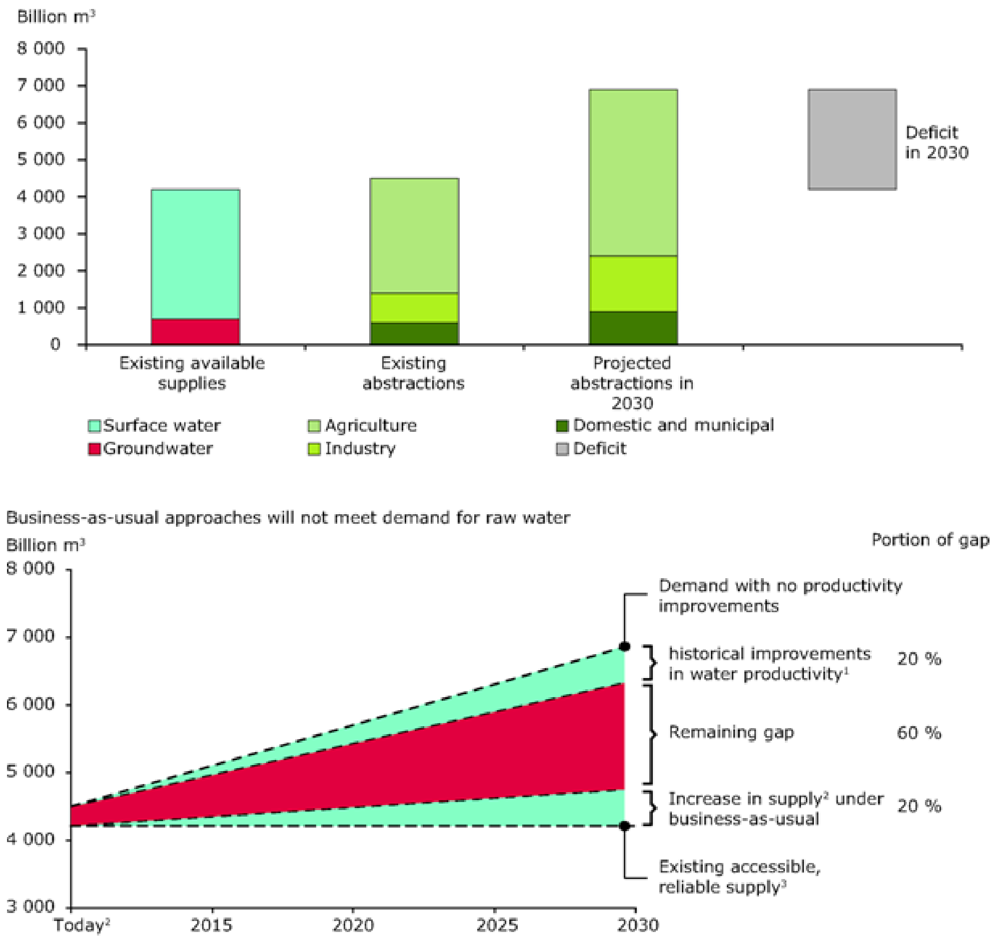


Figure 1: Projected increase in supply and demand of water resources. Source: EEA, 2010.

As underlined at the 6th World Water Forum Priorities for Action, water quality is inextricably linked to water quantity, since water that is of inadequate quality for use, reduces the overall availability of freshwater resources (UNEP, 2010, UNEP 2016). Natural systems rely on adequate water flows for dilution, filtration and purification, and thus, as water becomes scarcer, its quality is generally reduced (UNEP, 2010). This has significant implications for human society and water use, where water is scarce, and quality of water supply is inadequate for healthy use and consumption.

Developing a Global Compendium
on Water Quality Guidelines

Introduction

1.2.1 **Multisectoral Considerations**

The projected scenario in Figure 1 occurs alongside widespread water quality issues -the pollution and global degradation of water bodies from direct and indirect human pressures is threatening the future use and sustainability of our limited water resources. In relation to water resource quality and quantity, freshwater ecosystems are some of the most degraded systems on the planet (Millennium Ecosystem Assessment, 2005). Water quality degradation results from numerous pressures including nutrient and chemical pollution from agricultural, urban, and industrial runoff, land use alteration, thermal pollution, radioactive waste, introduction of non-native and invasive species, as well as structural changes to streams and rivers (Meybeck & Helmer, 1996; Meybeck, 2004; WWAP, 2012). Such pressures on water quality have repercussions much farther afield than the water bodies themselves, leading to impairment of human health and wellbeing, damage to ecosystem structure and function, as well as repercussions for food production, economic activity, and development (Lundqvist, 1998).

With over 10% of the global population without access to clean, safe drinking water supplies, it is evident that water quality has widespread ramifications for global society. Improving access to safe drinking water supplies, alongside addressing sanitation and hygiene issues, could prevent over 9% of the global disease burden (WHO, 2013).

Water quality issues also have a significant cost to the economy. Irrigation-induced salinity has an estimated global economic loss equivalent to US$11 billion per year, and freshwater eutrophication- which affects recreational water usage, waterfront real estate values, recovery of threatened species, and drinking water- has an estimated cost of $2.2 billion a year in the United States alone (Dodds et al., 2009).

1.2.2 **Climate Change Considerations**

The driving forces and impacts associated with climate change present additional stressors on water resource quality (WWAP, 2012; Cross & Latorre, 2015). Increased natural catastrophes, such as major floods can degrade water quality by transporting contaminants from upland sources into waterways. The increasing water temperatures from global warming can affect water quality by fostering excessive algae growth, pathogens, and dissolved organic carbons, affecting overall microbial life (OECD, 2013). Broadly speaking, climate change has the potential to exacerbate current stressors and interfere with water resource planning and governance. Consequently, it is important to acknowledge climate change in water quality management to ensure adequate adaptation and resilience of water quality considerations (OECD, 2013, Cross & Latorre, 2015).

1.2.3 **Sustainable Development Goals Considerations**

The United Nations (UN) adopted the Sustainable Development Goals (SDGs), which replaced the Millennium Development Goals, in September 2015. Water quality is a key consideration for many of the 17 SDGs, either directly or indirectly. Water holds the main topic for Goal 6: *to ensure availability and sustainable management of water and sanitation for all.* However, the issue of water quality does not stop there; it is a cross-cutting issue amongst other goals, such as Goal 12: *to ensure sustainable consumption and production patterns*, which involves using natural resources, including water, in a smarter, targeted manner. Other goals include understanding that water quality from "ridge to reef" involves interaction between the 'green investment' in water basins and the 'blue economy' of oceans, sea and marine resources (SDG 14). Moreover, the SDGs also address the importance of water quality to protect, restore, and promote the health of freshwater ecosystems, wetlands, and forests (SDG 15). Appendix A summarises the SDGs and their targets which relate to water quality.

Water management paradigms place an emphasis on water quality as a crucial element for ensuring water security within the SDGs. This report contributes to improved water quality by compiling information on the water needs of various uses in a global context and encourages an interdisciplinary dialogue.

Developing a Global Compendium
on Water Quality Guidelines

Introduction

1.3 Purpose of this Report

At the 2018 High Level Political Forum, Stefan Uhlenbrook (World Water Assessment Program of the UN Educational, Scientific and Cultural Organization (UNESCO)), discussed the current water quality problems- increases in freshwater pollution, climate change impacts, links between conflict and water-use, and the need for efficiencies in energy and agriculture- all of which contribute to his assessment that the world is not on track to achieve SDG 6 by 2030 (IISD, 2018). Inadequate water resource management globally has come at a cost, particularly in relation to water quality. The way forward, addressing current challenges and building the foundation for a smarter and more sustainable approach to water resource management in the future, requires us to call into question current water governance paradigms and explore new pathways. This report provides an initial overview of one such management pathway.

Adoption of forward-looking strategies is particularly important when considering increased competition for water resources as a driver of global water scarcity. Some challenges lending to increased competition include the uneven distribution of water resources, variable climatic factors exacerbated by climate change, burgeoning energy and industrial demands, and inadequate water management (WWAP, 2012). The severity of these challenges is underpinned by the fact that a significant proportion of increased water demands originate from regions that currently face severe water scarcity issues (FAO, 2011a). Therefore, as demand for water increases, the role of water quality in determining the suitability and thus the availability of water is brought into focus.

Directing water to the most appropriate use for its quality introduces greater efficiency and economy into the management of water resources across competing uses and aids in securing sustainability and security for future water use. It also reduces the extraction of new water which in turn increases environmental flows and the dilution effect, hence increasing water quality. As of 2018, there is no complete global overview of water quality guidance from a user perspective to provide easy access and interpretation of the available resources. This report introduces the structure for such a compendium - a collection of concise but detailed information about a particular subject – including a brief analysis and discussion.

1.4 Scope & Structure

The report collects and examines examples of existing recommendations for influent water quality, as applied to various human and ecosystem uses. It provides a non-exhaustive global summary of water quality guidance frameworks and reviews these frameworks to determine their utility. Building on the case studies, it raises critical, pertinent, and interesting questions, and underlines relevant perspectives and issues to direct future work on the topic. This structure presents the suggested framework for a larger proposed compendium.

As a complement to this report, in 2015 UN-Water and IWA produced a *Compendium of Water Quality Frameworks-Which Water for Which Use?* This compendium provides the most extensive and up-to-date overview of substantive national and international regulatory instruments and compiles selected laws and supporting case studies, with the aim to improve global water quality management. The selection of 46 instruments addresses a variety of economic sectors and water uses including industrial, domestic, agricultural, mining, recreational, environmental and power generation (UN Water, 2015). The compendium strives to enable the dialogue between countries regarding establishing effective water quality guidelines and regulations for different uses, and provides a solid starting point for further work in this arena.

Building off the UN-water compendium of regulatory tools directing water quality for specific purposes, this report only examines guidance tools for water quality. These are tools that recommend a practice, allowing some discretion or leeway in its interpretation, implementation, or use. Guidelines can come in a variety of forms, ranging from strict guidance such as a directive that is not voluntary yet still needs to be transposed into a final product of regulation, to recommendations that are encouraged yet voluntary to the target audiences. The scope of this report covers this full range of guiding documents.

The contents and outputs of this report will be oriented around three overlapping domains: water use, geographical scale, and multi-disciplinary perspectives (Figure 2). It is important to realise that this report does not seek to create new guidelines, but to provide a reference on existing guidelines in alignment with these three domains.

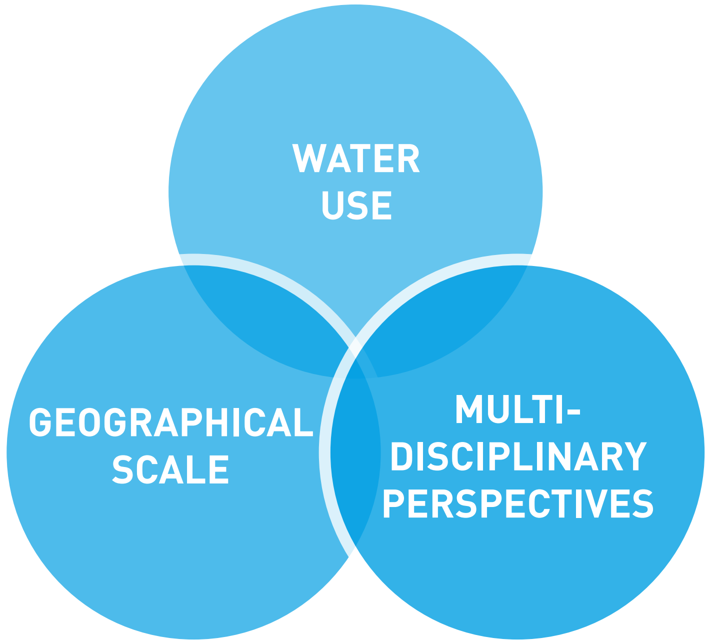


Figure 2: The three overlapping domains directing the structure of the report.

The structure of this document is composed of a general introduction, followed by five chapters which present and analyse selected water quality guidelines, finishing with a cross-sectoral discussion, proposal for a database structure to host a more complete compendium and conclusion.

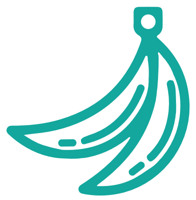
As the guidelines presented within a chapter are often dedicated to a single water use, the authors encourage a full examination of this report, to avoid silo-thinking. In particular, it is advised that chapter 6 on ecosystem water use be read alongside a review of all other water uses, as the outputs to other sectors constitute the input to ecosystems. Understanding the water quality guidance for ecosystems will help managers in other sectors manage the full cycle of water within their domain.

1.4.1 Water Uses

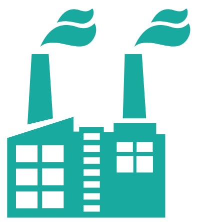
At present, there are few water quality guidelines that address the full range of uses. This report is no exception, but tries to expand the area considered to include five main categories of water use: domestic, agriculture, industry, energy, and ecosystems (it is noted that this is not an exhaustive list of all available water uses). These five sectors were chosen based on existing categories within water quality and management reports from international organisations including UN and the EEA, offering a comprehensive range of sectors that are considered as essential when considering water quality applications (WWAP, 2012).

An introduction to each of the water use sectors included within this document follows below.

Domestic
For the purpose of this project, domestic water use encompasses drinking water and water for household uses, including food preparation, washing, and personal hygiene. Guidelines for these applications typically have very strict criteria due to direct human consumption, water contact over a lifetime, and the need to account for sensitive life stages when people, including infants and the elderly, are more at risk (WHO, 2017).

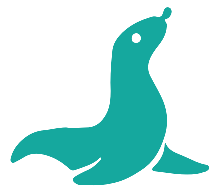


Agriculture
The agricultural sector covers water used for food, fibre, and feed production, including sprinkler, flood, and drip irrigation, among others, as well as water for livestock and aquaculture (WWAP, 2012). The agricultural sector alone accounts for 70% of global water withdrawals, and an even greater percent of consumption, and is thus a consequential sector when considering water consumption and its subsequent implications in terms of water resource quality (WWAP, 2012). International guidelines must acknowledge crop, livestock, and human health, and are particularly important when considering the widespread use of wastewater in agricultural processes.



Industry
Industry incorporates a wide range of sectors including food and beverage, medical and pharmaceutical, machinery and equipment, technology and electronics, mining, and construction. Generally, water quality standards range from a lesser quality of water for industry types able to utilise recycled and reclaimed water, to high quality water required for food, technological, and pharmaceutical processes (WWAP, 2012). While it has been estimated that industry accounts for 20% of freshwater withdrawals, standards and guidelines outlining water quality requirements for industrial processes are not yet readily defined (WWAP, 2012). Despite the varying water quality requirements within the industry sector, water of a higher quality than necessary for a specific use is often utilised due to cost or ease of supply (WWAP, 2012); this highlights the need and opportunity to define water quality standards across various industrial processes, and the potential for significant improvements in water use.

Energy
Water for energy is used in both primary (extracted, captured, and cultivated) and secondary (conversion of primary energies) generation methods, particularly those that undergo a transformation process, e.g. petroleum products, biofuel production, thermal processes, hydropower, solar/photovoltaic, and wind (Øvergaard, 2008). The links between energy and water are complex and widely acknowledged (e.g., in the water-energy-food nexus); but the water quality requirements for this water-intensive sector are not readily defined, and guidelines are hard to identify. The delineation of energy use as a separate category from industry reflects this sector's distinctive role in society and its distinct consumption of water as compared to other industrial uses. It also recognises the major growth that this sector will undergo in upcoming decades, with global energy consumption predicted to increase by a significant amount by 2050, a pertinent consideration for water consumption (EIA, 2017).



Ecosystems
Guidelines designed for aquatic ecosystems must consider the protection and maintenance of ecosystem structure (e.g. the distribution of species, biotic, and abiotic factors), function (e.g. energy flow and cycles) and dependent species (e.g. primary producers, secondary consumers) (Carr & Neary, 2008). Water quality specific to ecosystems use is an emerging research and policy focus in the water field, with the importance of preventing and controlling water pollution in aquatic ecosystems highlighted under the UN Thematic Priority Area (TPA) on Water Quality by UN-Water in September 2010 (Yillia, 2012). This recognition, along with the inclusion of ecosystems as a use category in this report, reflects better understanding and emerging focus on the importance of environmental considerations in water resource governance, as well as the essential role that water quality plays in ecosystem protection and restoration (WWAP, 2012).

1.4.2 Geographical Scale

This report aims to provide the start of a global summary on water quality guidelines, with outlines and analyses of guidelines on three scales:

- **international**
- **regional**
- **national**

The compilation of case studies is assumed to be an example of a global guide but not a comprehensive account of all current global water quality guidelines.

The guidelines presented in this framework were chosen based on geographical, developmental, and political settings, to provide a broad and balanced view of guidelines currently in use. The examples selected represent a strong English language focus, as these were the most accessible documents at the time of research.

1.4.3 Multi-disciplinary Perspectives

A multidisciplinary approach was employed, drawing on perspectives from a number of crosscutting issues, including institutional, legal, economic, social, environmental, technical, and global driving forces. This approach is to ensure a balanced and informed vision that provides a powerful platform from which to inform and influence policy and decision-making.

1.5 Objectives

1.5.1 General Objective

The main objective of this report is to provide the proposed framework and initial content to supply a more complete compendium on global water quality guidelines according to water use. Furthermore, the report aims to provide the justification and outline for such a compendium, as an online tool.

1.5.2 Overarching Objectives

In a context of global environmental, social and economic changes, as well as limited water resources, this project intends to contribute to more efficient water management through linking water resources quality to the needs of different uses. More specific aims include;

1. Reduce water demand conflicts by encouraging consideration of differences in water quality needs when allocating water resources.
2. Support decision-making by water management authorities who are concerned with managing different uses and different water qualities.
3. Contribute to improving awareness and access to information on existing water quality guidelines, to increase efficient water use and support further development of water quality frameworks.
4. Improve knowledge concerning certain water uses where international guidance on water quality does not yet exist.
5. Enrich the debate on water quality, particularly in relation to multidisciplinary aspects (technical, economic, legal, institutional, and social) and across different geographic scales (international, regional, national).

1.5.3 Framework Actions

1. Present water quality considerations and challenges in the context of five defined uses (domestic, agricultural, industry, energy, and ecosystems).
2. Identify and categorise existing water quality guidelines related to use at the international, regional, and national levels through case studies.
3. Provide perspectives and highlight issues related to water quality from a multi-sectoral perspective, pose pertinent questions, and propose solutions and new ways of addressing challenges.
4. Present a proposed structure for a larger compendium on the topic, as well as presenting a basic database structure to host the content online.

1.5.4 Target Audience

The primary intended audience for this report as well as a compendium on water quality guidelines is national and international organisations working on water quality issues who wish to support water management decision/policy-makers and regulators in both the public and private spheres. This includes those who manage water in primary and secondary industries, as well as those monitoring and regulating drinking water and environmental water.

A wider audience in academia and water law may also find this report and proposed compendium useful, as well as students who wish to learn more on the subject of water quality guidelines that are fit for purpose.

1.6 Methodology

In order to accomplish the goals of collecting and summarising case studies of global water quality guidelines, followed by an interpretation of these resources, the report follows defined methods of compilation and analysis. These methods also provide the suggested basic procedure for developing a larger compendium of water quality guidance.

This report has been worked on by a collection of IWRA staff, interns, editors and members, including panellists of the IWRA Water Quality Task Force. This Task Force had an open call to members and a selection of 14 experts with a range of geographical and technical expertise. This purpose of this diversity was to support each of the chapters of the report and create a balanced review.

To locate case studies, country representatives and water quality experts were consulted from the network of IWRA members and literature searches were conducted between 2014-2018. Criteria for inclusion of case studies within the report included;

- Guides of water quality standards for a certain use, specifically one of the five main categories of water use chosen for this report: (domestic, agriculture, industry, energy, and ecosystems)
- An aspect of guiding recommendations for water quality standards and procedures
- The most recent version of each guideline document
- An English language version of the document

Interpretation and analysis of selected guidelines was done by following a set of guiding questions. To evaluate each guideline, analysis followed the questions:

1. Is this a useful guideline? For whom?
2. Is this guideline clear and easy to read?
3. What types of standards are advised?
4. Is this guideline outdated or still relevant?
5. What is the uptake or outcome of this guideline?

In addition to the examination of individual guidelines, the discussion section of each chapter and later the full discussion followed the guiding questions:

1. What is the current state of water quality guidelines in this sector?
2. Are there sufficient guidelines to help direct this sector?
3. What has been done well?
4. Where should improvements, additions be made?
5. What parameters do the guidelines cover?
6. What are the challenges and opportunities for implementing the recommendations within the guidelines?
7. What are some emerging issues and key considerations in this sector?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CHAPTER 2

Domestic Water Quality Guidelines

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2.1 Context

Water quality is commonly understood in the context of domestic use, including human consumption and washing. The World Health Organization's (WHO) Guidelines for Drinking Water Quality are a key reflection of this, steering the international agenda with a concentration on water quality required for the protection of human health and the prevention of disease. While water quality guidelines for domestic use have numerous applications, this section will focus primarily on water quality requirements for drinking water and other household applications such as bathing and cooking.

In the context of the human domain, adequate water quality faces several pressures, including urban and chemical waste runoff, nutrient input, thermal pollution, and the introduction of contaminants of emerging concern such as pharmaceutical chemicals (Meybeck & Helmer, 1996; WWAP, 2012). Overall, demand for water is escalating, projected to increase by 55% worldwide by 2050, with the domestic sector contributing to this growth (Figure 3) (OECD, 2012a).

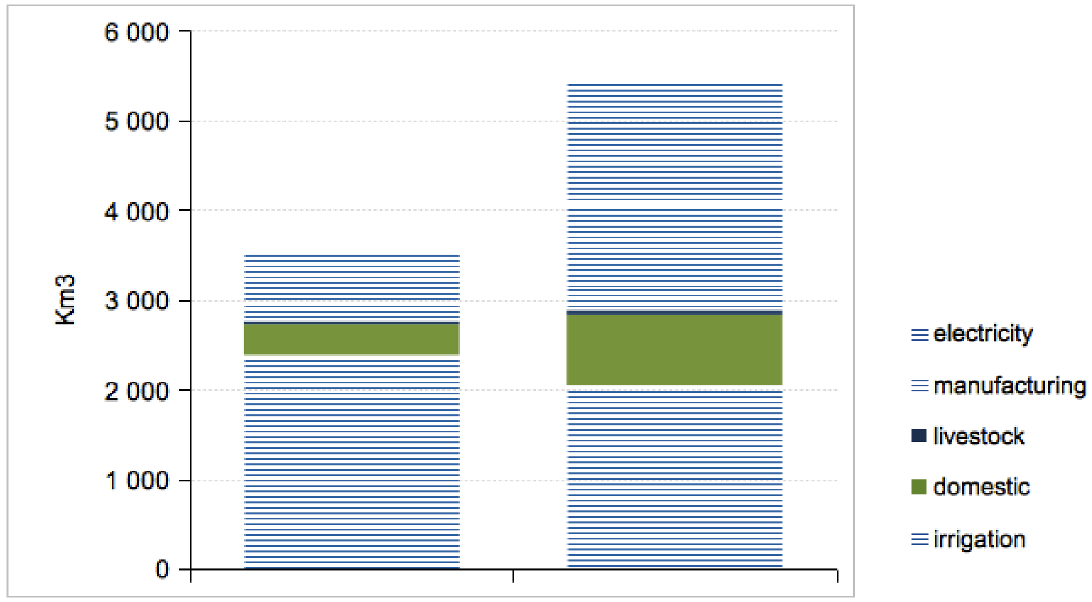

Figure 3: Increase in water demand by sector, from 2000 to 2050. Source: OECD, 2012.

Domestic water, which accounts for 12% of total water withdrawals (FAO, 2016), will represent a significant proportion of this growth in water demand, particularly since the world's population is projected to increase from the present population of 7 billion to 9 billion by 2050 (OECD, 2012b). Considering approximately 30% of the world's population lacks access to safe, reliable water supplies for drinking and sanitation, the future management of water resource quality for human consumption and other household uses remains a pertinent and relevant focus (WHO, 2018).

Change associated with population growth must also be considered in the supply of adequate quality water for human consumption, due to their considerable impacts on water supply and demand. As developing countries grow and their economies and living standards increases, shifts in industrial capabilities, economic productivity, and energy production also take place. Dietary characteristics begin to shift toward the consumption of more water intensive grain and meat products, and the demand for material products further increases (Msangi & Rosegrant, 2011; WWAP, 2012). Moreover, residential water use has a strong positive correlation with living standards, and as economies develop, there is a trend to demand and use more domestic water for activities such as toilets, bathing, and gardening (Zhang & Brown, 2005). These changes, when considered in the global context of human demand for high quality water, have significant implications for future water supplies, putting further stress on water availability.

Sources for Domestic Water Supply

Throughout history, humans have often chosen locations for settlement according to their proximity to water, as indeed each settlement requires at least one water source to sustain its population. There are several sources from which water can be supplied for domestic human needs, but there are two main sources; surface and groundwater. Surface water can be found in lakes, rivers or reservoirs and, groundwater is found in aquifers. A larger supply of surface water is commonly created by the construction of dams. In the United States, it is estimated that almost two-thirds of the population receive its domestic water supply from surface water, with roughly one third sourcing it from groundwater (Figure 4) (Dieter et al., 2017).

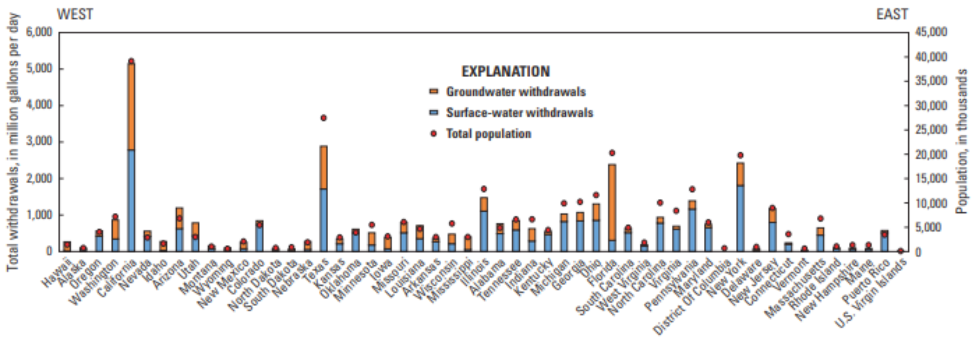

Figure 4: Total population and public-supply withdrawal, including their sources, from U.S. states in 2015. Source: Dieter & Maupin, 2017.

Aside from the two main water sources described above, other notable water supplies for domestic use include seawater and rainwater. Desalination facilities, such as those that exist in Barcelona and Tel Aviv, often use a reverse osmosis technology to remove the salt from the water and treat it to drinking water standards. In arid and coastal regions of the world, water supplied from desalination is becoming an important aspect of the public's water supply: for example, 55% of Israel's water is currently supplied from desalination plants (Jacobsen, 2016). Recycled water, previously used for human purposes, is another emerging source of water sometimes used for domestic water, such as in Singapore. Furthermore, rainwater is used as a water source in regions not connected to surface or groundwater, such as large part of rural areas in places like Australia. Rainwater can be collected and stored in a cistern, and the benefits of its harvesting are described in Box 1.

Box 1: Rainwater Harvesting for Domestic Uses

Rainwater is generally of a suitable quality for many domestic uses, including toilet flushing, laundry, and hot water applications (UNEP IETC, 2002; Coombes, 2006; Steffen et al., 2013), and can also be used for drinking water after being passed through a filtration or disinfection system (Coombes, 2006). While rainwater was historically collected in rural areas not serviced by municipal water systems, awareness of the benefits of collecting rainwater in urban areas is now growing. These benefits include providing a decentralized source of water that does not need to be transported from a distant water supply, providing water that can be used in cases of emergencies or natural disasters, and reducing the risks of flooding through capturing rain that would otherwise run-off as storm water (UNEP IETC, 2002).

Rainwater-harvesting systems are used to provide water for domestic uses around the world. For example, as of 2000, the Gansu province in China, had 2,183,000 rainwater tanks, which were used to supply drinking water to 1.97 million people and supplement irrigation for 236,400 hectares of land (UNEP IETC, 2002). Based on the success of this programme, by 2002, 17 provinces in China had adopted rainwater harvesting, with 5.6 million rainwater collection tanks supplying water to approximately 15 million people and providing supplemental irrigation for agricultural lands (UNEP IETC, 2002). Rainwater harvesting is also used extensively in some parts of the developed world. For example, as of 2006, rainwater was the primary source of drinking water for 13% of all Australian households, or roughly 2.6 million people (Coombes, 2006). The use of rainwater for domestic use therefore has significant potential to alleviate pressures on surface and ground waters, traditionally used in the domestic sector.

Providing guidance for rainwater use in the domestic sector is an important consideration however, as rainwater may have microbial and physico-chemical contamination via atmospheric deposition, leaching, animal excrements and weathering of roof/storage materials (Gwenzi et al. 2015). This contamination would make it dangerous and unsuitable for drinking water.

Human Settlement Pressures

The pattern and placement of human settlements is a major factor influencing the pressures imposed on water quality and demand patterns across regions. Urbanisation of human settlements is the predominant trend spanning the next two decades and by 2030, every region in the world will have an urban majority (Bernstein, 2002). Water quality stressors emerge when planning and urban infrastructure fail to match migration and population growth, leading to degraded water bodies and increased strain on scarce water resources (WWAP, 2012). At present, 80% of wastewater in developing countries is discharged directly into water bodies without prior treatment (UNESCO, 2017). Such mismanagement of waste, which gives rise to many challenges when water is withdrawn from downstream sources, is largely associated with the emergence of slums and the inadequate allocation of resources, planning, and policies associated with these settlements.

Perspective on Slums

When considering water quality for domestic use, urban areas, where populations now outnumber those in rural areas, emerge as an important factor influencing water supply and demand. Rapid urbanization, in the context of economic constraints and inadequate infrastructural development, has led to the emergence of slums, which accommodate approximately 30% of global urban populations (and up to 70% in least developed countries) (UN-Habitat, 2003a; Sclar et al., 2005). While it is recognized that water quality guidelines, largely driven by WHO initiatives, are widely applied in urban areas around the world, slums, which are mostly disconnected from formal city infrastructure, are often excluded from these rigorous water quality guidelines (UN-Habitat, 2003b). Box 2 provides one such example. This has significant implications for the health of populations living in these slum settlements, and it further increases the risk and spread of water-borne viruses and diseases. Slums, which were initially targeted in the United Nations' Millennium Development Goals, are now targeted in the Sustainable Development Goals, and are specifically defined by goal 11, target 1, which by 2030 aims to:

> *"...ensure access for all to adequate, safe and affordable housing and basic services and upgrade slums." (UN, 2015).*

At present, inadequate access to safe water resources is a key characteristic of slums. Thus, in the process of ensuring access for all to basic services and upgrading slums, it will be necessary to increase access to safe, reliable water supplies, further supported by goal 6, target 1 of the SDGs, which by 2030 aims to:

> *"...achieve universal and equitable access to safe and affordable drinking water for all." (UN, 2015).*

Box 2: Water Quality in the Langas Slum, Kenya

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The Langas slum, located in Eldoret, one of the fastest growing urban regions in Kenya, provides a key example of inadequate management and supply of water quality within a slum community. The water sources of the Langas slum include shallow wells, deep wells, and tap water, with 91% of residents using wells as their primary source of water.

Kimani-Murage and Ngindu undertook a study in 2007 to determine the fecal contamination of the community's domestic water sources alongside sanitary practices of slum residents. Results from this study revealed widespread contamination of well-water supplies; total coliforms contaminated 100% of water samples from shallow wells and 75% of water samples from deep wells, with thermo-tolerant coliforms found in 97% of shallow wells and 50% of deep well water sources. Tap water did not test positive for either total coliforms or thermo-tolerant coliforms. The research revealed that pit latrines located close to wells, combined with poor sanitary practices, acted as key contributors to the contamination of domestic water supplies in the Langas slum. The widespread contamination of the Langas slums' primary domestic water supply provides a notable example of the severely inadequate quality of water for domestic purposes prevalent in slum communities (Kimani-Murage & Ngindu, 2007).

Domestic Water Quality Requirements

The use and application of water in the domestic sphere is one of the most demanding of high water quality, with clean, pure water for drinking and household uses an essential requirement for good human health, such as the prevention of disease and widespread epidemics. Sufficient water quality is an important factor in addressing the global disease burden, with access to safe drinking water and adequate sanitation and hygiene having the potential to prevent a majority of water-borne diseases, including leptospirosis, cholera, and intestinal nematode infections (WWAP, 2012). Water quality for domestic use has been extensively documented, with international, regional, and national guidelines, frameworks, regulations and human health studies. This provides evidence of how domestic water quality can be effectively monitored and guided. However, the previously described pressures on water resources for domestic purposes reveal an urgent need for action in order to effectively and efficiently address future challenges of domestic water quality and disparities between water supply and water demand.

2.2 Existing Guideline Case Studies

Below are selected overviews of the application of water quality guidelines for domestic use at the international, regional, and national scales.

2.2.1 International

World Health Organization [WHO Guidelines for Drinking Water Quality (GDWQ)]

Water quality is a key factor for global health issues, especially as it relates to domestic purposes such as human consumption, and bathing. To address this on an international level, the Water Sanitation and Health division of the World Health Organisation (WHO) developed a series of normative guidelines that present an authoritative, up-to-date assessment of the health risks associated with water quality and the approaches for management of such risks (WHO, 2017). As the guidelines provided by WHO are at the international scale, the water quality criteria presented are not mandatory limits, but rather recommended values to provide a scientific and rational basis for individual countries and regions to develop their own national standards (AFEID, 2012). The first instance of guidelines from the WHO were the *International standards for drinking water* in 1958, followed by two updates leading to the WHO *Guidelines for Drinking-Water Quality* (GDWQ) in 1983–1984, followed by updates in 1993–1997, 2004, and 2011. Rolling revisions have allowed the most current edition (fourth) to remain up-to-date, with published appendices and expert reviews (WHO, 2017).

To address infectious diseases and other illnesses resulting from water-related exposure to toxic chemicals, the WHO introduced a harmonised and integrated approach combining risk assessment and risk management to control water-related disease. This approach is called the Stockholm Framework and it involves assessing health risks prior to the setting of health-based targets and guideline values, defining control approaches, and evaluating the impact of these actions on public health.

The GDWQ are more than just recommended values for water quality criteria; they provide a framework for systematically managing water quality and implementing the guidelines to ensure continual safe drinking water (see Figure 5). Using directions for

1. health based targets,
2. water safety plans, and
3. independent surveillance systems,

the framework puts focus on preventative and risk-based paths, supported by detailed information on microbial, chemical, radiological and acceptability aspects related to drinking water quality (WHO, 2017). Additionally, the GDWQ outline how water authorities should address water quality needs based on the context of a given region, emphasizing the importance of forming region-specific water quality plans, since regions will experience different social and environmental problems.

> *"When defining mandatory limits, it is preferable to consider the Guidelines in the context of local or national environmental, social, economic and cultural conditions." (WHO, 2017)*

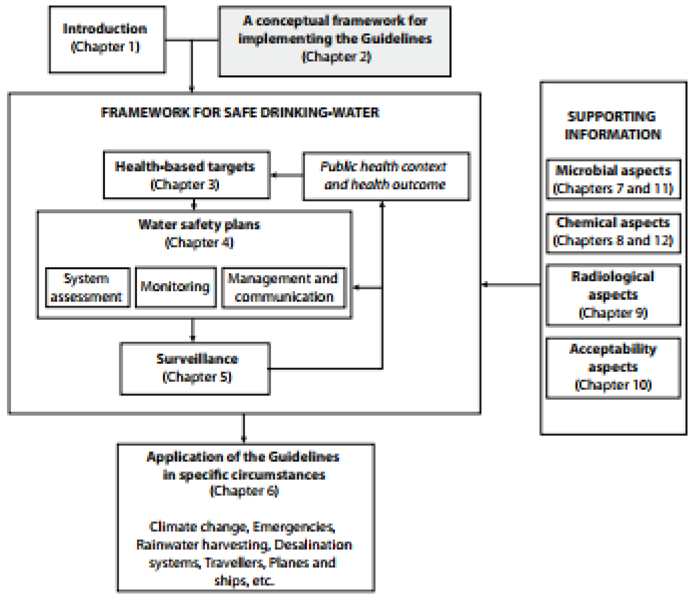


Figure 5: Conceptual framework of the WHO *Guidelines for Drinking-water Quality.* Source: WHO, 2017.

Translation to National Standards and Other Applications

The WHO's *Guidelines for Drinking-water Quality* are used across a range of regional and national settings and provide the official standpoint on water quality for the United Nations. The health-based targets outlined in the first section of the guidelines are the numerical base for national or regional drinking water quality standards (WHO, 2017). For example, the European Commission, Japan, Australia, and New Zealand use the guidelines as a scientific point of departure for their respective national drinking-water directives and standards, while the United States Environmental Protection Agency (US EPA) and Canada Health are actively involved in developing and updating their drinking water standards using the GDWQ (AFEID, 2012).

In the context of developing countries without defined water quality guidelines of their own for domestic purposes, the WHO GDWQ are often used directly as national standards. If resources permit, they are used indirectly to develop national standards, where national standards are tailored to country-specific settings (AFEID, 2012).

Other direct usage of the GDWQ is in the Codex Alimentarius Commission's *Codex Standards*; international standards, guidelines and codes of practice set for food provisions to ensure quality and safety of internationally traded food. Direct reference is given to the GDWQ in Codex Standard 227-2001 on bottled/packaged drinking water in that this water must comply with the health-related limits provided in the most recent GDWQ. Furthermore, the GDWQ are the guiding reference for water quality parameters within the UNEP Global Drinking Water Quality Index.

Based on the uptake of the WHO GDWQ described above, there is clear evidence that they are an essential tool for national level policymakers, water and health regulators as well as other international bodies such as the Codex Alimentarius Commission. As a continually updating resource, the GDWQ continue to improve on their drinking water guidelines and how to apply them. For example, the fourth edition discusses in detail the roles and responsibilities of stakeholders to set plans and monitor the quality levels, and the 2017 first addendum to the fourth edition includes revised risk assessments and additional guidance on risk management considerations, monitoring of lead and new microbial detection methods, among other additions.

Global Drinking Water Quality Index (GDWQI)

Indices are another means of guiding water quality information for a specific purpose. Guidelines and parameters are selected for a Water Quality Index (WQI) based on the desired output of the water (Da Costa Silva & Dubé, 2013), and they characterise quality based on its deviation from the normal or ideal index level. Reducing multiple factors into a single expression of water quality is a main advantage of WQI.

The main international WQI for domestic purposes is the Global Drinking Water Quality Index (GDWQI) by the Global Environmental Monitoring System (GEMS) Water Programme of the United Nations Environment Program (UNEP) (UNEP, GEMS, 2007). The GDWQI is based on the previous index model of the Canadian Water Quality Index, and data from GEMStat, a large database of over two million entries of water quality from inland waters (rivers, lakes, and groundwater) from 2800 monitoring stations around the world. It used equations established by the Canadian Water Quality Index to develop global indexes for drinking water quality based on human health and acceptability set by WHO (UNEP, GEMS, 2007). The result was a systematic evaluation of each monitoring station on the frequency and extent that parameters deviated from WHO guidelines, according to defined designations (Table 3).

Table 3: Water quality designations for the Global Drinking Water Quality Index. Source: UNEP, GEMS, 2007.

Designation	Index value	Description
Excellent	95-100	All measurements are within objectives virtually all of the time
Good	80-94	Conditions rarely depart from natural or desirable levels
Fair	65-79	Conditions sometimes depart from natural or desirable levels
Marginal	45-64	Conditions often depart from natural or desirable levels
Poor	0-44	Conditions usually depart from natural or desirable levels

There are several limitations of the initial GDWQI that may hamper its utility for guiding water for domestic use. One shortfall is that fecal coliform bacteria are not included as a criterion for the index, and so the GDWQI does not have any measure of microbial information, an important aspect of drinking water quality to determine health suitability. Furthermore, the data used for the index are from monitoring sites from a variety of source water bodies, not necessarily water intended for domestic purposes. However, evaluations of the quality of water from the GDWQI could be used to determine the most efficient use of these source waters, for example water that has a high scoring could be allocated for drinking water and lower scores could be directed to industry or grey water. Acknowledging the limitations, the GDWQI is still a good frame for more indices on drinking water quality, useful to reduce the bulk of water quality parameters into one value that is easily understandable, so there is potential to continue improving current global indices.

RAIN Water Quality Guidelines: Guidelines and Practical Tools on Rainwater Quality

Basic water quality guidelines also exist for specific sources of water, especially non-conventional water sources, such as rainwater. The RAIN foundation, an organization developed to aid in the implementation and promotion of rainwater harvesting (RWH) systems, created a document to guide users of RWH systems in using acceptable water quality for drinking purposes (RAIN, 2008). The tool summarises the available information on how to protect collected rainwater from contamination through simple means, recommending practical measures of quality protection rather than unachievable targets. The main body of these guidelines are descriptive, such as the example in Table 4, while the annexes provide more in-depth guidance that can be used in the field.

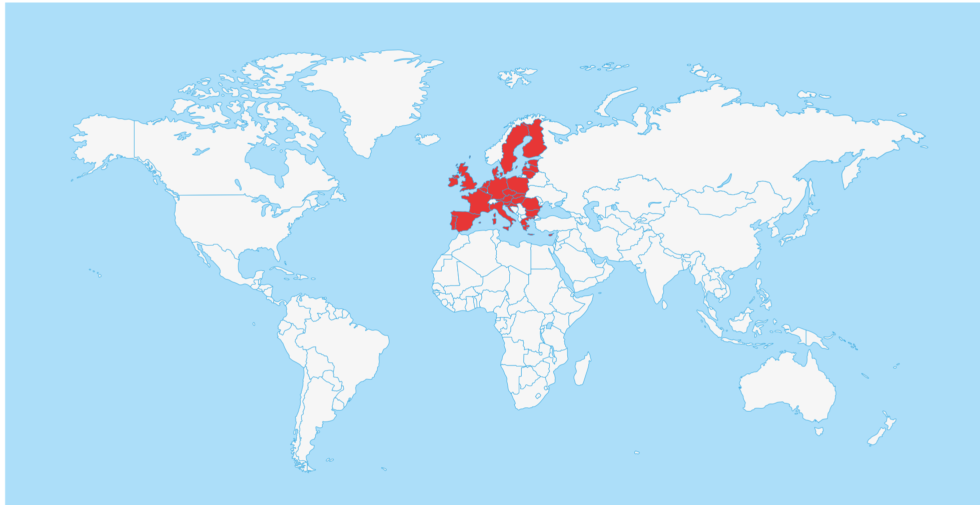
Table 4: Recommended methodology for baseline and long-term water quality surveys of RWH systems. Source: RAIN, 2008.

RAINs methodology for water quality surveys			
	Baseline survey	Long-terrm survey	
Period	After 1st rainy season after construction	After rainy season	
Nr. of RWH system	All RWH system, constructed that year	Random selection of 30% of all tanks(> 1 year old)	
Parameters	All parameters listed in table 2	Roofwater harvesting: • E-Coli, • Chlorine, if chlorination has been applied.	Surface runoff and sand dams: • E-Coli, • Turbidity, • Chlorine, if chlorination has been applied, • Aluminium, if it has been applied.
Period	November — December		

To improve on this, following WHO guidelines for such rainwater harvesting systems which advise system risk assessments, operational monitoring, verification, management plans and surveillance (WHO, 2017).

2.2.2 Regional

EUROPE



Europe faces numerous water challenges underlined by the concentration of countries within the region and the transboundary nature of its water resources (EEA, 2012). Such a setting necessitates a coordinated and cooperative policy and management approach to ensure sufficient water quality and supply for human consumption. Guidelines and directives are primarily driven by the European Union (EU) and the United Nations Economic Commission for Europe (UNECE), and are complemented by various other initiatives set by the UN and the Water Information System for Europe. Guidelines, specifically drinking water quality guidelines set out in both the EU Drinking Water Directive and UNECE's Protocol on Water and Health, were derived based on WHO's GDWQ.

EU Drinking Water Directive

The main instruction for water quality in the EU is not a suggested guideline but a legal framework, the *Water Framework Directive* (WFD). The WFD was adopted in 2000, providing overall direction for water use and management across the EU's 28 Member States, to protect and restore clean water and ensure its long-term and sustainable use (European Commission, 2016). Of note, the EU and consequently the WFD applies to only 28 of the 44 countries which make up Europe, with EU covering most of the north, west and central sub-continent (see Figure 6). Monitoring and reporting under the WFD occurs at the river basin scale for surface waters, groundwater, and protected areas (European Commission, 2016). Specific to domestic use, the *Drinking Water Directive* sets guideline values and monitoring procedures for water resources intended for human consumption and for use within the domestic household setting.

Figure 6: Map of European region, with members of the EU displayed in yellow and excluded European countries in white. Source: BBC, 2014.

Forming the cornerstone of the EU's potable water legislation, the *Drinking Water Directive (Council Directive 98/83/EC)* has the specific objective to:

> *"protect human health from the adverse effects of any contamination of water intended for human consumption by ensuring that it is wholesome and clean."*
> (Commission of the European Communities, 1998)

Wholesome and clean water is specified as being free from microorganisms, parasites, and other substances in concentrations that may constitute a threat to human health (Commission of the European Communities, 1998). Furthermore, it must also conform to 48 specified microbiological and chemical parameters.

As a regional guideline, the *Drinking Water Directive* is then translated into national standards by the 28 Member States. The Member States are free to choose their method of implementation, as long as the target standards are met and reported on to the European Commission every 3 years (European Commission, 2018). While the Directive does not allow countries to set water quality standards lower than directed in the guideline, they are allowed to set higher standards and additional requirements. For a limited time, Member States may be granted derogation, a departure from the EU standard, if it is deemed the threat does not pose a danger to human health and the standard cannot be met by reasonable means (European Commission, 2018).

Developing a Global Compendium
on Water Quality Guidelines

Domestic Water Quality Guidelines

UNECE

UNECE Protocol on Water and Health

Another major legal framework in the EU is the *Protocol on Water and Health*, or the first international agreement implemented to ensure the prevention, control, and reduction of water-related disease outbreaks in Europe. It entered into force in 2005 and has been ratified by 36 countries within the UNECE. Incorporating a holistic approach, it integrates safe drinking water supply, adequate sanitation and basin wide protection of water resources as key themes underlying the policy approach (UNECE, 1999). This protocol does not set out specific targets or guideline values for water quality; rather, it bases recommended targets on the WHO GDWQ and requires parties to monitor and enforce water quality standards within an institutional and legal framework (UNECE, 1999).

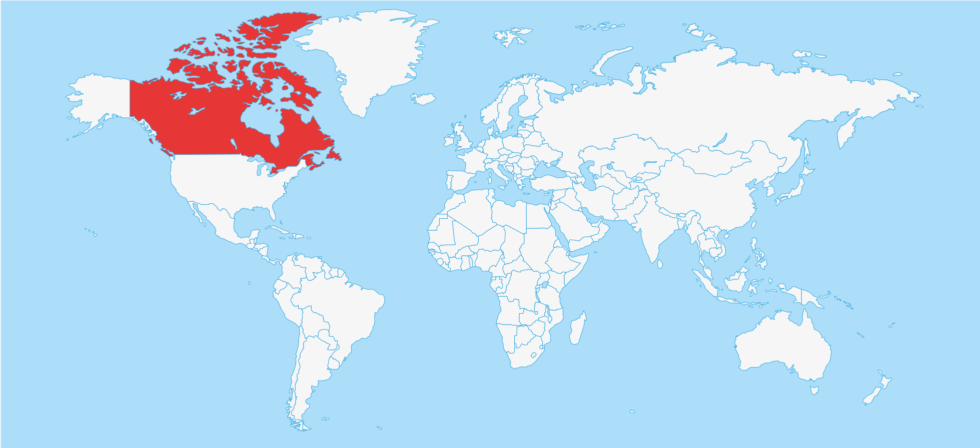
To aid in the implementation of this legally binding Protocol, several guidance documents were created by the WHO and UNECE. One such guiding document, entitled *Taking policy action to improve small-scale water supply and sanitation systems. Tools and good practices from the pan-European Region*, was developed by an international group of experts to facilitate policy tools to meet the water quality requirements among other binding conditions (WHO, 2016). Designed to inspire policymakers and practitioners of small-scale systems of water management, such as those in rural or small towns without the same resources as large urban areas, it includes descriptions of applicable policy instruments, step-by-step instructions on how to establish such instruments and case studies of good practices. While there is no guidance on technical water quality parameters, this document recommends tools on how to implement effective policy action.

Another guidance document to facilitate achievement and sustainability of compliance with the Protocol is the *Guidelines on the Setting of Targets, Evaluation of Progress and Reporting*. Unlike the more recent WHO publication on policy tools for small-scale water supply regions, the *Guidelines on the Setting of Targets, Evaluation of Progress and Reporting* help in the strategic framework of designing technical water quality targets and then monitoring these values (UNECE, 2010). This report also does not advise on the water quality target values themselves, but suggests the steps, considerations and resources necessary to set water quality targets for drinking water that is most appropriate for the local region.

2.2.3 National

National level regulations related to human water uses focus on water quality for direct consumption and recreational use. Differences between national guidelines reflect water sources and availability, local environments, public expectations, existing policy frameworks (that regulations may feed into), technological capabilities, and political will.

CANADA



[Guidelines for Canadian Drinking Water Quality (GCDWQ)](#)

In Canada, the responsibility for drinking water quality is shared between federal, provincial, territorial, and municipal governments, with provinces and territories holding primary responsibility for managing natural resources (including water quality for drinking water) and municipalities overseeing day-to-day treatment facility operations. However, water quality guidelines are published and overseen at the federal level by Health Canada. Developed by the Federal-Provincial-Territorial Committee on Drinking Water, the *Guidelines for Canadian Drinking Water Quality* have been in effect since 1968 (Health Canada, 2017).

The *Guidelines for Canadian Drinking Water Quality* (GCDWQ) provide maximum acceptable concentrations for various substances in drinking water supplies, based upon current, published scientific research on health effects, exposure levels, aesthetic considerations, and operational procedures. Specifically, contaminants are determined relevant for screening if they meet all three of the following criteria:

1. If exposure could lead to adverse health effects in humans
2. If the contaminant is expected to, or has the potential to be detected in a number of drinking water supplies
3. If the contaminant is or could be detected in drinking water at a level that may affect human health.

The guidelines take the form of three main tables:

1. microbiological parameters
2. chemical & physical parameters and
3. radiological parameters

Within these guiding tables, each parameter has information on the recommended maximum acceptable concentrations, aesthetic objectives as well as its common sources, health considerations and how to apply the guideline. Additionally, guidance documents are available for other parameters that do not meet these criteria for guideline development, such as potassium from water softeners (Health Canada, 2017). The guidelines incorporate a multi-barrier approach to safe drinking water, which aims to integrate all steps in the water supply system, considering source, treatment, and distribution systems using a preventative, risk-assessment approach. This approach serves as a template for the strategic alignment of the Canadian water quality guidelines.

The GCDWQ is critical for Canada because there are no national regulations for drinking water quality and as such the provinces and jurisdictions rely on these guidelines to direct drinking water quality. The guidelines are structured as summary tables on the Government of Canada's web page, with additional reading and guidance available, making the information simple and easy to follow for a variety of users. For further assistance in interpreting and using the guidelines, a supporting document entitled *Guidance for Providing Safe Drinking Water in Areas of Federal Jurisdiction - Version 2* (May, 2013) is provided. Overall, functional strengths of the GCDWQ are its easy accessibility, and regular updates, with the most recent version from 2017.

SINGAPORE

[Code of Practice on Piped Drinking Water Sampling and Safety Plans](#)

Over the last 50 years, Singapore has achieved an effective and diversified water supply in the challenging environment of a densely populated island. Singapore's diversified water supply comes from the 'Four National Taps', which includes water from local catchments, imported water, NEWater, and desalinated water. 'NEWater' refers to ultra-clean, reclaimed water, purified using advanced membrane technology and ultra violet disinfection, making it safe to drink. It is estimated that enhanced capabilities for producing NEWater and desalinated water will allow these two sources alone to meet 80% of Singapore's water demand by 2060 (PUB, 2016). In order to guarantee the quality of drinking water from these diverse sources, the National Environment Agency (NEA) of Singapore developed guidelines with the approval of the Minister of the Environment and Water Resources.

Section 80 of The Environment Public Health Act (Chapter 95), a key document for water pollution control in Singapore, sees the NEA responsible for the development of regulations relating to the quality of water supplied in any area or premise within the country. These regulatory standards, *Environmental Public Health (Quality of Piped Drinking Water) Regulations*, came into effect in 2008, were updated last in 2010, and dictate water quality standard values and sampling-monitoring practices that are broadly based on WHO's GDWQ. They consist of standards for 101 microbial, physical, radiological, and chemical water quality parameters, including E.coli, colour, turbidity, pH, heavy metals, benzene, and nitrate, amongst many others. The Public Utility Board publishes their drinking water quality reports annually, based on testing for these parameters.

In order to help water suppliers best meet these regulations and standards, a supporting document, *Code of Practice on Piped Drinking Water Sampling and Safety Plans,* was also created by NEA in 2008. These guidelines are based on WHO guidelines to outline best practices for water sampling and safety plans, acknowledging that plans should be targeted and based on multi-barrier approaches (NEA, 2008).

AUSTRALIA

Australian Government

[Australian Drinking Water Guidelines (ADWG)](#)

The *Australian Drinking Water Guidelines* fall under the National Water Quality Management Strategy, which is a joint approach undertaken by the Australian and New Zealand governments to protect water quality whilst supporting socio-economic development and growth (NHMRC & NRMMC, 2011).

The 2011 ADWG protect the safety and aesthetic quality of drinking water, and forms the authoritative Australian reference for water used for both drinking and domestic purposes. The ADWG are not mandatory standards, and it has been acknowledged that regional and local factors, including economic, cultural, and political factors as well as expectations by the public sector, need to be accounted for in order to provide a more balanced approach to guideline development and implementation (NHMRC & NRMMC, 2011). These are intended as direction at the national level, which states and territories could then use in a manner that is best suited for the local area (AFEID, 2012).

The ADGW guidelines are a huge resource, integrating two forms of water quality measurement:

1. health related values, which are concentrations or measures that, over a lifetime of consumption, do not constitute a significant risk to a consumer's health
2. aesthetic values, which ensure acceptable appearance, taste, and odour for all consumers

Two hundred and thirty eight criteria are included in the ADWG, including organic and inorganic chemicals, microorganisms, disinfectants, disinfection by-products, radionuclides, and qualitative standards (NHMRC & NRMMC, 2011). These guidelines were originally developed in direct alignment with the WHO GDWQ; however, they have since been adapted and adjusted with input from the National Health and Medical Research Council, water authorities, private industry, universities, and government departments. Other aspects of the ADGW include frameworks for managing water quality, detailed monitoring strategies and information/fact sheets on physical, chemical and biological characteristics, statistics analysis and disinfection.

The guidelines undergo a continual revision process, incorporating constant updates to reflect the most current, available knowledge on water resource quality, with the latest update in 2017 as of the writing of this report.

2.3 Discussion

As domestic water use can have direct and consequential impacts on human health, there has been significant research and guidance provided at the international and national scales. Most countries have some form of guidance, regulation and routine monitoring of water quality for this purpose. The structure of drinking water quality guidelines is set at different scales and provides different forms of guidance, such as indices, technical parameters, and implementation tools. Each aspect has its purpose and advantages. For an example, the *Global Drinking Water Quality Index* has been found to be useful to communicate changes in water quality (Da Costa Silva & Dubé, 2013). As the WHO guidelines and several of the national guidelines show, a comprehensive guideline includes a mixture of these aspects; not one guideline or regulation, but a mixture of several overlapping documents.

On a global scale, the WHO sets the benchmark for direction on drinking water quality. To determine the usefulness of a policy or guideline, the uptake and effect of such instruments must be examined. In the case of the WHO *Guidelines for Drinking Water Quality*, many governing bodies and other guidance support has been structured using these guidelines, such as by the European Commission and Japan. Acting as a baseline, national and regional governing bodies must then examine their local context to adapt the WHO GDWQ. Table 5 shows the range of values for certain parameters found on large-scale guidelines for drinking water quality, using WHO GDWQ as this baseline.

Table 5: Comparison of drinking water quality guidelines across selected parameters from guidelines provided by WHO, the EU and national ministries from the US and Australia. Source: UNEP & GEMS, 2007.

Parameter	WHO	EU[T]	USEPA	Australia
Ammonia	1.5 mg L^{-1}	0.50 mg L^{-1}	No GL	0.50 mg L^{-1}
pH	6.5-8	No G L-1	6.5-8.5	6.5-8.5
Chloride	250 mg L^{-1}	250 mg L^{-1}	250 mg L^{-1}	250 mg L^{-1}
Iron	0.3 mg L^{-1}	0.2 mg L^{-1}	0.3 mg L^{-1}	0.3 mg L^{-1}
Lead	0.01 mg L^{-1}	0.01 mg L^{-1}	0.015 mg L^{-1}	0.01 mg L^{-1}
Arsenic	0.01 mg L^{-1}	0.01 mg L^{-1}	0.01 mg L^{-1}	0.007 mg L^{-1}
Copper	2.0 mg L^{-1}	2.0 mg L^{-1}	1.3 mg L^{-1}	2.0 mg L^{-1}
Faecal coliform bacteria	0 counts/100 mL	0 counts/100 mL	0 counts/100 mL	No GL

T. WHO guidelines for drinking water were used as a basis for the standards for the EU Drinking Water Directive.

The WHO GDWQ advises national governments to use the recommended values for water quality parameters in nationally developed regulations for domestic water. However, two OECD member states, Canada and Australia, do not have legally enforceable drinking water quality standards at the national level. Canada and Australia are both federal state systems with strong guidelines directing drinking water quality, needed to support the lack of national regulation on the subject in their regions. A comprehensive review and analysis of the uptake of the *Guidelines for Canadian Drinking Water Quality* across Canada by Dunn *et al.* (2014) showed that the guidelines were used across most jurisdictions, but not in a consistent manner, with only 16 of the 94 advised parameters being applied uniformly. Affordability is a factor in this inconsistency, with small remote communities sometimes struggling to afford and meet strict water quality guidelines.

This raises the issue of whether mandatory standards or voluntary guidelines and systems knowledge produce the best results for safe and consistent water for domestic use. Alternatively, the AWDG have shown that guidelines can be translated by states into results that account for regional and local factors, including economic, cultural, and political factors as well as expectations by the public sector. These consideration need to be accounted for in order to provide a more balanced approach to guideline development and implementation

Upcoming considerations for regulation and guidance concern non-regulated emerging chemical contaminants and the guidance of wastewater and grey-water treatment for domestic purposes. NEWater in Singapore as well as examples in Namibia and the western U.S.A. demonstrates that this is a feasible source of domestic water. The role of public perception in acceptance of recycled water schemes is of vital importance to the success of the new water source (Lee & Tan, 2016). Residents of Toowoomba, Australia rejected the newly proposed recycled water scheme for drinking water in 2006 but the Public Utilities Board of Singapore was able to successfully re-brand their recycled water as NEWater to help improve public acceptance of this water source. Environmental buffers, such as depositing recycled water into surface and groundwater reservoirs may aid with this challenge.

The domestic water quality guidelines reviewed in this report have focused on drinking water purposes, however less global guidance exists for non-potable domestic uses, such as for flushing toilets, and gardening. There is an urgent need for further research into this area as restricting the use of water treated to drinking water standard for purposes where this quality is needed would significantly ease the pressure on the capacity of treatment plant and reduce treatment cost. The guidance document provided by RAIN on RWH systems is helpful to encourage and direct good practices for water quality management of this water source. Wastewater and grey-water also offer alternative options for water sources, and appropriate guidance could encourage its use and ensure it meets health related values. There are basic examples of direction for this, such as an information guide provided by the UK Environment Agency, however it still contains very little data on water quality guidance. Future work could focus on different sources of water for domestic purposes, either potable or non-potable, and specify the water quality requirements and implementation advice targeted at this purpose. This will require work on how to design and implement affordable dual distribution and waste disposal infrastructure to facilitate this.

CHAPTER 3
Agricultural Water Quality Guidelines

CHAPTER 3

Agricultural Water Quality Guidelines

3.1 Context

Irrigated agriculture feeds the majority of the world's population, and provides raw materials such as fibres and oils (FAO, 2011a). Withdrawing more than 7130 km^3 of water per year, the agricultural sector is the largest user of water. It surpasses both the domestic and industrial sectors and accounts for, on average, 70% of global water withdrawals (FAO, 2013, WWAP 2017) while in many water scarce basins it can account for up to 90% of extractive water use. Because of this, and the sector's ability to use water of marginal quality, it has the potential to play a critical part in meeting future demand for water for all uses, as it could reduce extraction of new water and replace it with water of different qualities.

Water use in the agricultural sector involves the production of food, feed, fibre and other products, accomplished through the cultivation of crops and raising of domesticated animals. Agricultural producers use either natural rainfall patterns (rain fed agriculture) or irrigation using surface, reclaimed, or groundwater resources. This report focuses on irrigated water, as it is not possible to control rainwater. Irrigated crops are mainly used for the production of food production for human consumption and feed for livestock, but also for fibre and biofuel production. Other uses of water include livestock watering, pesticide and fertilizer applications, crop cooling, and frost control (CDC, 2009). This report will consider water quality and the role it plays in agriculture through impacts on crop viability, livestock health, soil health, and sustainability, in addition to the health of both farm workers and consumers.

Agriculture has undergone widespread expansion and intensification over the last five decades, initiated by the Green Revolution in the 1960s which was one of the major drivers of the rapid expansion of irrigation, fertilizer use, and pest control measures (WWAP, 2012). Water, both of adequate quality and quantity is an intrinsic requirement of the agricultural sector and, as a resource, is vital in producing adequate and sustainable food to meet the needs of the world's rapidly expanding population which FAO estimates will consume 70% more food in 2050 than in 2009 (FAO, 2011a). Meeting future demands in a sustainable manner calls for a shift in the underlying approach to water resource management in the agricultural sector.

The fundamental water challenge in the agricultural sector, regardless of a country's economic developmental status, is to promote the widespread use of recycled wastewater and greywater rather than high quality surface water and groundwater, within appropriate health and safety constraints. Smarter water quality use is thus a critical requirement for the realisation of this vision.

Interactions of Water Quality and Agriculture

The interactions between water quality and agriculture are both extensive and multifarious. The focus of this report is on water consumed by the agricultural sector; however, agriculture can also impose significant impacts *on* water resource quality through altered landscapes and increased nutrient runoff, which in turn, can cause erosion, sedimentation, and eutrophication in surface waters. Though these are important factors to consider in terms of water quality, they will not be addressed in this chapter since the focus remains on water quality requirements for use by the agricultural sector.

Water source is also an important determinant of water quality. Water used by the agricultural sector can be drawn from a variety of sources depending on the geographical, developmental, and legislative settings of a region (see Box 3). Moreover, historical and cultural factors such as traditional practices and socio-cultural norms can also influence the source of water chosen for agricultural applications. Common water sources in the agricultural sector include (CDC, 2009; Jacxsens et al., 2012):

- Domestic/grid water supply
- Natural still surface water (lakes)
- Rivers and streams
- Impounded water (dams, ponds, reservoirs)
- Rainwater
- Seawater (seawater, desalinated seawater, brackish groundwater)
- Groundwater
- Treated and untreated wastewater

Box 3: Surface and Groundwater Resources

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By definition, *surface water* refers to any water readily available from the surface of the Earth, whereas *groundwater* refers to water that flows or seeps downward, saturating soil, rock crevices, and the pores of geologic material. Differences between these two resources, particularly the water quality implications of their use, grow in importance as groundwater resources become increasingly exploited for agriculture. Groundwater represents 43% of the total consumptive water use for irrigation (Siebert et al., 2010). The expansion and exploitation of groundwater resources in the last three decades raises several pertinent points for water quality and future availability. Aquifer depletion and groundwater pollution are currently key challenges in a number of irrigated areas resulting from intensive groundwater use. A lack of data on the baseline water quality of groundwater resources, combined with often non-existent guidelines to direct its use within the agriculture sector, leaves significant gaps in the sustainable use and management of this resource.

Water sources contaminated with pathogens, chemicals, heavy metals, and excessive salinity pose health risks to crops, livestock, farm workers, and consumers. In addition to health risks, inadequate source water quality can also contribute to significantly lower crop quality and yields, influence the mortality and growth rate of livestock and cause long-term landscape changes through impacts such as salinization. These landscape changes undermine the viability of agricultural lands and requiring significant capital and labour to rehabilitate.

The range of challenges associated with the use of inadequate water quality in agriculture underline the importance of considering guidelines and criteria related to water applied in this sector. Proper use and consideration of water source, combined with safe, effective, and

Developing a Global Compendium
on Water Quality Guidelines

Agricultural Water Quality Guidelines

efficient application measures, can contribute to an agricultural sector that is sustainable, productive, and secure – a vital requirement for the development and growth of a healthy society. The following sections discuss four main challenges facing irrigated agriculture: (1) the use of wastewater, (2) salinization, (3) climate change, and (4) heavy metal contamination.

Wastewater and Marginal Water Quality Use in Agriculture

The agricultural sector holds significant potential to benefit from the use of marginal or lower quality water (Molle et al., 2012). Wastewater, which is commonly enriched with beneficial nutrients, can be a valuable resource for the agricultural sector when managed correctly. Not only is it a recycling of previously used water, it provides livelihood benefits and food sources, especially advantageous in impoverished areas (Raschid-Sally & Jayakody, 2008). However, a key challenge of using water of marginal quality is maximising the benefits whilst protecting and minimising the risks to public health and the environment, as identified in the Hyderabad Declaration on Wastewater Use in Agriculture (IWMI, 2002). This is a particularly important consideration as the supply of this resource is likely to increase in the future and it enables increased agricultural production without increasing the use of good quality water. It also allows for good quality water to be transferred to other purposes needing better quality without reducing the production of agricultural produce.

There are a number of marginal water types utilised by farmers, including wastewater from domestic and urban uses, saline or sodic agricultural drainage water, and groundwater (Mateo-Sagesta & Burke, 2008). The use of wastewater (often referred to as reclaimed water in higher income countries) varies significantly between global geographic and development settings (Table 6). This often corresponds with unplanned use in developing nations, and planned use in developed regions, an important distinction as planned use usually involves more careful water quality assessment, and unplanned use is an order of magnitude greater than planned (Scott et al. 2010).

Table 6: Country setting and their associated typical wastewater use scenario. Source: Mateo-Sagasta & Burke, 2008.

Country setting	Drivers	Wastewater use	Technologies employed/level of treatment	Level of risk to human, agriculture and environmental health
Low-income	Severe water scarcity, poverty, lack of sanitation	Reused wastewater is used for urban and peri-urban agriculture. There are usually no regulations on its use.	None/ untreated	Serious
Middle-income	Water scarcity, interest in recycling nutrients, high demand	Wastewater is used for irrigated agriculture, following the WHO guidelines.	Low-cost technologies/ Partially treated or untreated	Moderate
High-income	Water scarcity, environmental protection, stringent standards for wastewater discharge, high demand	Reclaimed wastewater is used primarily for agricultural and sometimes landscape irrigation, less often for domestic use. The highly effective sanitation and treatment technology reduces risks.	High-cost technologies	Almost zero

Wastewater, frequently of marginal quality, is increasingly used for agriculture in both developing and developed countries. Already, wastewater exists as an important resource on a global scale; it is estimated that more than 10% of the world's population consumes food produced by wastewater irrigation (Osterath, 2017). The principal forces driving its use include increasing water scarcity and stress, widespread degradation of freshwater resources, poverty, and high demand from rapidly increasing population centres, particularly in urban areas, driving demand for food and fibre (see Box 4). However, the unregulated use of untreated water has significant health and environmental impact in many developing countries.

To note, water reuse can and is being used as a source of water for all the water uses examined in this report. Because the global principal use is for irrigation and agricultural purposes, guidelines for its use are examined in this chapter.

Box 4: An Urban/ Peri-Urban Perspective on Wastewater use


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The use of recycled, marginal quality wastewater derived from residential, commercial, and industrial sources is a particularly important resource for urban and peri-urban agriculture in developing countries. The rise of urban agriculture stems from a rural influx to cities contributing to rapid urbanisation, an increased need for food security, and enterprising farmers who recognize opportunities presented by cities with regards to increased demand for fresh fruit and vegetables. The main factors driving wastewater use in developing countries include a lack of alternative water sources, a reduction or elimination of fertilizers, their lower energy costs, and greater practicality with peri-urban farmers able to provide high value vegetables in close proximity to cities' demand (Sato et al., 2013).

Water used in urban and peri-urban agriculture is often outside the boundaries of formal water quality guidelines; however, for many farmers it represents the only available and viable resource with which to water crops and livestock (Mateo-Sagesta & Burke, 2008). The urban and peri-urban landscape thus emerges as an important perspective when considering the need for water quality guidelines in agriculture.

Treated wastewater is also an increasing source of water in high value peri-urban agriculture in many developed countries. An example of this is in Australia where there are two major sewerage treatment plants in Adelaide which supply new vineyard development and vegetable production at its fringes. This increases high value agricultural production and also generates revenue for the sewerage plants and reduces the volume of effluent into the ocean.

While use of wastewater is extensive, data surrounding usage and sources is limited, particularly on a national level. Research conducted by Sato et al. (2013) found that out of a total of 181 surveyed countries, only 62 had information on wastewater use, representing only 34% of all countries surveyed. Such data reveals a considerable need for improved reporting on wastewater usage and highlights the general lack of acknowledgment of its importance within the water sector.

Wastewater use constitutes environmental risks, as well as risks for the health of farmers, food chain workers and consumers, due to two primary contaminant types: microbial and chemical (US EPA 2012; WWAP 2017). Wastewater used to irrigate crops comes from a variety of sources with varying microbial qualities which may pose risks to human health through the fouling of field soils and produce (Solomon et al., 2003). In the chemical category, wastewater can contain a number of pollutants including salts, metals, metalloids, pathogens, residual drugs, organic compounds, endocrine disruptor compounds, and active residues derived from personal care products (WHO-FAO, 2006). These pollutants present risks to human health via two main exposure pathways: direct contact with wastewater, affecting farmers, field workers, and proximate communities, and through the consumption of contaminated products, affecting consumers (Bos et al., 2010).

While risks are often contained, both through irrigation techniques (drip irrigation) and the rinsing of crops, the results of inadequate water quality are still evident, even in countries with well-developed limitations on marginal water quality use. It was found that vegetables, fruits, and nuts accounted for approximately 4.5% of the food-borne disease outbreaks in the United States between 1999 and 2002 (Bradford et al., 2013). At the same time, in developing nations, disease burden associated with unrestricted irrigation (any form of wastewater irrigation and products intended for direct consumption) commonly results in helminth infection, bacterial infections, and symptomatic diarrheal disease in consumers (Blumenthal & Peasey, 2002).

The improper use of marginal quality wastewater in agriculture is a rapidly growing challenge that requires action from a number of levels. An initial consideration is the wastewater management model as a whole, considering the downstream effects that wastewater imposes, and greater consideration and integration of social, economic, and health implications into guidelines and policies (Huibers et al., 2010). Additionally, it is essential to remain mindful of technical and economic constraints, particularly in developing countries, with respect to the integration of practical guidelines into risk management frameworks. As guideline values may not yet be available to cover the range of wastewater uses, a reconsideration of current standards and institutional arrangements to facilitate implementation of newly considered guidelines would help to ensure the protection of both farmers and consumers (Bos et al., 2010).

Reclaimed water in the developed world often derives from high-tech and expensive facilities that produce high quality water, but there are emerging low-tech options as well. Box 5 describes the practice of constructed wetlands for filtering wastewater for reuse.

Wastewater use in agriculture transcends geographical, political, and planning boundaries, most notably when it is strongly influenced by public opinion and cultural values. Such a perception imposed onto the water sector results in significant inefficiencies and waste in the water sector in such countries. Historically, the use of wastewater for agriculture was not culturally accepted in some developed countries either. However, this trend may be changing, potentially in response to growing awareness of drought and the need to reserve clean water for indoor domestic uses.

Box 5: Constructed Wetlands: Reducing the Risk of Wastewater Reuse

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While there are public and environmental health risks associated with reusing wastewater in agriculture, there are also low-tech techniques that can be used to minimise the risks associated with utilizing this potentially valuable source of water. One such technique is the use of constructed wetlands. Constructed wetlands (CWs) are beds of macrophytes (aquatic plants) growing in sand, gravel, or soil that are designed to mimic the ability of natural wetlands to improve water quality. Wetlands are able to reduce or remove contaminants through multiple treatment mechanisms, including sedimentation, filtration, microbial interactions, uptake by vegetation, and chemical adsorption and precipitation (Kivaisi, 2001). CWs are generally designed for Biological Oxygen Demand (BOD), solids, and nutrient removal (WHO-FAO, 2006), but can also effectively treat water for pathogens, metals, sulphates, organics, total suspended solids, and other toxic substances for reuse in agriculture (US EPA, 2012). They can be designed to target pathogen removal, through using a combination of dense vegetation, which increases filtration and the adsorption of bacteria to sediment particles, as well as open water zones, which increase UV disinfection (Greenway, 2005).

According to Kivaisi (2001), CWs could be particularly useful in the developing world, considering that they are low cost and have low technology requirements compared with conventional treatment systems. Kivaisi (2001) also emphasizes how wetlands can serve multiple purposes, so CWs could be used for biomass production or swamp fisheries, among other uses. While other low-tech systems exist that could be used to treat wastewater, this example nonetheless demonstrates the potential to minimize health risks associated with reusing wastewater for agricultural applications.

Serious risks arise from the use of wastewater if not treated properly, however there are also significant benefits when managed correctly. Indeed, a growing recognition of its resource value and the nutrients it provides are pushing and supporting its proper and safe use in agriculture and broadening the scope of its application. This is to such a degree to change the perception of wastewater to be viewed as a rich resource rather than as solely waste (Molle et al., 2012). This may require persuasion to motivate users, such as the financial compensation that cities in Spain and Mexico provide farmers with to use reclaimed water rather than freshwater. For overall basin management in these settings, economic research has shown that it is cost-beneficial to take this approach to water use (Heinz et al., 2011). Another benefit is that the use of wastewater frees up high quality water for other uses (Ayers & Westcot, 1985). The SDGs further support its use, specifically (2) zero hunger and (6) clean water and sanitation.

Salinization

Salinization occurs in three ways. Irrigation induced salinization results from the dominance of evaporation over precipitation, impeding the flushing of water-soluble salts from the soil and eventually leading to an accumulation of these salts in the surface layer. Whilst this phenomenon occurs under natural conditions, human irrigation practices, particularly when using marginal quality saline water, dramatically accelerates this process. This irrigation results in large loads of water-salts delivered to the soil, leading to a much higher salt load than can be washed out by natural precipitation. Groundwater salinization can also occur when groundwater reserves are overdrawn (common with irrigation) in coastal areas reducing pressure in the aquifer and thus allowing seawater to penetrate the aquifer. Dry land salinity is where saline groundwater, normally kept at depth by deep-rooted native vegetation, rises to surface soil height when native vegetation is removed. This process takes large areas of agricultural land out of production each year

The agricultural sector faces numerous challenges when salinization occurs. Most notable of these challenges is the reduction of soil-water availability for crops, leading to decreased quality and productivity of harvests and, livestock illness which can in some cases lead to their premature death (Ayers & Westcot, 1985). Additionally, widespread land degradation associated with salinization can result in large tracts of land that are unsuitable for cultivation and require significant time, effort, and investment to rehabilitate and return to arable conditions.

Toxic Heavy Metals

There are a number of risks related to water quality for agriculture from heavy metals. Heavy metals may enter source water either from anthropogenic activities, such as industrial pollution, or natural reactions, such as metal erosion, sediment re-suspension or metal evaporation in water bodies (Tchounwou et al., 2012). In Georgia, untreated wastewater from mining industries release heavy metals into agricultural water sources. Lead, cadmium, manganese, copper, and zinc concentrates in irrigation water sources, transmitting these toxic elements into the food production that feeds the whole country (Withanachchi et al., 2018).

One of the most widespread heavy metals contaminating groundwater is Arsenic, presenting a particular challenge for agriculture due to the sector's widespread dependence on this resource for irrigation (Smedly & Kinniburgh, 2002). High arsenic concentrations in groundwater are common in a number of countries including Bangladesh, West Bengal (India), Vietnam, Argentina, Chile, Mexico, China, and Hungary (Smedley & Kinniburgh, 2002; Roychowdhury et al., 2005). In most parts of Bangladesh, Arsenic levels in groundwater are above the threshold value of ecological pollution indices. Farmers there irrigate their land (mostly rice paddy fields) with shallow groundwater wells that have high levels of Arsenic (Hasibuzzaman et al., 2017). The health consequences of arsenic contamination are widespread, with a significant portion of the population in affected territories of Bangladesh suffering from side-effects, including arsenical skin lesions and, in prolonged and severe cases, chronic disease and cancer (Chowdhury et al., 2000).

Another example of heavy metal contamination is in Sri Lanka, where the intensive use of chemical fertilizers, weedicide, pesticides and insecticides in agriculture increases Arsenic and Cadmium concentrations in water sources, especially in the dry areas. This heavy metal pollution has been one of the main causes for Chronic Kidney Disease of Unknown Etiology (CKDu), a disease that causes devastating health effects and a vicious socioeconomic problem for small-scale farmers living in these regions. The death rate due to CKDu is increasing in Sri Lanka through citizens consuming food produced using contaminated water, as well as using it as a drinking source (Jayasumana et al., 2014).

Applications of Water and Related Quality Requirements in Agriculture

The use of water in the agricultural setting covers a range of applications, each with differing demands of water quality, including; (1) crop irrigation, (2) watering of livestock, and (3) freshwater aquaculture. These are explored in detail below.

Crop Irrigation

Irrigation withdraws the most significant proportion of water in the agricultural sector, and is employed to maximise crop yields and enable food production across a range of climatic regimes that would not otherwise support agriculture. Thus, irrigation plays a vital role in global food production; increasing crop yields by 100-400% and contributing to 40% of the world's food production on 20% of the world's arable land (FAO, 2013). The quality of water used in irrigation ranges from potable (domestic) water obtained from the water grid, to groundwater, saline water, drainage water from fields and urban areas, recycled water, and wastewater. It is significant to note that 6 to 20 million hectares of the world's cropland are irrigated with untreated wastewater (Osterath, 2017). Similarly, there are a range of irrigation techniques utilized including flood (furrow) irrigation, drip irrigation, and various types of spray irrigation with various water use and energy efficiency ratios. These techniques vary according to crop type, geography, and economic boundaries. When using marginal water quality for agriculture, the irrigation technique utilized may also impact the health risk to farm workers, with flood and spray irrigation techniques posing a high risk of exposure and localized irrigation techniques (drip irrigation) posing a low risk of exposure (WHO-FAO, 2006).

For the purpose of this report, irrigated crops include food and fibre, biofuels, and forestry. From a public health perspective, some crops require higher quality water than other crops. For example, non-food crops (e.g. fibre, forestry, and bio-fuel crops), crops that must be cooked before eating (e.g. rice and potatoes), and crops that are processed before consumption (e.g. wheat) pose less of a risk to consumers when irrigated with wastewater than other crops that are consumed directly (WHO-FAO, 2006). The water quality required for irrigated agriculture also varies widely according to the nature and behaviour of soils, salt resistance of crops, soil fertility, and the yields and quality standards required for each agricultural produce (Soifer, 1987).

The water quality used for irrigation is consequential and if the chemical constituency is not properly considered, irrigation can lead to salinization, deterioration of soil fertility, and reduced crop quality and yields (Soifer, 1987). Such issues can eventually lead to serious longer-term impacts to the landscape, such as desertification, transforming once arable lands into barren and unproductive terrain.

To summarise water quality criteria relevant to irrigation, Table 7 consolidates the most relevant constituents from several studies that address irrigation water quality criteria under the two principal headings of chemical risks and microbial risks.

Table 7: Water quality constituents relevant to irrigation.Source: modified from Tyrrel & Quinton, 2003; Bowman, 2009.

Risk type	Criteria	Condition	Impact from extreme levels
Chemical risks	Sodium (sodicity)	High sodium relative to calcium and magnesium content	Leads to swelling and dispersion of soil clays, surface crusting, pore plugging. Overall, it obstructs infiltration, creating permeability problems, and increasing runoff
	Salinity	Dissolved ions in pore water	Reduces water availability for plants (sodium ions compete with plants for water leading to 'physiological drought')
	pH and alkalinity	Measurement of number of hydrogen cations in solution	Low pH (acidic): accelerated irrigation system corrosion High pH (basic): formation of insoluble minerals leading to sodicity and impairment of irrigation systems
	Specific ions (chloride, boron, sulphate)	Electrically charged particles	Essential in small amounts but toxic in high concentrations
	Nitrogen	Nitrate ions	Inadequate nitrogen can lead to plant malnutrition, excessive concentrations can impair crop quality or cause excessive vegetative growth
	Heavy metals	Arsenic is the most common	See page **
Microbial risks	Microbiological pathogens	Total coliform and *Escherichia coli* (*E. coli*) are considered bacterial indicator species. Also the shiga toxin producing other *Escherichia coli* strains, *Salmonella* spp.. *Camplyobacter* spp., *Listeria* monocytogenes and protozoan parasites *Cryptosporidium parvum* and *Giardia duodenalis*	Severe risks to human and animal health

Water for Livestock

Water quality is essential for the good health and productivity of livestock. When considering water quality for livestock, several factors must be considered: the performance of livestock, the potential of water to act as a carrier for disease, and the potential for the quality of water to affect the suitability of livestock for human consumption (Faries et al., 1998). Water quality problems for livestock include (Faries et al., 1998):

- High concentration of minerals (salinity)
- High nitrogen content
- Bacterial contamination
- Blue-green algae outbreaks
- Petroleum, pesticides, and fertilizers (which commonly enter the water through accidental spills)

Of these, salinity is one of the most common problems encountered in livestock watering, with a high salt load potentially leading to physiological impacts or, in more extreme cases, death. Other elements commonly found in water, such as iodide and manganese, are often not in high enough concentrations to pose any danger to livestock. Of course, tolerance of livestock to various water quality constituents differs according to age, diet, stress levels, and the physiological condition of the animal, a notable detail for the development of water quality guidelines.

Box 6: Aquaponics: A bio-integrated Food System for Reducing Water Consumption

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There is a rich cultural history associated with the integration of aquaculture and agriculture. In China, for example, the integration of rice farming and fish farming can be traced back 1700 years (FAO, 2001). Today, the same basic principles are being applied in aquaponics, which links re-circulating aquaculture with the hydroponic production of vegetables, herbs, and flowers. Aquaponics is considered a "bio-integrated food system" in that the waste products from one biological system are used as nutrients in another biological system (Divers, 2010). The aquaculture fish tanks generate nutrient-rich effluent, which is used to fertilize the hydroponic plants. The plant roots and rhizobacteria from the hydroponics system remove the nutrients from the water, essentially acting as a biofilter. After water passes through the hydroponic beds, it is generally clean enough to circulate directly back into the fish tanks. In this way, water can be continuously reused through biological filtration and re-circulation.

As water is continuously reused, aquaponic systems can be a viable plant and fish production system in arid environments. While some water is lost through evaporation, transpiration, and sludge removal, in a commercial-scale installation at the University of the Virgin Islands, an aquaponic system operated continuously for four years without having to completely replace the water (Rakocy et al., 2004). In contrast, conventional intensive aquaculture systems require large amounts of fresh water to supply dissolved oxygen and remove unwanted metabolites (McMurtry et al., 1997). Aquaponics also enables local food production in a variety of other environments that may be inhospitable for conventional agricultural practices, like densely populated urban areas and areas with short growing seasons. Overall, aquaponics provides a mechanism to optimize water use in aquaculture, while also diversifying and expanding local agricultural production practices.

Aquaculture

Aquaculture, the breeding and harvesting of plants and animals in aquatic environments, is an important sector of food and protein production internationally, contributing to 40% of the world's total fish production (NOAA, 2014). The freshwater component of aquaculture is significant, accounting for approximately 60% of the world's aquaculture production and 56% of its value (FAO, 2011b). Both surface and groundwater constitute important resources for aquaculture and proper water quality is a vital consideration for the survival, growth, reproduction, and

Developing a Global Compendium
on Water Quality Guidelines

Agricultural Water Quality Guidelines

success of farmed species. In addition to the biological requirements of fish and other aquaculture species, water quality contributes to the suitability and quality of aquaculture products for human consumption, with certain contaminants having the potential to negatively influence taste and/or cause toxic contamination of farmed aquatic species (Zweig et al., 1999). Water quality elements considered most important to this sector include temperature, dissolved oxygen, turbidity, salinity, acidity, carbon dioxide, nitrogenous compounds, and pH. Additionally, the incidence of heavy metals, organic compounds (like hydrocarbons), antibiotics, anti-microbials, phytoplankton, and algal toxins are important considerations for both farmed species' and human health (Zweig et al., 1999; FAO, 2011b). Box 6 describes one type of hybrid aquaculture with the potential to improve water problems in the sector.

3.2 Existing Guideline Case Studies

Below are selected overviews of the application of water quality guidelines for agricultural use at the international and national scales. In the research done for this report, regional guidelines for agricultural water were not found.

3.2.1 International

FAO Water Quality for Agriculture

The premier international resource for water quality guidelines for agriculture was developed by the Food and Agricultural Organisation (FAO). First published as *Irrigation and Drainage Paper 29* in 1989, these guidelines were updated and re-released under the title *Water Quality for Agriculture* in 1994. The report is intended as a 'field guide' to provide direction to farmers and the food production sector on assessing the suitability of water for irrigation (AFEID, 2012). The aim of the guidelines is to maximise food production from the available supply of water. The guidelines further define water quality in relation to other major factors interacting with crop production.

The main water quality guidance in this FAO report are directed at irrigation water, with a focus on crop production, soil condition, and farm management. It outlines the recommended values for common constituents in surface water, groundwater, drainage water, sewage effluent and wastewater (Table 8). These are defined in relation to specific challenges encountered when using water for agriculture, including salinity, rate of infiltration, specific ion toxicity, and other miscellaneous effects. As the units of measurement for certain constituents are not common knowledge, provision of laboratory determinations and calculations are also provided. The FAO guidelines incorporate discussions on restrictions of water quality, common challenges, and further present management alternatives that may offer solutions to water sources of a reduced quality.

Table 8: Guidelines of parameters for interpretations of water quality for irrigation.
Source: modified from Ayers & Westcot, 1985.

Potential Irrigation Problem		Units	Degree of Restriction on Use		
			None	Slight to Moderate	Severe
Salinity *(affects crop water availability)*[2]					
	EC_w	dS/m	<0.7	0.7 – 3.0	> 3.0
	(or)				
	TDS	mg/l	<450	400-2000	> 2000
Infiltration affects infiltration rate of water into the soil. Evaluate using ECw and SAR together)[3]					
SAR	= 0 – 3 and Ec_w =		>0.7	0.7 – 0.2	<0.2
	= 3 - 6 =		> 1.2	1.2 – 0.3	< 0.3
	= 6 – 12 =		>1.9	1.9-0.5	<0.5
	= 12 – 20 =		>2.9	2.9- 1.3	< 1.3
	= 20 – 40 =		>5.0	5.0 – 2.9	<2.9
Specific Ion Toxicity *(affects sensitive crops)*					
	Sodium (Na)[4]				
	surface irrigation	SAR	< 3	3 – 0	> 9
	sprinkler irrigation	me/l	< 3	> 3	
	Chloride (Cl)[4]				
	surface irrigation	me/l	<4	4 – 10	> 10
	sprinkler irrigation	me/l	< 3	> 3	
	Boron (B)[5]	mg/l	<0.7	0.7 – 3.0	> 3.0
	Trace Elements (see Table 21)				
Miscellaneous Effects *(affects susceptible crops)*					
	Nitrogen (NO_3 - N)[6]	mg/l	<5	5 – 30	> 30
	Bicarbonate (HCO_3)				
	(overhead sprinkling only)	me/l	< 1.5	1.5 – 8.5	> 8.5.
	pH		Normal Range 6.5 - 6.4		

The FAO water quality guidelines also consist of a section on water quality for livestock, with a focus on the use of saline water, magnesium content, and toxic substances. Factors highlighted as important considerations further include water source, seasonal changes, age and condition of the animal, feed composition, and animal species.

Finally, the FAO *Water Quality for Agriculture* concludes with 24 case studies of examples where marginal or poor quality water is being managed successfully to meet FAO guidance for agriculture. It must be noted that the data upon which these examples, and indeed the entire FAO guidelines document, are based is predominantly derived from the Western United States of America. Thus, information may vary significantly for different geographic and climatic settings since the true suitability of water quality is largely dependent on the specific conditions of use and management capabilities of the user.

WHO-FAO Guidelines for the Safe Use of Wastewater, Excreta and Greywater

Another major international guideline for water quality directed at agricultural purposes are the *Guidelines for the Safe Use of Wastewater, Excreta and Greywater* released by the WHO and FAO in 2006. These guidelines are the most comprehensive global guide for marginal water use, and are presented in four volumes to reach the most appropriate audience (WHO-FAO, 2006):

1. **Policy and regulatory aspects**
2. **Wastewater use in agriculture**
3. **Wastewater and excreta use in aquaculture**
4. **Excreta and greywater use in agriculture**

The purpose of these volumes is to provide scientifically sound information to encourage resource recovery and wastewater use while protecting the health of farmers and consumers. They strive to maximise benefits from use of scarce resources as well as public health.

The second volume, *Wastewater use in Agriculture*, focuses on threats from microbial hazards and toxic chemicals originating from various types of wastewater. It supplies a basis for the development of national wastewater use standards and regulations concerning agricultural practices, encouraging countries to adopt the guidelines according to their social, economic and environmental conditions (AFEID, 2012). The volume's general framework explains requirements to promote safe use concepts and practices, focusing on health-based targets and minimum procedures, instead of merely water quality targets, which were the focus of its predecessor, the 1989 WHO guidelines. The guidelines and regulations for food crop irrigation with reclaimed water are intended to minimize risks of chemical and microbial contamination of the crops, especially those grown for raw consumption, such as lettuce, cucumbers, and various fruits. Treatment processes, water quality standards, and monitoring regimes are specified that minimise risks for use of reclaimed water for irrigation of crops that are ingested by humans

ISO Guidelines for Treated Wastewater use for Irrigation Projects

The International Organisation for Standardisation (ISO) released the *Guidelines for Treated Wastewater use for Irrigation Projects* in 2015 to promote healthy, hydrological, environmental and good operation, monitoring, and maintenance of water reuse projects. Based on the 'fit-for-purpose' principle in-line with the objectives of the Compendium, the guidelines aim to advise water quality of reclaimed water that is appropriate for the end user. While it acknowledges the many users of reclaimed wastewater, the ISO guidelines also acknowledge that agricultural irrigation will remain the largest consumer of this water source, and so target their guidance on water quality suitable for it.

Key recommendations from the guidelines state (ISO, 2015);

- **meticulous monitoring of water quality within the operation;**
- **proper design and maintenance of the irrigation systems to ensure their proper long-term operation;**
- **compatibility between the treated wastewater quality, and the intended soil and crops to ensure a viable use of the soil and undamaged crop growth;**
- **compatibility between the treated wastewater quality and its specific use to minimize possible contamination of groundwater or surface water sources.**

The ISO guidelines comprise four parts covering the basis and development of a reuse project for irrigation to the monitoring and upkeep, however unlike the other guidelines reviewed in this report, the ISO guidance on the subject comes at a cost and only the introductory chapters are available freely to the public.

Codex Alimentarius Code of Hygiene Practice for Fresh Fruits and Vegetables

As introduced in the previous chapter, the *Codex Alimentarius* provide guidelines or codes of conduct for many categories of food and beverages to be consumed, as international food standards set out by FAO and WHO. While many of the guidelines cover secondary industries relating to food production, the *Code of Hygiene for Fresh Fruits and Vegetables* is relevant for agricultural water use, as this food category often does not have further processing before human consumption.

The guidelines of the *Codex Alimentarius Code of Hygiene for Fresh Fruits and Vegetables* are based around the concept of Good Agricultural Practices and Good Manufacturing Practices and set criteria based on the concepts of 'clean water' and 'potable water', as defined below.

> *Clean water*: **"water that does not compromise the food safety in the circumstances of its use."**

> *Potable water*: **"water that which meets the quality standards of drinking water such as described in the WHO Guidelines for Drinking Water Quality."**

The structure of the document is a general outline of hygienic practices, then detailed annexes covering the topics ready-to-eat fresh pre-cut fruits and vegetables, sprout production, fresh leafy vegetables, melons, and berries. However, little additional guidance on water quality is provided in the *Code of Hygiene for Fresh Fruits and Vegetables*, other than complying with the WHO guidelines on the safe use of wastewater and excreta in agriculture and aquaculture to avoid microbial or chemical risks to the fresh foods. The report advises an adequate supply of potable water for food production which meets the most recent WHO guidelines or higher standards, clearly separated from non-potable water systems.

3.2.2 National

UNITED STATES

Guidelines for Water Reuse

The 2012 US Environmental Protection Agency (EPA) *Guidelines for Water Reuse* present and evaluate an extensive set of international agricultural water reuse guidelines, and define water quality thresholds of chemicals and global water quality standards for non-food crop irrigation. The guidelines specify selected health-protection measures and associated pathogen reductions for wastewater reuse in agriculture, and an updated guideline of numerical chemical thresholds for irrigation water. Furthermore, they review regulatory frameworks for water reuse, global experiences and American case studies in depth.

Working off the success of the 2004 US EPA *Guidelines for Water Reuse,* which influenced many other countries to provide similar guidance, the 2012 update acknowledges new applications

and technologies in-line with updated WHO-FAO revisions on global guidance (US EPA, 2012). As regulations are made at the local or state level in the United States, the *Guidelines for Water Reuse* provide national guidance to assist in local development of reuse programs and regulations.

The document is in-line with the objectives of this report in that it provides information on water reuse for many purposes, including urban, potable, environmental, industrial and groundwater recharge. Table 9 outlines the various categories of use by reclaimed water and describes the number of states which as of 2012 already hold regulations or guidelines for these topics. More detailed summary information is provided within the document from a survey of all guidance tools across each state for each water use. The agriculture sector is significant, however, as it represents the largest proportion of reused water in the country (US EPA, 2012).

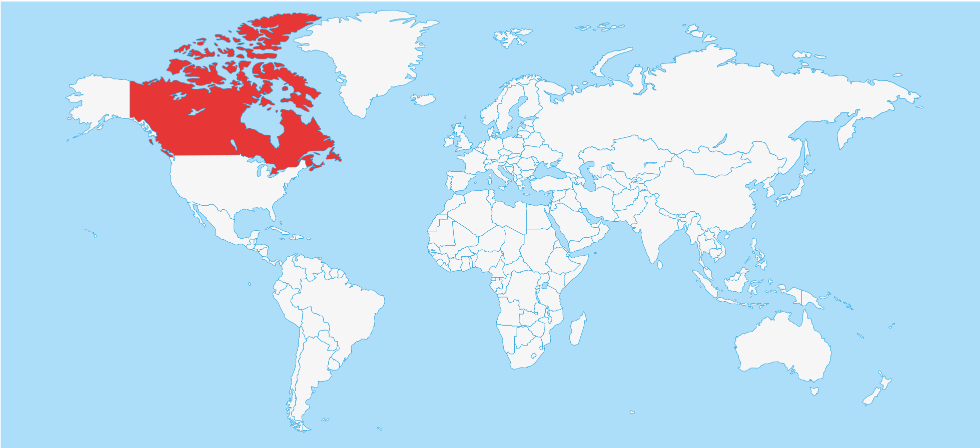
Table 9: Summary of the quantity of American states with rules, regulations or guidelines for water reuse for specific categories of use. Source: US EPA, 2012.

Category of reuse		Description	Number of States or Territories with Rules, Regulations, or Guidelines Addressing Reuse Category
Urban Reuse	Unrestricted	The use of reclaimed water for nonpotable applications in municipal settings where public access is not restricted	32
	Restricted	The use of reclaimed water for nonpotable applications in municipal settings where public access is controlled or restricted by physical or institutional barriers, such as fencing, advisory signage, or temporal access restriction	40
Agricultural Reuse	Food Crops	The use of reclaimed water to irrigate food crops that are intended for human consumption	27
	Processed Food Crops and Non-food Crops	The use of reclaimed water to irrigate crops that are either processed before human consumption or not consumed by humans	43
Impoundments	Unrestricted	The use of reclaimed water in an impoundment in which no limitations are imposed an body-contact water recreation activities (some slates categorize snowmaking in this category)	13
	Restricted	The use of reclaimed water in an impoundment where body contact is restricted (some states include fishing and boating in this category)	17
Environmental Reuse		The use of reclaimed water to create, enhance, sustain, or augment water bodies, including wetlands, aquatic habitats, or stream low	17
Industrial Reuse		The use of reclaimed water in industrial applications and facilities, power production and extraction of fossil fuels	31
Groundwater Recharge — Nonpotable Reuse		The use of reclaimed water to recharge aquifers that are not used as a potable water source	16
Potable Reuse	Indirect Potable Reuse (IPR)	Augmentation of a drinking water source (surface or groundwater) with reclaimed water followed by an environmental buffer that precedes normal drinking water treatment	9
	Direct Potable Reuse (PPR)	The introduction of reclaimed water (with or without retention in an engineered storage buffer) directly into a water treatment plant, either collocated or remote from the advanced wastewater treatment system	0

1. Individual stale reuse programs often incorporate different terminology so the reader should exercise caution in comparing the categories in these tables directly to state regulatory definitions

It is worth noting that California's Title 22 standards were the first regulations for water reuse in the world, originating in 1918. Still in law today, they provide stringent standards to protect public health and have been a guiding regulation and inspiration for other states and parts of the world to learn and copy (Mateo-Sagasta & Burke, 2010). Based on the degree of disinfection of water, the standards state what specific use the water can be designated for, such as air conditioning, commercial laundry, decorative fountains, and irrigating animal feed and other unprocessed crops. Overall, they assist the state in encouraging the safe use of recycled water, with the long-term plan to increase use of this water source by at least 2 million acre feet a year from 2002 levels by 2030 (Water Education Foundation, 2018).

CANADA



Canadian Water Quality Guidelines for the Protection of Agricultural Water Uses

The Canadian Council of Ministers of the Environment (CCME) developed the first version of the Canadian Water Quality Guidelines in 1987 to provide the basic scientific information on the effects of water quality variables in all water usages sectors, including agriculture. With the framework of the national guideline, the Canadian Water Quality Guidelines for the Protection of Agricultural Water Uses was implemented in 1993 and updated in 1999. This guidance is a collection of documents, including a short introduction, factsheets on 30 chemicals found in pesticides, fertilizers or agricultural water, a summary table and the *Protocols for Deriving Water Quality Guidelines for the Protection of Agricultural Water Uses (Irrigation and Livestock Water)*.

The final component of the collection, the *Protocols for Deriving Water Quality Guidelines for the Protection of Agricultural Water Uses (Irrigation and Livestock Water)* work as a driving guideline in the irrigation and livestock sectors to protect crops and livestock from contaminants which transform through water. There are two key principles in the *Protocols* for irrigation water quality guidelines;

(1) the sensitivity of non-target crops
(2) maximum irrigation rates for crops

In the livestock water quality guidelines, there are four key principles;

(1) tolerable daily intake rates of the contaminant for livestock species
(2) daily water intake rates of livestock
(3) livestock body weights
(4) potential for bioaccumulation in livestock products

Overall, the *Protocols* guidance provides support for deriving water quality levels and guidelines for irrigation and livestock agricultural practices in Canada through setting forth the procedure for derivation, data set requirements and guiding principles, while providing basic limits, such as the maximum residue level of 0.10 mg·kg-1 for agricultural chemicals allowed in edible plant and livestock tissues (CCME, 1999).

PHILIPPINES

Guidelines on the Procedures and Technical Requirements for the Issuance of a Certification allowing the Safe Re-Use of Wastewater for Purposes of Irrigation and Other Agricultural Uses

Water quality guidelines, particular to the safe reuse of wastewater directed for agricultural purposes in the Philippines, were released in 2007 following the 2004 Clean Water Act in the country (DA, 2007). The Department of Agriculture in Philippines created this guideline based on their previous water quality guidelines and the new water quality policy (Clean Water Act). The document is a guideline on how to comply with the Clean Water Act through the appropriate procedures and requirements of the Department of Agriculture in the Philippines, while also building on the regulations from the 2004 regulation to provide more specific information. Not only does it give information, it also provides forms that can be used directly by agricultural water managers, encouraging farmers to keep accurate and detailed records of water quality parameters on their sites (see Figure 7). Overall, the document covers the following subjects for irrigation, fertilization, and aquaculture:

- General requirements and procedure for the issuance of certification from the Department of Agriculture to use wastewater
- Technical requirements for the re-use of wastewater
- Methods of analysis
- Distribution methodology and design
- Administrative provisions
- Monitoring and reporting

AGRI/AQUA SELF MONITORING REPORT FORM

Name of Grantee:____
Type of Establishment: __________________________________
Address: ____
Quarter: ____________________________ Year: ___________

I. Wastewater Reuse for Irrigation and Other Agricultural Purposes

Type of Wastewater Reuse	Site of Irrigation/ Other Agricultural Purposes	Average Rate of WW Delivered (m^3/day) x days	Volume of wastewater for Irrigation and Other Agricultural Purposes (m^3/month)		
		_____(m^3/d) x_______	__20_ _	__20__	__20__
		_____(m^3/d) x_______			
		_____(m^3/d) x_______			
		_____(m^3/d) x_______			
		_____(m^3/d) x_______			

II. Characteristics of Wastewater Re-used for Irrigation

PARAMETERS	VALUES
FOR CROP PRODUCTIVITY AND PROTECTION OF ENVIRONMENT	
Bicarbonates (mg/L)	
Biochemical Oxygen Demand (BOD_5) (mg/L)	
Electrical Conductivity (µS/cm)	
Free residual chlorine (mg/L)	
pH	
Sodium Adsorption Ratio (SAR)	
Sodium (Na) (meq/L)	
Total Nitrogen (TN) (mg/L)	
Total Phosphorous (TP) (mg/L)	
Total Suspended Solids (mg/L)	

Figure 7: An example report form in the *Guidelines on the Procedures and Technical Requirements for the Issuance of a Certification allowing the Safe Re-Use of Wastewater for Purposes of Irrigation and Other Agricultural Uses.*
Source: DA, 2007.

3.3 Discussion

Agriculture is an interconnected web of land and water management, regulations across local, regional, national, and international levels, and, not to be overlooked, social drivers. Establishment of extensive and inclusive water quality guidelines provides several opportunities for the agricultural sector, which vary according to the developmental setting of a country. In developed countries, such guidelines could promote the widespread use of recycled wastewater and greywater rather than high-quality surface water and groundwater, which are commonly used in the agricultural sector. In developing countries, guidelines can help protect land, animals and people from the risks of using untreated wastewater for irrigation and livestock.

The definition and establishment of agricultural water quality requirements on an international level was first spearheaded by the FAO in 1985 (later updated in 1994), setting out water quality requirements for irrigation with a focus on crop production, soil condition, and farm management. The Codex Alimentarius, established by FAO and WHO, also addresses the quality of water intended for agricultural purposes, and focuses on ensuring that water used in this sector protects the health and safety of farm workers and consumers.

While these guidelines form an important foundation, expansion to the remaining agricultural uses as well as the incorporation of geographical considerations, is needed. Defining water quality requirements based on both application and geographical setting allows water resources to be applied more effectively according to use and presents a potential to drastically economise the agricultural sector's water use. In addition, the appropriate application of water quality guidelines ensures the protection of the health of farm workers and consumers, lowering the disease burden of populations and protecting the long-term health of agricultural soil and land.

A large component of the water quality guidelines explored in this report focus on recycled wastewater, encouraging the use of this water in agriculture, and making use of water that otherwise would not be utilised directly. Utilising water of inadequate quality, even where regulations exist, is a challenge related to wastewater use in the agricultural sector (Molle et. al., 2012). The WHO-FAO provides an excellent four-volume resource for the safe use of recycled water, and the ISO has also created guidance for wastewater for irrigation projects. This latter piece of guidance is limited in its accessibility due to its price.

It is recognised that unplanned use of wastewater in developing countries means that adequate standards of water quality are often difficult to meet, yet examples in the literature demonstrate that safe irrigation can be achieved in developing regions through phased planning with consistent improvements that often span decades and low-cost interventions (Scheierling et al., 2011). The WHO-FAO guidelines offer instruction for countries at all development levels rational options, even when treatment is not available, for ensuring the safe use of wastewater within agricultural practices. Public officials should encourage compliance to such guidelines through providing initiatives to farmers where possible. This could be either through direct compensation or through implementing risk-reduction programmes (Wichelns, et al., 2011). Such risk-reduction programmes could provide technical advice to farmers or consist of certification programmes for "consumer-safe" produce to encourage its sale for customers in the community. Wichelns et al. (2011) identifies the advantages of involving more stakeholders into the discussion of wastewater reuse for agriculture, including marketers, consumers, who can help shift the market demand and who also have a vested interest in the safe and sustainable use of agricultural water. This may require adequate awareness and education activities, as well as social marketing to encourage behaviour change, as recommended by the post-treatment or non-treatment options in the WHO-FAO guidelines.

A limitation of most of the above guidance on recommended water quality for agricultural use, specifically of recycled wastewater, is the omission of contaminants of emerging concern (CECs) such as pharmaceuticals and personal care product residuals. As these are an increasing component of domestic wastewater that can cause problems in the environment and to humans, further water quality guidance including these constituents is needed.

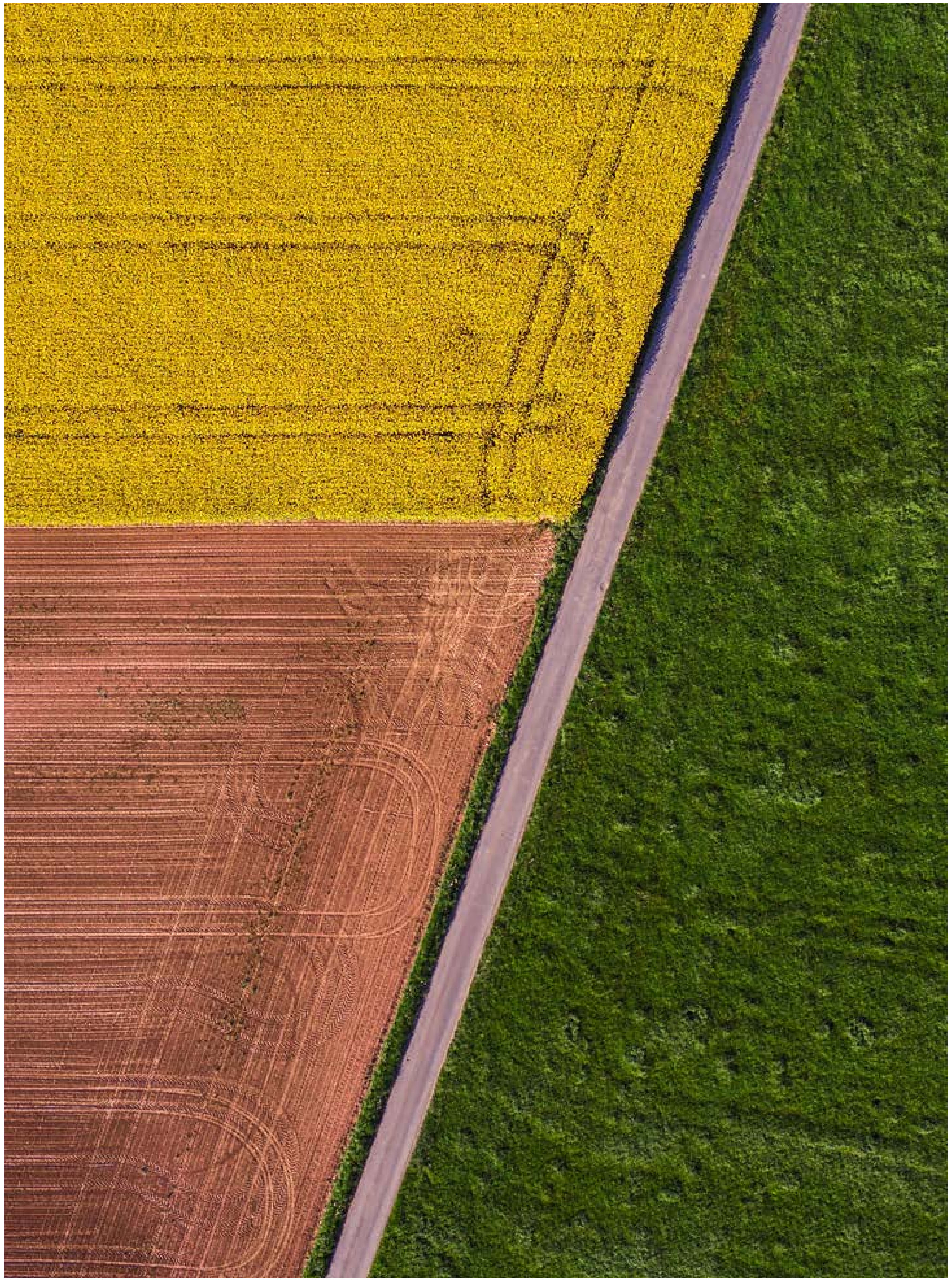
The above stated water quality guidance was directed at developed countries, while more water quality guidelines should be created in developing countries, where untreated wastewater is commonly used in agriculture. Infrastructure investment is vital to treat wastewater for reuse in developing countries; however, this is difficult to achieve due to its complexity and a lack of institutional awareness (Rutkowski et al. 2007). They suggest a formal mechanism to encourage interactions between stakeholders and influence proper wastewater disposal and reuse. While regulations and institutions cease to exist in these settings, Qadir et al. (2010) recommends the use of source control and farm-level post-harvest measures as a start to reducing risk from wastewater reuse in these settings. More local guidance, building on the international references, would define where and when this marginal water use is appropriate, highlighting situations where water treatment facilities are necessary and potentially reducing the disease burden commonly associated with inappropriate applications of poor quality water. Guidelines could also incorporate possible treatment techniques, including the use of constructed wetlands and other low-tech approaches, to improve the ability of farmers to safely re-use wastewater and greywater.

On a national level, water quality guidelines are relatively limited; perhaps this reflects the widespread use of potable water in more developed countries and a general lack of oversight in developing countries regarding water use in the agricultural sector, with farmers sourcing water from wherever it is available. As an example, a large review of water quality criteria directing livestock watering water was conducted by Valente-Campos et al. (2014), with findings that many chemicals, including those from pesticides, have no maximum values set at national or local scales for this use. However, there are challenges to setting national regulations and standards. A summary of these challenges is provided in Table 10, as well as recommendations for overcoming each challenge, which the US EPA presents as an approach to assess the suitability of any agricultural reuse guideline (US EPA, 2012). Directing water more appropriately in the agricultural sector could ultimately improve water use efficiencies, health outcomes, decision making, and management processes.

Another important point to consider for water within the agriculture sector is food and the water wastage associated with food waste. Food contains water (e.g. vegetables contain between 70- 99% of water by weight) and is produced and processed with water through agricultural practices. Water footprints demonstrate a clear analysis and a general understanding of the hidden water volume in the supply-chain as consumption or pollution (Hoekstra, 2015). Food wastage is a topic that is often not considered in relation to water use, but the World Resources Institute reports that globally, food loss and waste represent approximately 173 billion cubic meters of water consumption per year (Lipinski et al., 2013). In other words, 24% of all water used in food production goes towards food that is lost or wasted. Estimates suggest that 25-50% of crops, fruits, or vegetables produced in many developing countries are not consumed as a result of production, transportation, distribution, and storage losses (Biswas & Tortajada, 2009). Addressing issues such as food wastage is an important component of a new paradigm of water management, considering the interplay of factors that contribute to the sustainable use and management of water. Reducing food wastage increases the productivity of agriculture and reduces the demand for high quality water.

Table 10: Challenges and solutions for water reuse standards development and implementation. Source: adapted from US EPA 2012.

Observation	Recommendation
Guidelines, frequently copied from developed countries, are directly adopted as national standards.	Each country should adapt the guidelines, based on local conditions, and derive the corresponding national standards. In developed countries, these resulted from a long period of investment in infrastructure, during which standards were progressively improved. Cost and maintenance implications of too strict standards in the short term should be taken into account.
Guideline values are treated as absolute values, and not as target values.	Guideline values should be treated as target values, to be attained on a short, medium or long term, depending on the country's technological, institutional or financial conditions.
Treatment plants that do not comply with global standards do not obtain licensing or financing.	Environmental agencies should license and banks should fund control measures, which allow for a stepwise improvement of water quality, even though standards are not immediately achieved. However, measures should be taken to effectively guarantee that all steps will be effectively implemented.
There is no affordable technology to lead to compliance of standards.	Control technologies should be within the countries' financial conditions. The use of appropriate technology should always be pursued.
Standards are not actually enforced.	Standards should be enforceable and actually enforced. Standard values should be achievable and allow for enforcement, based on existing and affordable control measures. Environmental agencies should be institutionally well developed in order to enforce standards.
Discharge standards are not compatible with water quality standards.	In terms of pollution control, the true objective is the preservation of the quality of the water bodies. Discharge standards should be based on practical (and justifiable) reasons, assuming a certain dilution or assimilation capacity of the water bodies.
Number of monitoring parameters are frequently inadequate (too many or too few).	The list of parameters should reflect the desired protection of the intended water uses and local laboratory and financial capacities, without excesses or limitations.
There is no institutional development that could support and regulate the implementation of standards.	The efficient implementation of standards requires an adequate infrastructure and institutional capacity to license, guide, and control polluting activities and to enforce standards.
Reduction of health or environmental risks due to compliance with standards is not immediately perceived by decision makers or the population.	Decision makers and the population at large should be well informed about the benefits and costs associated with the maintenance of good water quality, as specified by the standards.



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CHAPTER 4

Industrial Water Quality Guidelines

CHAPTER 4
Industrial Water Quality Guidelines

4.1 Context

Industry encompasses secondary processes such as manufacturing, transformation, and production of raw materials into economic goods, as distinguished from primary industries that involves the retrieval and production of raw materials, most notably mining, energy production and agriculture (Kenessey, 1987). Industry is composed of many diverse sectors such as food and beverage processing, paper production, textiles, and pharmaceuticals, all of which rely on water (Mobley, 2001). Industrial water consumption accounts for approximately 20% of the world's freshwater withdrawals (WWAP, 2014). Globally, industry's water use is projected to increase: manufacturing alone is expected to demand 400% more water by 2050 than in 2000 (WWAP, 2015). Advancements in technological efficiency may mitigate this growing demand, but industry will remain a major user of water with significant potential for the use of treated wastewater for many processes. Of concern here is how the industry sector can benefit from using water of different qualities in a more efficient and sustainable manner.

Geographic Concerns

The structure of industries varies greatly depending on the level of economic development in which they operate. Hence, most of the anticipated growth in water use for manufacturing is projected to occur in rapidly growing economies (WWAP, 2015). Additionally, populations are expected to grow in these countries and become increasingly wealthy due to industrial development. This means the demand for manufactured goods will also increase. Developing nations are thus faced with meeting increasing resource demands without depleting their water supplies. This will be further complicated by the need for higher quality water for high-tech industries, such as silicon chip manufacturing, likely to emerge in these developing economies. The challenge is to implement more efficient water management techniques that will account for all water users. In this endeavour, it will be important to consider the different water quality requirements of various users, particularly those of growing industries, so that water resources and the relative quality of water sources may be allocated more responsibly.

Conversely, nations with developed economies are struggling to mitigate the negative environmental effects of past industrial development, while managing shared transboundary water resources. Water quality requirements of different users are important for the allocation and conservation of water resources in this context as well.

Diversity in Water Qualities for Industry

Discussing water quality guidelines for industry is complicated as it incorporates many sectors, and thus, it is not possible to define "universal" water quality standards for industrial users. Water quality requirements are highly dependent on both industry type and the application of water within that industry (Manivasakam, 2011); consequently, water quality requirements differ dramatically by user. For example, a lesser quality use such as industrial processes for paper mills may use reclaimed water and treat the water to remove or neutralize substances harmful to the product, whereas food and beverage manufacturing requires the use of high-quality water for human consumption where a product may come into direct contact with people or has the potential to contaminate a product that may come into contact with people. Therefore, when discussing this sector it is important to create sub-divisions of industry. Boxes 7 and 8 provide insight into two sub-divisions of industry in the pulp and paper industry as well as the manufacture of semi-conductors.

Box 7: Pulp & Paper Industry and Water Quality

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The pulp and paper (P&P) industry is a prolific user of water, requiring over 50 cubic meters for the average ton of product (Gunderson, 2012). Due to this industry's large water utilization, reuse is a topic of interest although reclaimed water is a challenge given the contaminants that must be removed (e.g. suspended solids, chlorinated organics, oils, microorganisms). Paper production involves a number of processes that exemplify why even the same industry can have markedly different requirements for water quality.

Wood pulp is initially disintegrated, dyed and refined so that its fibres can be used to manufacture paper (Manivasakam 2011). Each step requires water for uses as diverse as cooking wood chips, washing pulp and maintaining slurries, as well as for conventional boiler feed and cooling tasks.

Calcium-magnesium hardness is a major issue because the precipitation of inorganic scale can impact both the manufacturing equipment and the paper products. Iron precipitates and manganese oxides can stain the paper and interfere with the stability of resins that are used to manufacture it. As such, iron and manganese concentrations of less than 0.1 mg/L and 0.05 mg/L, respectively, are required (Manivasakam 2011). Suspended solids and colour can affect the strength and appearance of the paper, while microorganisms can affect its texture and odour. Total hardness of the water must be below 100 mg/L; however, TDS (total dissolved solids) levels as high as 500mg/L are acceptable for some processes and products. Even dissolved gases, such as carbon dioxide, must be minimized to prevent corrosion and to protect products. Carbon dioxide can be an issue for groundwater sources because its dissolved concentrations often exceed the limit of 10 mg/L.

Because the P&P industry demands large volumes of relatively high quality water, its future may include relying on a wider range of sources that will likely involve different levels of pre-treatment.

Developing a Global Compendium on Water Quality Guidelines

Industrial Water Quality Guidelines

Industry's diversity of water quality requirements are further complicated by the various uses of water within the sector such as in cooling, washing, dilution, and transportation processes, as well as its integration into different products and its use as a solvent in a number of industrial practices (USGS, n.d.). Water quality demands and the overall impacts that impurities may have vary widely based on product type, equipment used, and the nature of a particular impurity. Table 11 lists water parameters of concern for specific industries or purposes.

Table 11: Some of the quality parameters of concern for listed industries and purposes (cooling water and boiler influent are common to many industries) according to data presented by Rommelmann et al. (2003) and Manivasakam (2011).

Industry/Purpose	Chemical	Physical/Biological
Pulp & Paper	Phosphates, iron, manganese, sulphides, silica, hardness	Suspended solids, organic matter, colour, microbes
Chemicals	Silica, hardness, pH, iron, manganese	Suspended solids, microbes
Textiles	Iron, manganese, nitrate, nitrite	Colour, turbidity, organic matter
Ceramics	Hardness, sulphate, TDS	Colour, microbes
Electroplating	Iron, hardness, chlorides, bicarbonate	Turbidity, colour
Food Processing	Iron, manganese, hardness	Turbidity, odour, microbes
Laundry	Iron, manganese, bicarbonate, pH	Turbidity, colour
Tannery	Iron, manganese, bicarbonate	Turbidity, colour, organic matter
Cooling Water*	Corrosive conditions, pH, hardness	Scale & biofilm residues, turbidity
Boiler Influent*	Hardness, sulphate, silica, pH, oils, TDS	Scale & biofilm residues, turbidity

The American Water Works Association conducted a study that examined the water quality requirements associated with using reclaimed water for a range of industrial purposes (Rommelmann et al. 2003). Industry is considered a good candidate for reclaimed water because its systems have year-round demands, unlike those of agriculture that are often more seasonal. In general, the study suggested that major water quality issues include bacterial and organic residues, ammonia, sulphate, nutrients, suspended solids, and inorganic scale. It also indicated that water quality requirements for boilers were quite high, whereas those for many of the petroleum industry's processes could be met with water of a lesser quality.

Although many industries are sensitive to a similar suite of water quality indicators, the sensitivity is different (Manivasakam, 2011). For instance, textile manufacturing requires a turbidity of less than 5 NTU (Nephelometric Turbidity Unit), but can tolerate hardness as high as 70 mg/L. By contrast, the manufacturing of PVC (Polyvinyl chloride) requires a maximum hardness of 1 mg/L, while tanneries can use water with a turbidity as high as 20 NTU. Even within the same industry, there can be substantial differences in the required water quality, depending on the product or process. For example, producing fine paper requires the water's colour to be 20-fold clearer and its silica concentration to be 5-fold less than that for producing unbleached Kraft paper (Manivasakam 2011).

Industry also encompasses a broad scope of business structures that are regulated in different ways. These business structures may include private companies, publicly traded companies, and partially or fully nationally owned companies, each with their own water quality concerns and demands.

Box 8: Manufacturing of Semi-conductors and Water Quality

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The manufacturing of semiconductors is a $250 billion industry, one of the largest industrial sectors in the world. Water is an essential component of the manufacturing process, with a significant proportion of the water used required to be of ultrapure quality, a stringent water quality objective that limits resistivity, silicon content, total organic carbon, dissolved oxygen, critical metals, critical ions, and bacteria to basically negligible or absent levels. Such stringent guidelines come at a cost; annual spending on water and wastewater systems by the United States semi-conductor industry total approximately $1 billion.

Such water quality requirements and usage highlight a need for the consideration of efficiency and economization. Intel, one of the largest producers of semi-conductors in the United States, provides a key example of how water quality considerations can lead to significant savings in this sector, both in terms of money and water consumption. From 1995 to 1996, Intel introduced the use of scale inhibiting chemicals into their water treatment procedure, improving the application of grey water in their New Mexico computer chip plant. These steps to tailor water quality to use led to an increase in water use efficiency by 65%, saving 209 million gallons of water in 1996. In addition, the use of a High Recovery Reverse Osmosis Process in 1999 pioneered steps in water treatment to ensure the dissolvability of silicon, a key requirement in the purification process which further increased water treatment efficiency by 85% and led to water savings of approximately 2600 liters per day.

Such actions demonstrate the importance of water quality in the industrial sector and how relatively simple steps to overcome water quality challenges have the potential to drastically increase water use efficiency. (Global Water Intelligence, 2009)

Water Quality as a Business Risk

The World Economic Forum identified the water crisis as the most impactful risk in its 2015 *Global Risks* report. Disruption or contamination of existing water supplies poses a serious risk to large businesses, which must develop long-term strategies for the management of their supply chains (WEC, 2015). Complicated water quality needs for specific uses exacerbate that risk.

Inappropriate water quality can lead to a decrease or cessation of production, relocation of an industrial facility, or an increase in the burden of finding an alternative water supply (UNEP, 2010). For example, water containing pathogens or contaminants that affect human health may have profound impacts on the food and beverage processing sector of an industry. Aside from harmful health impacts to individuals, this type of impurity may result in a massive loss of profit, product recall, delay in production, and temporary or permanent closure of an industrial facility. As another example, high-tech sectors such as microchip manufacturers can only use ultrapure water, which is filtered before use to remove all contaminants. Microchips are so small in size, and their individual parts are so sensitive that any particle or additional chemical in the water may scratch and damage the product (AXEON, n.d.). Similarly, various other industrial sectors are concerned with the effects of water impurities, such as scaling and corrosion, on industrial equipment (SDCWA, 2009). Such effects may lead to machinery malfunctions, compromised product quality, and economic losses.

Water Quality as a Business Opportunity

Although water quality poses a significant risk to the industrial sector, it also presents an opportunity for industries to adapt to different sources of varying water quality. For instance, reclaimed water is more resistant to episodic droughts, particularly in closed systems, and can provide stability to industries located in drought-prone regions. Moreover, because water treatment is expensive, it may be more cost-effective for a business to locate closer to a water source, or reuse and implement treatment based on its needs, rather than use whichever water source is most conveniently available.

Given that water use and water quality needs within the industrial sector are so complicated and critical to production, water quality is largely self-regulated or constrained by specific product requirements or equipment availability. Filtration equipment manufacturers and distributors must cater to the needs of customers where it is profitable (Mobley, 2001). Likewise, where a specific use is serviced, an industry water user's requirement for water quality is limited by the type of filtration equipment available on the market. Water analysis has also become an important support industry, with its own field of experts available for hire, to ensure that self-imposed industry standards are met (Mobley, 2001). Thus, it is likely that industries will benefit from using water more intelligently through the use of smart water management, automation techniques and through better tailoring water quality to needs.

4.2 Existing Guideline Case Studies

As populations continue to increase worldwide, material demands are also increasing. This ultimately impacts manufacturing rates as well as water use within the industry sector. Due to its broad nature and scope, there are currently no universal water quality guidelines encompassing the industry sector in its entirety. Water quality guidelines within the industry sector are typically context-specific and defined by industry type. They may also vary between and within countries, depending on regional or national authorities, as well as existing laws and legislations. Greater insight into existing water quality guidelines within the industry sector is provided below.

4.2.1 International

General Principles of Food Hygiene

The Codex Alimentarius was first established by the Food and Agriculture Organization of the UN (FAO) and the World Health Organization (WHO) in 1963, with the purpose of developing consistent international food standards to protect consumer health (WHO-FAO, 2009). The *General Principles of Food Hygiene* are guidelines included in the Codex Alimentarius which are recommended to be used by industrial food producers who manufacture products such as canned or packaged foods. The fourth edition is the latest version as of 2018, and was released in 2009.

These guidelines address many aspects of food hygiene including water quality in relation to food handling, processing, and storage. According to section 5.5 of the *General Principles of Food Hygiene*, only potable water should be allowed to come into direct contact with food in order to avoid food contamination (WHO-FAO, 2009). The definition for potable water in these guidelines is taken from the WHO *Guidelines for Drinking Water* (see Chapter 2). The *General Principles of Food Hygiene* also include a section on ice and steam, which highlights how these components should be produced, handled, and stored to minimize risk of contamination, and used only if they do not compromise the safety and suitability of food. Non-potable water can be used in certain food processes in cases where it does not come into direct contact with food, or compromise its safety and suitability (WHO-FAO, 2009). For example, non-potable water can be used in fire prevention and control applications, refrigeration, steam production, and various other similar purposes not connected with food, however, users must take proper precautions to avoid food contamination (WHO-FAO, 2009). It is also recommended that non-potable water systems be identified and kept separate from potable water systems.

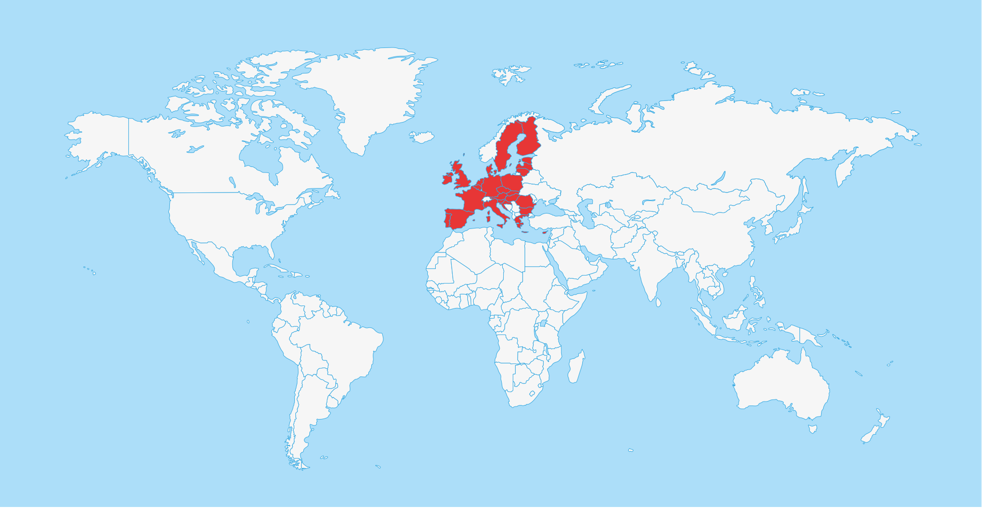
WHO Good Manufacturing Practices: Water for Pharmaceutical Use

Water is the most common substance used in the production, processing, and formulation of pharmaceutical products. Due to its unique chemical properties, water is able to absorb, dissolve, and suspend various chemical compounds, including contaminants that may represent a direct health hazard or have the potential to react with other substances and create a new health hazard (WHO Expert Committee, 2011). To minimize health hazards associated with the pharmaceutical industry, the WHO *Good Manufacturing Practices: Water for Pharmaceutical Use* guidance document was first released in 2005, and subsequently updated in the WHO Technical Report Series, No. 970, Annex 2, 2012.

The WHO *Good Manufacturing Practices: Water for Pharmaceutical Use* provides information on the current specifications for water for pharmaceutical use and guidance concerning the quality of water required for specific applications. This includes the manufacture of active pharmaceutical ingredients and dosage forms, and guidance on good manufacturing practices relating to the design, installation, and operation of pharmaceutical water systems (WHO Expert Committee, 2011). The focus is on water that is processed, stored, and distributed in bulk form. This includes drinking-water, bulk purified water, bulk highly purified water, and bulk water for injection. Drinking-water quality for pharmaceutical use is consistent with the quality level defined in the WHO *Guidelines for Drinking Water Quality* and is typically used as minimum-quality feed water in the preparation of bulk purified water. The document also specifies preparation methods for each aforementioned grade of water and highlights how each should be protected from recontamination and microbial proliferation (WHO Expert Committee, 2011). It further emphasizes how each grade of water should meet relevant pharmacopoeial[1] specifications for chemical and microbiological purity (including endotoxins) with set action and alert limits (WHO Expert Committee, 2011).

4.2.2 Regional

EUROPEAN UNION



Water Quality Demands in Paper, Chemical, Food and Textile Companies

A consortium of 12 companies in the European Union compiled a list of water quality demands for four industries (paper, chemical, food, and textile) to address the issues of product quality, safety and stability, worker's health, as well as water that is of a higher quality than required. The resulting guidance document, funded by the 7th Framework Programme of the European Union on Water Treatment Technologies and Processes, identifies water quality requirements that are intended to serve as guidelines when no other information is available (Aqua Fit4Use 2010). The guidelines are based on the water's function, rather than its source, and address problems arising from requirements that are both under-prescribed (inadequate quality) and over-prescribed (surfeit quality). The document notes the absence of references regarding water quality demands for many processes, in which case the type of water commonly used for those processes was designated as demand guidelines (AquaFit4Use 2010).

One of the objectives of *Water Quality Demands in Paper, Chemical, Food and Textile Companies* is to develop reliable and cost-effective tools, methods and technologies for the sustainable use of water possessing a quality tailored to industry specifications. Among the four major water-using industries considered in the document, the common water quality demands include limits for a wide range of dissolved and suspended solids, odour, colour, pH, microbes and temperature. Issues associated with not meeting these standards range from corrosion and scale/biofilm accumulation to interference with added reagents and generation of defective products.

1. Pharmacopoeias are a collection of legally binding standards and quality specifications for various medicines at the national, regional, and international scales (WHO, 2013a). Pharmacopoeias provide quality specifications for active pharmaceutical ingredients, finished pharmaceutical products, and general requirements (e.g. dosage forms), as well as for specified or recommended limits for various impurities or classes of impurities (WHO Expert Committee, 2011). Specific to water, different grades of water quality may be required to fulfil different tasks, depending on the route of administration of the pharmaceutical products. Defined water quality guidelines, requirements, and other specifications for different grades of water in bulk and dosage-form can be found in relevant pharmacopoeias. At present, some 140 independent countries worldwide are employing 46 national, two regional (European and African), and one international pharmacopoeias (WHO, 2013b).

4.2.3 National

SOUTH AFRICA

South African Water Quality Guidelines Volume 3: Industrial Use

Guidelines for industrial water quality are outlined in the second edition of Volume 3 of the 1996 *South African Water Quality Guidelines*, prepared by the Department of Water Affairs and Forestry. These guidelines for industrial water use consider water quality as it pertains to specific industrial processes, such that the overall water quality requirements of any industry can be defined as the sum of the specific water quality requirements of each process type (Department of Water Affairs and Forestry, 1996). The level of water quality that is advised for fitness of use within various industrial processes is assessed based on the potential to cause the following:

- damage to equipment (e.g. corrosion and abrasion)
- problems in the manufacturing process (e.g. precipitates and colour changes)
- impairment of product quality (e.g. taste and discolouration)
- complexity of waste handling

Four water quality categories are defined and industry-specific water uses are allocated to each of these four categories based on the stringency of water quality required for each use. Category one covers processes that require high quality water, whereas category four incorporates water uses that can utilise water of basically any quality without serious repercussions (see Table 12). Water use requirements for each process type are defined according to common water quality problems associated with water use (e.g. corrosion, fouling, scaling, etc.), the effects of inappropriate water quality, constituents of water identified as a source of concern, and specific cases that may influence water quality requirements. Table 13 provides a full list of processes and water uses according to each category in the guidelines.

Developing a Global Compendium
on Water Quality Guidelines
Industrial Water Quality Guidelines

Table 12: A description of the four water categories within Volume 3: Industrial Use of the *South African Water Quality Guidelines*. Adapted from: Department of Water Affairs and Forestry, 1996.

Category	Water Quality	Technology & Costs Required
Category 1	Processes that require a high-quality water with relatively tight to stringent specifications of limits for most or all the relevant water quality constituents.	Standard or specialised technology is essential to provide water conforming to the required quality specifications. Consequently, costs of in-house treatment to provide such water are a major consideration in the economy of the process.
Category 2	Processes that require water of a quality intermediate between the high quality required for Category 1 processes and domestic water quality (Category 3).	Standard technology is usually sufficient to reach the required water quality criteria. Cost for such additional water treatment begins to be significant in the economy of the process.
Category 3	Processes for which domestic water quality is the baseline minimum standard.	Water of domestic quality may be used in the process without further treatment, or minimum treatment using low to standard technology may be necessary to reach the specifications. Costs of further in-house treatment are not significant in the economy of the process.
Category 4	Processes that, within certain limitations, can use water of more or less any quality for their purposes without creating any problems.	No additional treatment is usually required and there is therefore no further cost.

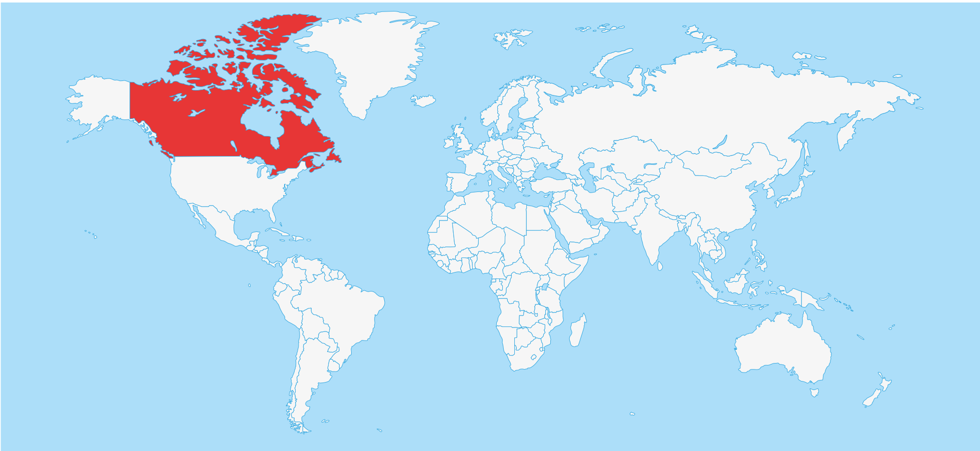
Table 13: The processes and water uses associated with each of the four water categories within Volume 3: Industrial Use of the *South African Water Quality Guidelines*. Adapted from: Department of Water Affairs and Forestry, 1996.

Category	Process	Water use
Category 1	Cooling water	Evaporative cooling (high recycle)
	Steam generation	High pressure (HP) boiler: demineralisation of feed water
	Process water	Phase separation
	Product water	Petrochemicals
		Pharmaceuticals
	Wash water	No residual washing (electronic parts)
Category 2	Cooling water	Evaporative cooling (high recycle)
		Solution cooling
		Water heating
	Steam generation	HP boiler: demineralisation feed
	Process water	Solvent
		Heat transfer medium
		Lubrication
		Gas cleaning
	Product water	Beverages
		Dairy products
		Petrochemicals
	Wash water	Reaction vessel washing
Category 3	Cooling water	Evaporative cooling: (once through)
		Bearing cooling
		Mould cooling
	Steam generation	Low pressure (LP) boiler: (softener feed)
	Process water	Solvent
		Dilution agent
		Transport agent
		Gland seal
		Vacuum seal
		Lubrication
		Descaling (iron and steel)
		Gas scrubbing
	Product water	Beverages
		Food products
		Baking
		Confectionary
		Chemicals
		Surface washing (table tops, walls)
	Utility water	Domestic use
		Fire fighting
Category 4	Cooling water	Ash quenching
	Process water	Transport agent
	Utility water	Dust suppression
		Fire fighting
		Irrigation
	Wash water	Rough washing (floors, rough apparatus, trucks, raw materials)

After defining these categories for industry, Volume 3 of the *South African Water Quality Guidelines* provides recommendations for water quality levels, differentiated for the four categories, for the following constituents:

- **Alkalinity**
- **Chemical Oxygen Demand**
- **Chloride**
- **Iron**
- **Manganese**
- **pH**
- **Silica**
- **Sulphate**
- **Suspended Solids**
- **Total Dissolved Solids**
- **Total Hardness**

CANADA



Canadian Water Quality Guidelines (CWQG)

The Canadian Water Quality Guidelines (CWQG) was published in 1987 by the Canadian Council of Resource and Environment Ministers (CCREM), and appendices were added in later years up until 1999. Its full contents cover water quality suggestions for the major uses: domestic, recreational, agricultural, environmental and industrial. Chapter 5 covers the water quality guidelines for various industrial water supplies including for:

- **Heating and cooling generation**
- **Steam electric power generation**
- **Iron and steel industry**
- **Pulp and paper industry**
- **Petroleum industry**
- **Food and beverage industry**
- **Chemical and allied industries**
- **Textile industry**
- **Tanning and leather industry**

As of 2018, the industrial water quality guidance provided in the CWQG is more than 30 years old, with few or no updates since then. In 1999, the *Canadian Environmental Quality Guidelines* superseded the 1987 CWQG and the CCREM ceased publication of CWQG (CCME, 2008). This has since been replaced with the *Canadian Water Quality Guidelines for the Protection of Aquatic Life* (see Chapter 3 and 6). Within the updated versions of Canadian water quality guidance, there is no longer guidance for water quality intended for industrial purposes, and the focus is on effluent water quality in the environment.

4.3 Discussion

At present, there is a dearth of readily accessible information on the water quality needs of industrial users for decision makers. Most available information is in the form of engineering textbooks, equipment manuals, and internal facility policies. There is very little information regarding industrial water quality needs written for an audience outside industry users. The guidelines presented in this chapter offer recommendations for a variety of industry types, with focus on food processing, pharmaceuticals and high-tech industry (e.g. microchips), all of which require sophisticated water treatment facilities.

Given the diverse and complicated nature of the industrial sector's water quality concerns, water quality guidelines for industrial use typically focus on particular sectors (e.g. *WHO Good Manufacturing Practices: Water for Pharmaceutical Use*) and are derived according to different drivers or motivation. The most heavily regulated sectors are those with health and safety concerns, such as food and beverage manufacturers and pharmaceutical companies. This is evident through the two available international guidelines contained in this report, the *WHO-FAO General Principles of Food Hygiene* and *WHO Good Manufacturing Practices: Water for Pharmaceutical Use*.

In some countries, industrial water use is regulated according to whatever quality water is protected and mandated for other uses (such as domestic) and, therefore, cannot be used by specific industrial sectors. Furthermore, the use of municipal (potable) water for industry is often not practical or appropriate considering the quantity utilized and the quality demanded. In some cases, the quality is unnecessarily high and in other cases it is inadequately low simply because potable water standards focus mainly on protecting human health and preserving the distribution system. By contrast, industry water standards often focus on supporting or preventing specific chemical reactions and shielding critical equipment.

Often, industry must treat its influent water, at least for specific processes, no matter what the source. For industries which require high quality water, such as for semiconductors as described in Box X, it may be beneficial for companies to use water of a quality below drinking water standards. As these industries require a high level of water treatment beyond drinking water standards, it could be cost effective for them to buy cheaper low quality water and then treat it to their needs. This frees up higher quality water in the environment for other uses, such as domestic purposes and ecosystems.

Industry's use of their own recirculated water frequently requires specialized water treatment technologies appropriate for effluent chemistry, as well as for influent quality demands. Such recirculated (recycled) water is a common source of industrial water, such as in Canada, where it accounts for approximately 53% of water intake in the manufacturing industry (Statistics Canada, 2009). The pursuit of cost savings by industry is considered to be the driving force

for optimizing operations and water allocations, thereby decreasing water consumption and wastewater discharges that require extensive treatment. For these benefits as well as reducing water needs by this sector, guidelines and regulations should encourage industries to recycle a certain proportion of water within their facilities. This would also lead to greater production and use of smart water technologies.

Besides cost and resource savings, climate change may also pressure industry to secure and maintain adequate water supplies under the threat of increasing unpredictability in the timing and location of water resource impacts. The lack of locally available water resources may eventually force the relocation of industries that are not able to import water at an acceptable cost (WWAP, 2012). The concept of industries coming together in clusters or groups that could share the costs of treating wastewater streams has been proposed as a possible solution for cost savings (Tan et al., 2009). Given the differences in influent water quality demanded by industries, the challenge would be to find a general water treatment technology that could provide an acceptable source water for the industries, presuming that further treatment would likely be tailored for each member of the group.

Finally, there needs to be a break in the link between industrial production and environmental degradation in order to promote greater sustainability and cleaner production technologies. However, there may be the perception that only water effluent from industrial sites needs quality guidance for environmental protection, due to historical environmental degradation from industrial pollution. This can be seen through the shift in guidance documents from the CCREM (now the Canadian Council of Ministers of the Environment (CCME)) to exclude water for industrial purposes from its guidelines in later editions.

Acknowledging the benefits of using the appropriate water quality for various industrial processes, both for private companies and for higher level water managers, will assist in allocating the appropriate water to these purposes, while maintaining the safety of products produced through secondary industry processes. This shift in water quality use can happen quickly due to industry's private ownership structure, which gives it flexibility and allows fast change when opportunities exist. We suggest the production of more guiding documents on water quality across all industrial sectors, particularly for processes that require low quality water where little guidance is available, to encourage and assist companies to use water of the appropriate quality.

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CHAPTER 5

Energy Water Quality Guidelines

CHAPTER 5
Energy Water Quality Guidelines

5.1 Context

The energy sector has important links with water and a unique and reciprocal relationship with the water industry which sets it apart from other sectors. Among all the domain uses discussed in this report rely on water to some extent, only energy is necessary for the production and transportation of clean water (Rodriguez et al., 2013). The energy sector is considerably water intensive. Worldwide, energy production withdraws an estimated 583 billion cubic meters of water per day, which accounts for 15 percent of total global water withdrawals (WWAP, 2014). Additionally, satiating the water needs of other sectors, such as for domestic and agricultural purposes, is extremely energy intensive (Rodriguez et al., 2013). For example, the United States uses 13% of its electricity to treat and transport water, and up to 90% of a single farm's energy expenses in the United States can be spent obtaining the right quantity and quality of water (Smedley, 2013). Energy and water are intrinsically linked, and a gain in efficiency for one is often a gain in efficiency for the other. Given that the substitution to use water of lesser quality has the potential to cause great gains in efficiency, the impacts associated with the use of improper water quality are crucial considerations for effective management within the energy sector.

Energy is derived from a variety of sources including the sun, water, wind, uranium, biomass and fossil fuels (WWAP, 2012). To obtain energy in a useable form, these sources must undergo certain processes such as coal and uranium mining, oil and gas exploration and production, hydropower generation, and thermoelectric generation. Some of the energy sector's processes cross into the territory of other water uses, discussed in other sections of this report. For example, biofuel production involves agriculture, whereas the manufacture aspect of photovoltaic panels and wind turbines for the production of renewable energy belongs to the industry section. For these reasons, those forms of energy production are not included in this chapter. Many of these processes require water, further emphasized in the 2012 *World Water Development Report*, which states that

> **"All forms of energy require water at some stage of their life cycle."**

For example, up to 2500 liters of water can be used to produce one liter of biofuel (WWAP, n.d.), a concentrated solar plant can use as much water for cooling as a thermoelectric power plant (Mielke et al., 2010), geothermal energy typically requires a water source for cooling (Kagel, 2008), and wind turbines require water for the mining, manufacturing, and transportation of individual turbine parts (WWAP, 2012). These energy processes differ in water intensity requirements. For context, Figure 8 depicts the intensity of water consumption for electricity production processes from different energy or fuel sources.

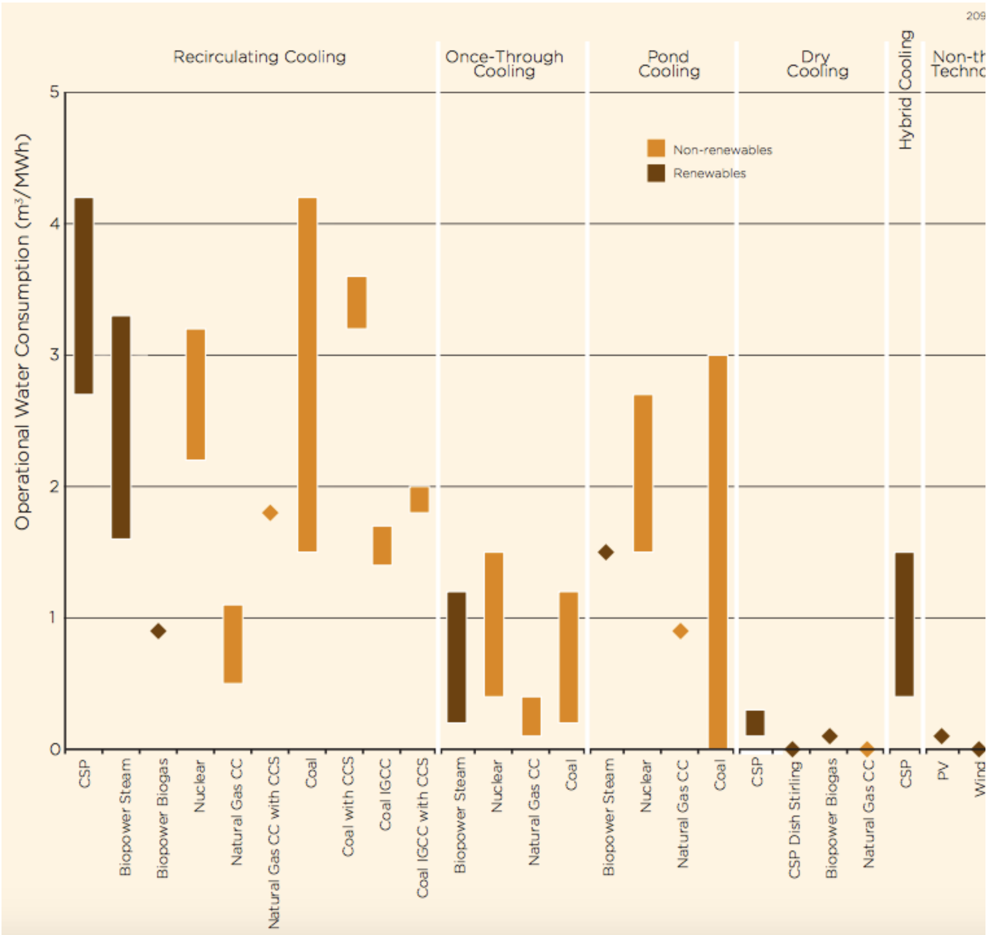

Figure 8: The volumes of operational water consumption for the production of various types of energy. Source: IPCC, 2011.

As is the case with other sectors, this report focuses, not on the well-documented effects of energy production and energy-related processes on effluent, but on the quality of water used by this sector. It encompasses guidelines regarding the level of water quality deemed appropriate for those particular processes. The following sections will address the growing demand for energy and the consequential increase in demand for water by the sector as well as the water quality requirements of various water intensive energy processes.

The Growing Demand for Energy

The demand for energy is growing. By 2040, energy demand is expected to grow by 37% (IEA, 2014). This projected growth will not be uniform everywhere but will vary geographically. The Unite States Energy Information Association's (US EIA) 2014 *International Energy Outlook* and the International Energy Agency's (IEA) *World Energy Outlook: Executive Summary* describe the dichotomy between the outlook for OECD nations and nations with developing economies (IEA, 2014). According to the US EIA and the IEA, the demand for oil in economically developed nations with "well-established oil markets" has already reached its apex due to innovation and efficiency (IEA, 2014). Economies experiencing rapid economic growth, on the other hand, are correspondingly experiencing a rapid growth in demand.

Exxon comes to similar conclusions in its *Outlook to 2040*, however, it groups China and India together since they represent half of the projected increase in demand. Exxon also isolates 10 countries which are expected to experience a significant growth in energy demand due to better living conditions and growing populations (ExxonMobil, n.d.). These include OECD member nations Turkey, Mexico, Saudi Arabia, Iran, Thailand, Indonesia, Egypt, Nigeria, South

Developing a Global Compendium on Water Quality Guidelines

Energy Water Quality Guidelines

Africa, and Brazil. Exxon has dubbed these nations "key growth" countries and expects them to play a pivotal role in the global future of energy (ExxonMobil, n.d.).

Figure 9 illustrates the baseline global water stress as of 2014, measured by a percentage representing a region's total annual water withdrawals compared to its total annual available flow (Gassert et al., 2015). Many of the key growth countries in the energy sector are located in arid regions or regions currently experiencing water stress. The means to exploit water for energy production needs to be sustainable and the energy sector must bear responsibility for this. It is therefore imperative to take advantage of existing opportunities to minimize the impact of increased water stress by determining the appropriate water quality for energy processes. This will contribute to sustainably meeting both the growing water demands of the energy sector and the changing energy demands of the world.

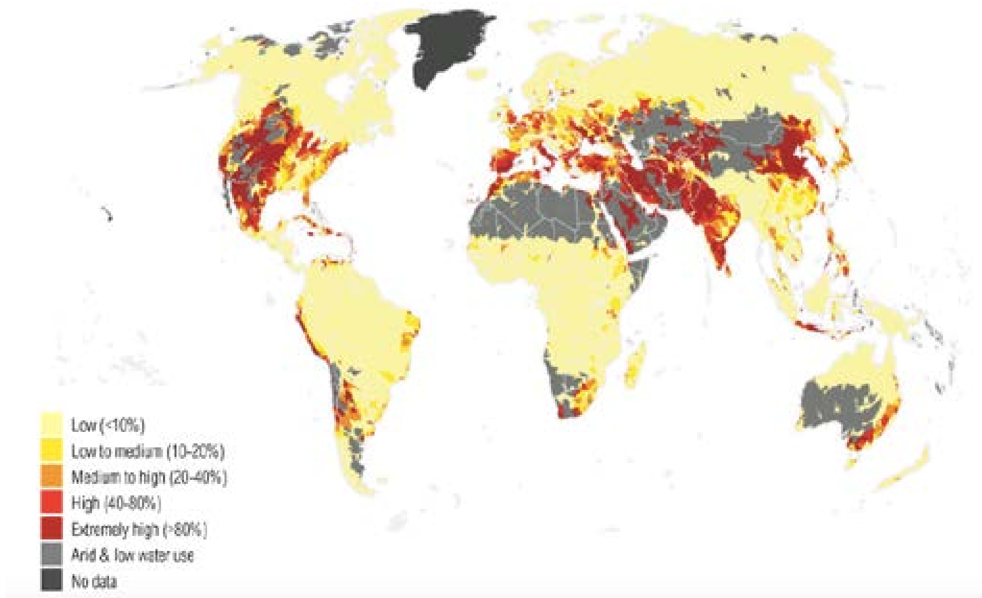

Figure 9: Baseline Water Stress as a percent of total annual water withdrawals over total annual available flow. Source: Gassert et al., 2015.

Water and Water Quality Demands of Different Energy Processes

The energy sector has multiple water quality concerns, many of which are application-specific. Some applications, such as hydraulic fracturing, necessitate water of a particular constituency, while for others, the primary concern relates to the efficiency of a chemical reaction or the prevention of corrosion. The following pages outline the specific considerations for mining, production of oil and natural gas, midstream fuel processing and thermoelectric generation; however we acknowledge that there are many more energy related applications not discussed in this report.

Mining

A large portion of the fuel used for energy is produced by mining. Mining is defined as the extraction of minerals and other substances from the earth (Hartman & Mutmansky, 2002). Some examples of mined substances include

- **coal, a common fuel used to generate electricity**
- **uranium, which is used in nuclear reactions to produce electricity**
- **oil, most commonly used in engines for transportation**
- **gas, which is commonly burned to produce electricity or used in motor engines to enable transportation**

Mining also provides materials for other important energy processes. For instance, it provides rare earth metals used in the manufacture of photovoltaic panels and wind turbines, as well as copper, which is used to transport electricity.

In mining, water is commonly used for the process and removal of materials, and for safety measures such as dust control. Mining techniques vary depending on mineral type and form, location, economic considerations, and existing environment and safety laws (Harraz, 2011). Coal, which is considered a soft rock, may be extracted using a variety of methods both above and below ground, depending on the depth of the seam (Great Mining, n.d. a&b); copper ore is often extracted using open pits (Gupta, 2013); and oil is typically obtained by drilling wells into pressurized reservoirs (Oil & Gas School, 2014).

Water quality can have significant effects on costly equipment and materials that represent significant saving opportunities through using water more efficiently. The water intensive nature of the mining industry illustrates these opportunities. Water quantity requirements also differ by mining method used. For coal, surface mining typically uses less water than underground mining, while conventional natural gas production uses much less water than hydraulic fracturing to recover natural gas from shale formations (Water in the West, 2013). Globally, the extraction of hydrocarbons produces between 15 and 18 billion cubic meters of contaminated freshwater a year (WWAP, 2014).

Production of Oil and Natural Gas
A particularly relevant subset of mining is the production of oil and natural gas. Conventional oil and gas drilling relies on the pressure within a reservoir to pump oil and natural gas to the surface. When the natural pressure in a well decreases, water is pumped into the reservoir to increase pressure and enable further extraction of oil and gas (Rigzone, n.d.). Hydraulic fracturing, a form of unconventional oil and gas drilling, entails injecting water into shale formations to fracture the rock and release the oil or gas previously trapped within the rock's pore spaces (Kershner, 2012).

Hydraulic fracturing - also known as fracking - is an extremely water-intensive process. The total quantity of water used to extract the oil or gas depends on well design, the operator, and the particular shale formation (USGS FAQs, n.d.). For example, an average well in the Barnett Shale may use approximately 3 million U.S. gallons of water over its lifetime, while one in the Horn River Shale may use more than 15 million U.S. gallons of water (USGS FAQs, n.d.).

The quality of water used in hydraulic fracturing is very important for the process' effectiveness. Most water for fracking contains a solid material proppant such as sand to hold pore spaces in the rock open, as well as chemicals, which serve various purposes in different geologic contexts that may be encountered by the producer (FracFocus, 2015; USGS FAQs, n.d.). The water used in fracking is of extremely poor quality by traditional definitions of water quality regarding purity and suitability for human health and safety. However, the water's constituency is very particular and considered by some to be protected proprietary information (USGS FAQs, n.d.). Box 9 provides a potential alternative water source for fracking that could match its quality requirements.

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on Water Quality Guidelines
Energy Water Quality Guidelines

Box 9: Seawater as an Appropriate Alternative Source for Hydraulic Fracturing


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It is possible to use seawater for hydraulic fracturing, however it can only be used if the chemistry within the reservoir rock permits (Carlyle, 2013). Chemicals found inside the reservoir can react with the seawater, causing complications such as scaling and corrosion (Carlyle, 2013). For example, dissolved barium and seawater can cause barium sulfate scale, which can impact the well and production (Carlyle, 2013). Saltier water may be more beneficial for hydraulic fracturing operations in certain reservoirs, however, the costs and greenhouse gas emissions associated with the transportation of sufficient quantities of seawater to fracturing sites often render seawater as an unviable option in many cases where it would otherwise be of an appropriate quality (King, 2011).

While seawater can be an alternative, it is highly subject and geography specific and its use may increase the probability to contaminate the groundwater resource. These factors must be considered before adoption.

Midstream Fuel Processing
Petroleum refineries use 1-2.5 gallons of water to create one gallon of petroleum product. Most of this serves to process fuels and cool excess heat.

Just as with other industrial and energy processes, corrosion of equipment is a major concern for refineries. The constituents that cause corrosion may originate from the water or unprocessed petroleum (Addington et al., 2011). Water is used as a solvent to remove corrosion-causing elements from the petroleum (Addington et al., 2011). Additives are also introduced to speed up the process and de-acidify the petroleum. These additives react differently with the water, depending on its pH and thus pH is a key quality parameter for petroleum refineries (Addington et al., 2011).

Another water quality concern for refineries is the output water. Once water goes through the refining process, it is contaminated with harmful chemicals and must therefore be treated before reuse. This processed water is called "sour water" and contains hydrogen sulfide and ammonia, which must be stripped from the water to avoid corrosion (GT Technology, n.d.). Controlling the pH level of the water is also significant to complete the stripping process (GT Technology, n.d.). This degradation of the water must be recognised and treated appropriately before reuse in the industry.

Thermoelectric Generation

Electricity is key to industrial and economic development, and growing economies increasingly rely on electricity. Of all the processes within the energy sector, thermoelectric power generation produces the most electricity (75% of the world's energy generation as of 2012) and uses the most freshwater (IEA, 2012). In many nations, more than half of freshwater withdrawals are used for thermoelectric power generation, producing approximately 80% of the world's electricity (WWAP, 2014). In Europe, thermoelectric power accounts for 43% of total freshwater withdrawals, and the United States withdraws more water for thermoelectric power generation than it does for agriculture (WWAP, 2014).

Thermoelectric generators produce electricity by burning fuel (usually coal or natural gas) or by channeling a nuclear reaction to boil water and produce steam which turns a turbine (Duke Energy, n.d.; NEI, n.d.). The generator then converts the rotational kinetic energy from the spinning turbine into electricity (Duke Energy, n.d.). Most of the water used in thermoelectric power generation is for cooling waste heat rather than producing steam to turn the turbines.

Thermoelectric generators use three main types of cooling systems (Zammit, 2012):

1. *once through*, which withdraws the largest quantity of water, but consumes very little
2. *recirculating cooling*, which requires small, periodic withdrawals to replace the water consumed through evaporation
3. *dry cooling*, which requires no water, but uses far more electricity, often making it the less viable option out of the three in terms of cost

Water quality matters in these cooling systems because it can impact the life time of the equipment or structure it comes into contact with. Water of different quality can affect different materials in different ways. For example, water with excess chloride can corrode many metals and ammonia can crack and corrode copper alloys (SDCWA, 2009). These challenges can typically be overcome by using additional filters and additives in the cooling systems (SDCWA, 2009).

5.2 Existing Guideline Case Studies

5.2.1 International

IAEA **Efficient Water Management in Water Cooled Reactors**

The *Efficient Water Management in Water Cooled Reactors* guideline is part of a nuclear energy series of publications from the International Atomic Energy Agency (IAEA), released in 2012. The central purpose of these publications was to encourage the peaceful use of nuclear energy through developing research and design and best practices for application (IAEA, 2012). The objective of the *Efficient Water Management in Water Cooled Reactors* document is to assist in reducing water consumption in nuclear power plants, to address global water scarcity as well as to help new adopters of nuclear energy in regions with water insecurity. It does this by first outlining the current practices of water use in all stages of nuclear power plant development, from construction, to operation and decommissioning. The next two chapters describe available technologies for various cooling systems in facilities, and then technologies for treating or finding usable water for these cooling systems (IAEA, 2012). Water reduction strategies are presented, finishing with a discussion on recommended direction for future nuclear power plants to reduce water use and improve general efficiency.

Although the focus of the guidelines is on technologies for water quality treatment, rather than the quality of water itself, they also examine potential sources of water for power plant uses, as shown in table 14. Reclaimed wastewater and desalination are two new sources of water that are promoted if proper quality care is taken to protect power plant facilities and processes.

Table 14: Water sources available for power plant needs, with a description of past experiences. Source: IAEA, 2012.

Sources of water supply		Extent of utilization by fossil plants
Surface water	Rivers and streams	Widely used, especially in older plants.
	Lakes and ponds	Widely used — natural and man-made lakes.
	High-salinity waters	Limited usage at this time.
Groundwater	Shallow wells	Used mainly where surface supplies are unavailable.
	Deep wells	Used mainly where surface supplies are unavailable.
Municipal water	Treated surface water	Widely used, mainly at plants within a municipal distribution area.
	Treated groundwater	Widely used, mainly at plants within a municipal distribution area.
Wastewater	Internally generated	Practiced in some zero liquid discharge designs. (This approach requires an outside water supply for use elsewhere in the plant.)
	Externally generated	Minimal usage, but an important potential source for future plants.
Underground water	Mine pool water	Used in the area of coal field such as Pennsylvania or West Virginia

These guidelines inform current practices of water use and consumption in nuclear power plants around the world, and outline the advantages and disadvantages of strategies to reduce water use. It uses real case studies and so could be a good reference for water managers, provided they will need to consider local conditions. A conclusion of the report is that several technologies can be employed to reduce water withdrawals or consumption, but often these come at a cost. Generally, the greatest reduction technique is in improving the thermal efficiency of cooling processes in power generation (IAEA, 2012). While there are recommendations in the report relating to water quality for nuclear power generation, there is a stronger focus on water quantity considerations and suggestions to reduce water use and promote efficiency in order to keep nuclear power generation sustainable in a water stressed environment.

5.2.2 National

UNITED STATES OF AMERICA

Use of Degraded Water Sources as Cooling Water in Power Plants

The *Use of Degraded Water Sources as Cooling Water in Power Plants* report was published in 2003 through joint partnership between the Electric Power Research Institute, Inc. (EPRI), the Public Interest Energy Research Program and the California Energy Commission. The goal is to give basic tools and guidelines to public and private groups in order to direct alternative water sources (degraded, defined here as non-potable water) to be used for cooling in power plants (EPRI & California Energy Commission, 2003). While a lot of the information can be used broadly, there is a focus in California with a review of regulations and rules for reclaimed water use there.

A number of topics are covered for guiding the use of non-potable water for power plant usage, with a strong focus on technology from technical feasibility, and commercially available as well as emerging technologies. The second chapter, however, is devoted solely to water quality requirements for cooling systems. It describes the evaluation of constituents of concern in new water sources and a six-step methodology designed for evaluating water sources for suitability for being used within cooling towers (EPRI & California Energy Commission, 2003):

1. Identify and characterize the source water(s)
2. Evaluate constituents of concern
3. Identify cooling tower design and operating Impacts
4. Determine the need for treatment
5. Evaluate treatment requirements
6. Evaluate disposal issues

Figure 10 shows the conceptual frame of this methodology.

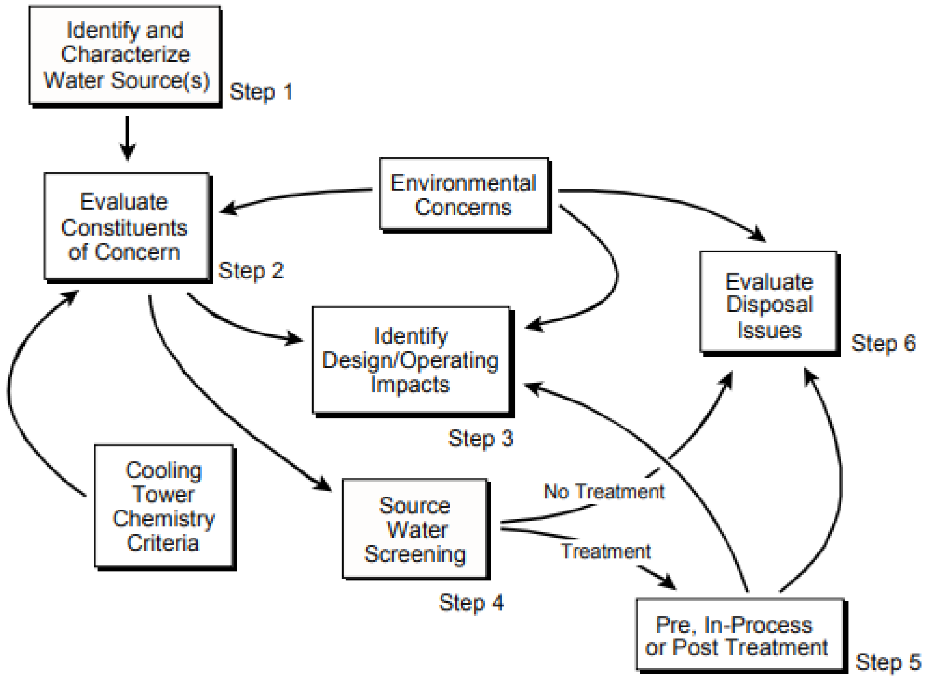


Figure 10: The six-step methodology to evaluate water sources for acceptable quality standards for cooling towers proposed in *Use of Degraded Water Sources as Cooling Water in Power Plants.* Source: EPRI & California Energy Commission, 2003.

Besides the theoretical overview of the guidelines of this methodology, the report practically applies them to four real water sources in California. These water samples are chemically screened, evaluated and compared based on the constituents of concern identified in the guidelines.

Use of Reclaimed Water for Power Plant Cooling

This document, created by the National Energy Technology Laboratory of the U.S. Department of Energy, was printed in 2007 to act as a reference and encouragement for the use of non-traditional water sources -reclaimed water from municipalities –for power plant cooling. It acknowledges the large volumes of water needed for this purpose and covers a range of thermoelectric power plants, including fossil/biomass/waste, nuclear, geothermal steam, natural gas and coal. Because of this and reductions in traditional freshwater sources, this document provides information on the alternative water source of reclaimed water which is widely available across the United States. It uses some of the water quality guidelines from the 2003 *Use of Degraded Water Sources as Cooling Water in Power Plants* report and builds on this to provide regulatory information relevant across the United States.

A good overview of using reclaimed water for power plant cooling in the United States is provided, with informative tools such as descriptions of regulatory frameworks imposed by states and federal bodies to govern this activity as well as types of additional water treatment suggested for the use of reclaimed water. There is also a case study of an example power plant using this water source near Washington, DC. Of particular note is the first national effort to compile a database of power plant facilities that are using reclaimed water for cooling. This database lists 57 American facilities using reclaimed water as of 2007, with the states of Florida, California, Texas, and Arizona having the largest numbers of facilities.

UNITED KINGDOM

[Cooling Water Options for the New Generation of Nuclear Power Stations in the UK]

Similar to the American guidelines explored above, these UK guidelines outline cooling systems in power plants to discuss current practices, available technology, and recommendations to improve efficiency, safety and management. Created by the Evidence Directorate of the Environment Agency in England in 2010, it draws information on England's experience with nuclear power stations and future directions in order to investigate and evaluate options, both for managers and regulatory agencies (Environment Agency, 2010). Additionally the document discusses cooling water systems from direct and indirect cooling water systems, intake and outfall designs, how design affects performance of the cooling option and issues such as temperature differentials between water intake and discharge (Environment Agency, 2010).

A large focus of the second half of the document and conclusion is on the environmental impacts of discharged cooling water from nuclear power stations in the UK. This is in regard to thermal discharges and their potential biota, chemical and radionuclide pollution to environmental systems. Its output is a table comparison of cooling options and the level of environmental concern for each, with such concerns as efficiency, water abstraction, ground fog, noise and discharge. Overall, the document is useful for gaining an understanding of cooling water systems for nuclear power generation and their associated impacts and water use, especially in England. It has several recommendations on water quality embedded within the cooling system options, considering temperature as the key defining characteristic of water in these uses.

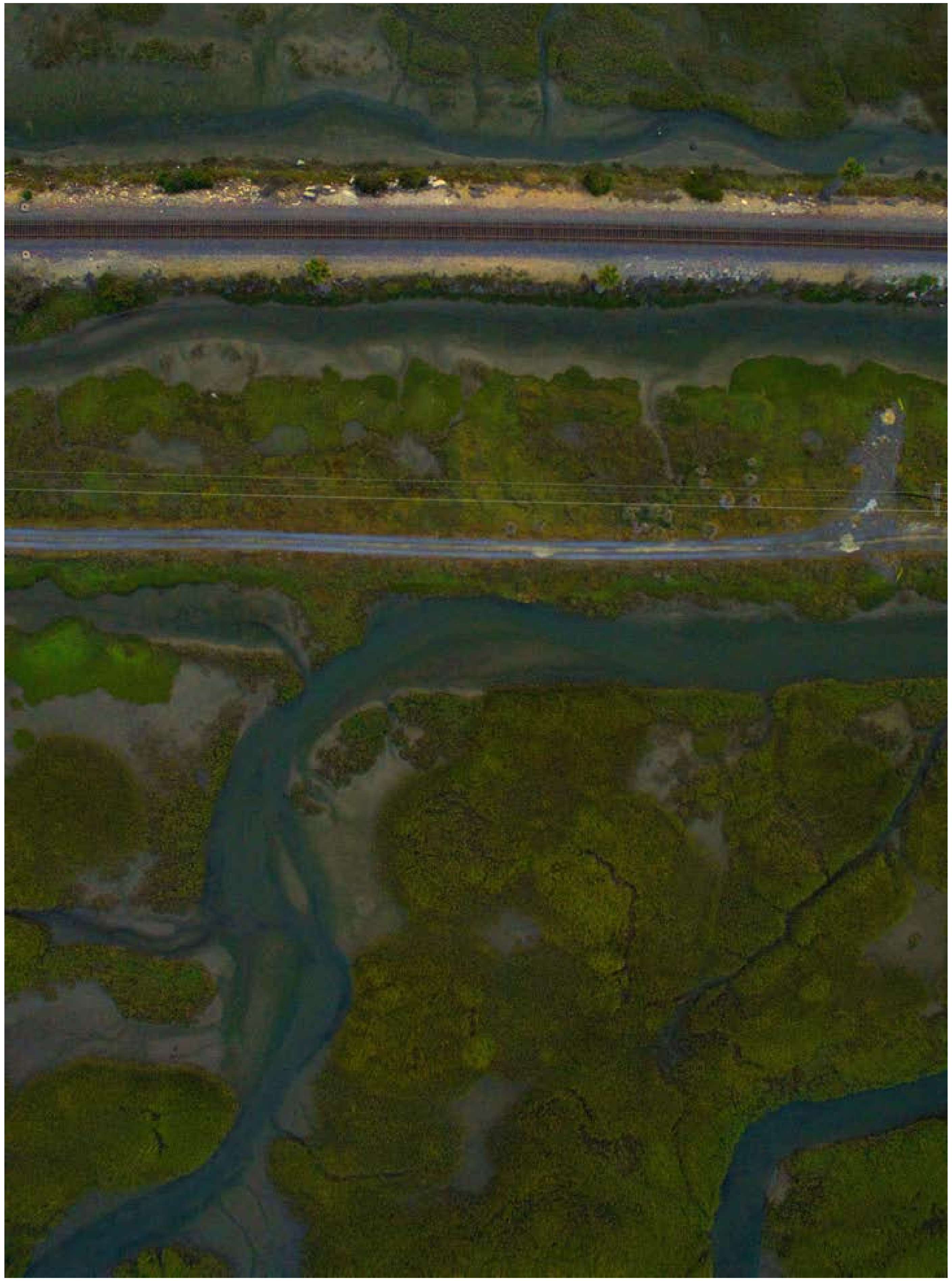
5.3 Discussion

Water and energy are intrinsically linked. Recognising their interdependence is important as demand for both water and energy increase. Energy is needed to transport water for its various uses, and water is used in significant quantities for most energy production generation. This interrelatedness forms the "energy-water nexus" to signify the trade-offs between these two valuable resources (Rodriguez et al., 2013). However, the energy sector also presents significant opportunities for using water of different qualities. Due to qualities of scale of locations, the sector has significant opportunities to tailor the water quality they need from the water quality available.

The increase in water use by the energy industry is quickly becoming a global concern. However, there are no international guidelines for the quality of water used by the entire energy industry, in its many different water using sectors and processes. Similarly wanting are regional and national guidelines. Where they do exist, they are specific to one sector, often the cooling systems of thermoelectric generation of fossil fuel and nuclear plants. This is important as thermoelectric power plants withdraw significant quantities of water for cooling, albeit a large amount of this is not consumed so can be reused or returned to the environment if properly treated. Furthermore, the emphasis of guidelines for managers of these facilities is mainly on water quantity rather than quality, or on the quality of discharged water from the facility, as is often the case for mining wastewater. Little attention is paid to the quality of the water entering these facilities.

The guidelines provided in this chapter focuses on thermoelectric generation because of a lack of documents found for other energy forms. Hydropower consumes very little water and there are minimal associated quality concerns, however small solids such as silt and sand can cause serious impacts to generators. Regarding water used in mining, there is a dearth of readily available information on the desired water quality for water used in mining, and whether or not water quality needs differ based on the mining method used or by mineral type. The World Bank (2013) acknowledged the global increase in renewable energy such as wind and photovoltaic, but evidenced little concern for their water needs as they consume negligible quantities of water. However, as these industries take off, it is necessary to consider the water quantity and quality these industries will require.

Overall, more publically available guidelines are needed at the international, regional and national levels to address water quality requirements within the energy generation sector. Futhermore, Corporate Social Responsibility and related projects in the energy sector should be promoted to address the harmful impact of certain energy production methods on the environment and to ensure sustainable energy production.



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CHAPTER 6

Ecological Water Quality Guidelines

CHAPTER 6

Ecological Water Quality Guidelines

6.1 Context

Aquatic ecosystems have experienced significant changes over centuries, with alterations including straightening and canalization of water ways, disturbance to floodplains and land reclamation, all with significant implications for the health and resilience of water bodies and their associated ecosystems. Declining global water quality, particularly in the context of aquatic ecosystems, has already caused significant disturbances in overall water use, ecosystem health, and biodiversity. There are many sources of contamination to aquatic environments used by ecosystems, but a joint FAO and IWMI report identified agriculture as the leading contributor of pollution to global water systems, from the runoff of excessive pesticides, nutrients, salts, sediments, organic matter and pathogens (FAO-IWMI, 2018).

Water quality requirements for ecosystems use is an emerging research and policy focus in the water field. The importance of managing and preventing the degradation of aquatic ecosystems was highlighted under the UN Thematic Priority Area (TPA) on Water Quality by UN-Water in September 2010 (Yillia, 2012). The United Nations Environment Programme (UNEP) alongside the United Nations University and Institute for Environment and Human Security (UNU-EHS), have since developed the International Water Quality Guidelines for Ecosystems, which aim to direct the development and implementation of national and regional water quality guidelines for the protection and restoration of ecosystem values. These guidelines represent a first effort to define water quality guidelines for ecosystems on a global level, addressing a recognized data gap regarding water quality requirements for freshwater ecosystems. A number of countries including Australia, New Zealand, Canada, and South Africa have independently developed and implemented national level water quality guidelines specific to aquatic ecosystems, and therefore, provide key case studies for guidance.

Ecosystem as a Concept

An ecosystem can be defined as an interactive system established between a group of living organisms and the environment in which they live (Tansley, 1935). The concept of an ecosystem is fundamentally integrative and dynamic, involving the structure, function and development of species, as well as the natural environment across both spatial and temporal scales. Crucially, the act of defining an ecosystem creates a discrete framework in which the interactions between individuals, populations, communities and their abiotic environments can be studied (Likens, 1992). Ecosystem science therefore represents an attempt to understand what influences and drives the patterns and processes observed in the environment (Likens et al., 2009). It must be noted, however, that placing boundaries on the complex and diverse interactions which take place within ecosystems ultimately creates a precept that is constructed for the utility of the investigator (Likens, 1992). Such delineations are a necessity for research and policy to contribute effectively and efficiently to our overall understanding of ecosystems and ecosystem management capabilities; however, defined boundaries are an anthropogenic interpretation rather than an absolute representation of ecosystem dynamics. Accordingly, water quality criteria and associated guideline values developed for ecosystems use are a reflection of our current understanding of ecosystems' form and function, so flexibility and adaptation are requisites for policies and guidelines.

Water Quality Considerations

The key difference between water quality for ecosystems and that of other uses is the inclusion of biotic factors. Water quality guidelines specific to ecosystems ideally incorporate physical, chemical, biological, and microbiological indicators with objectives centered on the maintenance and protection of organism assemblages, processes, and functions that underpin aquatic ecosystems. Accordingly, this leads to a level of complexity and specificity within water quality criteria related to water body type, climatic, and geographic settings. Such factors alter not only the physical and biological parameters of aquatic systems, but also the behaviour of pollutants within systems. For example, some pollutants such as heavy metals may be transferred between trophic levels, ultimately bio-accumulating in apex predators. At the same time, other pollutants may degrade in aquatic ecosystems relatively quickly, having a minimal impact on ecosystem structure and function. Degraded water quality can reduce biodiversity in aquatic ecosystems since fewer species are tolerant of polluted environments, which ultimately affects ecosystem resilience. In ecology, resilience refers to the ability of a system to return to a state of equilibrium following a disturbance (Holling, 1973). Biodiversity can increase the resilience of ecosystems since it can help ensure that following a disturbance to a system, enough species will survive to maintain ecosystem structure and function, as well as key ecosystem services.

The assessment of water quality from an ecosystems approach involves a shift in thinking, moving from the notion of water bodies as static water sources to water bodies as dynamic, living systems. Such a shift is precipitated by an emerging awareness of the inherent value of freshwater ecosystems. Alongside their intrinsic natural worth, freshwater ecosystems hold social, cultural, spiritual, and economic values. These values are largely based upon the overall biodiversity and healthy functioning of an ecosystem, a state that is predominantly underpinned by good water quality. The emergence of the Ecosystem Services (ES) concept, used to describe the natural processes and functions providing essential resources and services to human society, is evidence of our emerging and growing valuation of natural systems. ES was popularised in the 2005 Millennium Ecosystem Assessment where four key ES were described to showcase the often overlooked benefits that ecosystems provide to people, see figure 11. Box 10 provides more detail on this concept and builds on this valuation concept to include payment for ES.

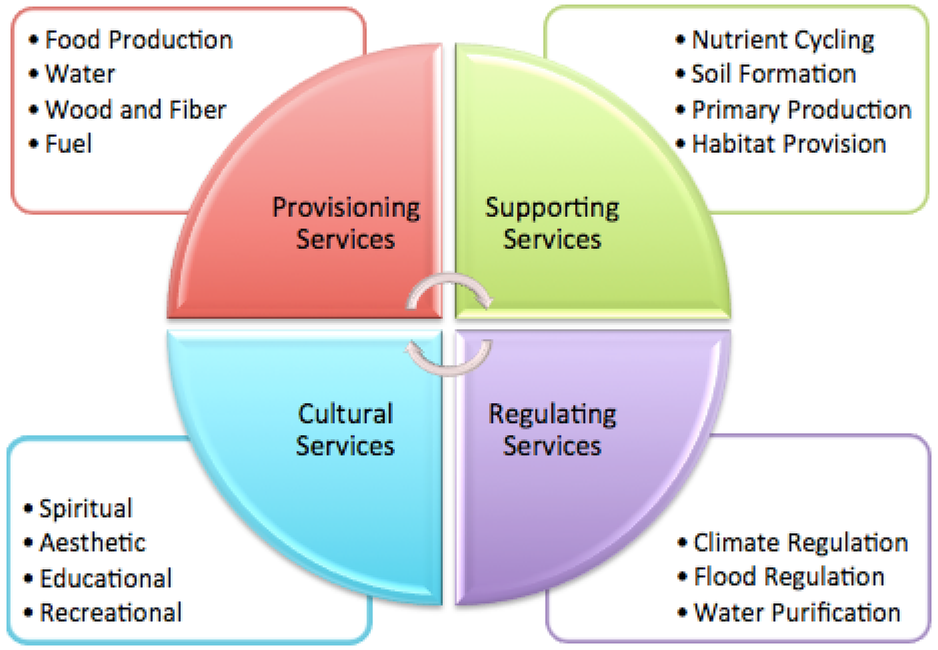

Figure 11: The four main ecosystem services, as outlined in the Millennium Ecosystem Assessment. Source: Millennium Ecosystem Assessment, 2005.

For freshwater ecosystems, these services include the filtration, purification, and cycling of freshwater, primary production, nutrient cycling, and vast cultural and spiritual worth. While degraded water quality can be remediated through natural processes, there are limits to the degree with which ecosystems can deal with inadequate water quality. Thus, the management of water quality must in turn consider the needs of ecosystems in order to ensure the preservation of ecosystem values and the promotion of sustainability moving forward.

Developing a Global Compendium on Water Quality Guidelines

Ecological Water Quality Guidelines

Box 10: Payment for Ecosystem Services

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Ecosystem services, as defined in the Millennium Ecosystem Assessment (2005), are "the benefits people obtain from ecosystems." Depending on the structure and function of an ecosystem, different ecosystems will ultimately provide different services. According to the Millennium Ecosystem Assessment (2005), ecosystem services are commonly classified into four main categories:

- ***provisioning services***, which include the natural production of food, timber, and water;
- ***regulating services***, which control or mitigate climate, natural disasters, waste, and disease;
- ***supporting services***, which enable nutrient cycling, soil formation, and crop pollination; and
- ***cultural services***, which ultimately yield recreational, aesthetic, and spiritual benefits.

Ecosystem services can also be classified according to geographical scale, value to society, or by ecosystem type (WRI, 2009).

At present, markets for ecosystem services are emerging in countries around the world. One such example is the payment for ecosystem services (PES) scheme in which voluntary or conditional transactions take place between service providers and beneficiaries. The key idea behind PES schemes is that service providers manage and maintain the flow of predefined ecosystem services in exchange for something of economic value (UNEP, 2008). Since PES schemes often involve transfers of wealth, they also have the added benefit of contributing to poverty alleviation through empowerment of the poor in cases where the poor are recognized as valued service providers (UNEP, 2008).

One example of a successful PES scheme is the Environmental Services Payment Program (FONAFIFO) established in Costa Rica, where landowners are compensated for actions and activities that contribute to environmental sustainability such as agroforestry, reforestation, and the conservation of natural forests (GEF, 2014). Another example is the Payment for Hydrological Environmental Services Program in Mexico, where economic incentives are provided to forest owners who effectively minimize deforestation practices on their lands, particularly in areas experiencing severe water problems (GEF, 2014); this type of incentive ultimately enhances watershed protection and facilitates the recharge of local aquifers.

Management Objectives for Ecological Water Quality

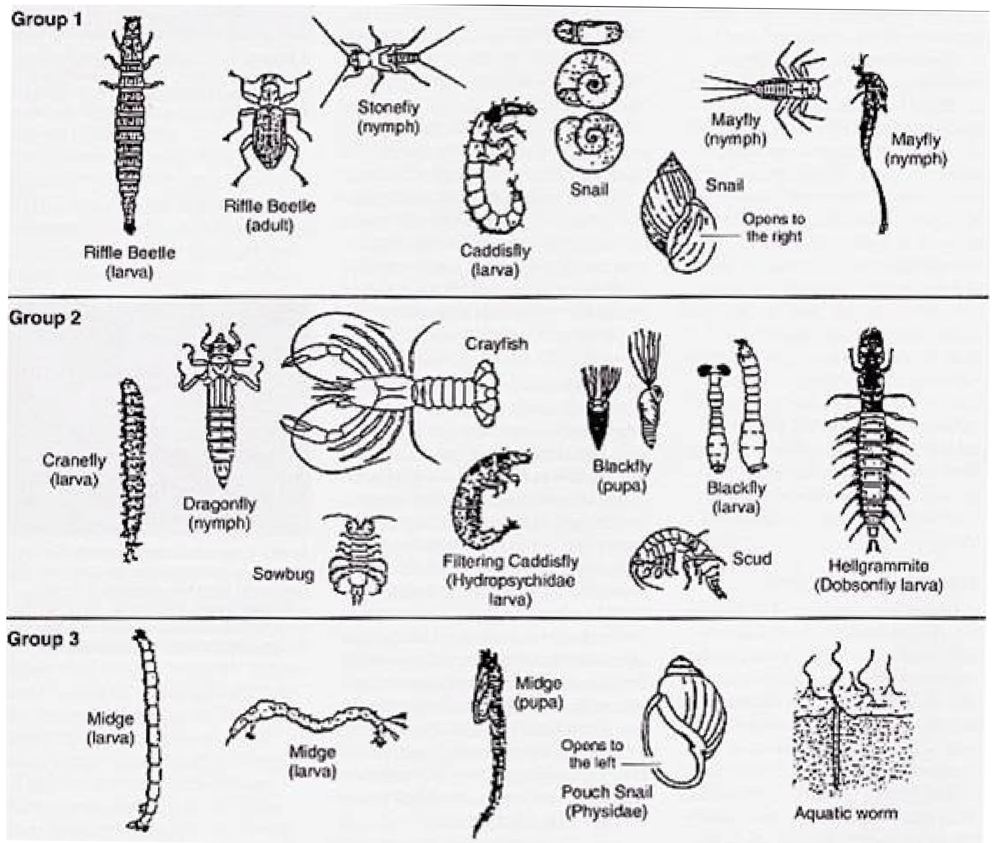


Figure 12: A key to benthic macroinvertebrate monitoring for ecological water quality, categorising organisms into three groups: Group 1 are the least tolerant to pollutants with group 3 as the most tolerant to pollutants. The dominance of organisms from one of the groups signifies fair to poor ecological water quality. Source: https://sites.google.com/site/gis515es/

Acknowledgement of the importance of aquatic ecosystems in the overall biosphere as the depositories of biodiversity, providers of ecosystem services, and essential water resources, highlights the importance of developing water quality guidelines for the protection of aquatic ecosystems. Good management practices can help preserve water quality for ecosystems and other human uses, benefiting drinking water supplies, food production, recreational waters, and treatment costs. These management needs are helping to drive the development of water quality guidelines for ecosystems; thus, the development and implementation of water quality guidelines for ecological use is an important precursor to effective environmental management.

Water quality, when approached from an ecosystems perspective, is characterized by a combination of biotic and abiotic factors, namely hydrological, physico-chemical, and biological in origin. These factors incorporate the climatic, geomorphological, and geochemical conditions within a drainage basin, as well as the underlying aquifer, local geology, surrounding land cover, proximity to ocean, and flora and fauna assemblages (Meybeck & Helmer, 1996).

Influencing and interacting with these natural features are anthropogenic impacts. These originate from land use changes associated with urban, agricultural and industrial activities, such as untreated waste discharges, nutrient runoff, chemical leaching, altered flow regimes, thermal pollution, contamination from mine tailings, salinization, acidification, and erosion (Meybeck & Helmer, 1996; Meybeck, 2004). Such anthropogenic activities often contribute to the pollution of natural water bodies, negatively affecting flora and fauna populations, as well as natural ecosystem functioning. This in turn can reduce the resilience of aquatic ecosystems and their role in the provision of ecosystem services. Management of water bodies for the protection of ecosystem values involves an understanding of the linkages between ecosystem

properties and how anthropogenic affects the physical, chemical, and biological processes that underpin adequate ecosystem functioning (Carr & Neary, 2008). Such knowledge, alongside a scientific and technical understanding of the habitat, catchment conditions, water resource quality, and uses of the water are a prerequisite for a comprehensive and balanced approach to the development and implementation of water quality guidelines (Hart, Maher & Lawrence, 1999).

Specific water quality issues that result from such negative external influences as described above include excessive nutrient levels, increased acidity, chemical incidences, trace metals, toxic substances, high sediment loads, and incursions of pathogenic organisms (WWAP, 2012). In light of these external influences, monitoring water quality in aquatic ecosystems is an essential tool for establishing baseline water quality levels and in determining the effects of water management schemes.

Box 11: Bioassessment Protocols for Monitoring the Biological Integrity of Aquatic Ecosystems

© Mate Moinor

Biological integrity can be defined as "a balanced, integrative, adaptive community of organisms having a species composition, diversity and functional organisation comparable to that of natural habitat of the region" (Karr & Dudley, 1981). While chemical and physical approaches to monitoring water quality are commonly used, these approaches cannot capture the complexity of ecological health or biotic integrity (Karr, 1991). Given the limitations of chemical and physical water quality monitoring criteria, efforts have been made to develop bioassessment protocols capable of determining whether or not a stream is capable of supporting resident biota (Barbour et al., 1999).

The original Index for Biotic Integrity (IBI) was designed to evaluate the impacts of humans on streams and watersheds by assessing various attributes of fish communities compared with regional reference streams that haven't been impacted by human influences (Karr, 1991). The United States EPA later designed a more comprehensive Rapid Bioassessment Protocol to provide a cost effective way to monitor the biological properties of streams and to provide a mechanism for incorporating biological data into stream management decisions (Barbour et al., 1999). The European Union also developed an 'Assessment System for the Ecological Quality of Streams and Rivers throughout Europe using Benthic Macroinvertebrates' under the Water Framework Directive (Hering et al., 2004). Today, IBI's and bioassessment protocols have been adapted for various types of streams around the world and the methods for implementing these protocols continue to be refined. The continued refinement of these tools will improve our ability to assess the impacts of water quality impairments on aquatic ecosystems.

Overall, water quality guidelines designed for aquatic ecosystems must consider specific criteria based on the protection and maintenance of ecosystem structure (i.e. the distribution of species, biotic, and abiotic factors), function (i.e. energy flow and cycles) and dependent species (i.e. primary producers, consumers, and decomposers). Since guidelines cannot incorporate all variables present in aquatic ecosystems, elucidation of the key aspects of water quality that contribute most strongly and sustainably to fundamental ecological features and processes must be targeted. This approach requires a thorough understanding of the habitat, underlying structure, and function of an ecosystem, as well as the nature and scope of interactions with external influences (Hart, Maher & Lawrence, 1999). This robust understanding is essential in the creation of achievable and measureable outcomes for water quality (Likens et al., 2009). However, such an understanding is rare, and in the absence of in-depth knowledge and appropriate management tools, water quality guidelines are generally based on physico-chemical indicators, single-species dose response assays, and broad water quality objectives. Reforming water quality guidelines and management tools to better reflect the complexity of aquatic ecosystems is therefore a key challenge in this domain.

Developing Water Quality Guidelines for Ecosystems

Water quality guidelines provide an objective means of determining the quality of water required for ecosystem protection and are the means by which scientifically based criteria values (e.g. chemical, radiological, microbial, and biological indicators) are transformed into a form utilizable by management bodies. Overall, creation of water quality guidelines must be guided by clear objectives and goals, underlined by an understanding that the management of water bodies as integrated ecosystems requires a holistic and long-term multidisciplinary approach (Hart, Maher & Lawrence, 1999; Likens et al., 2009).

Ideally, environmental values should have the approval and support of the community, wider region, and special interest groups, should align with sustainable directives both locally and on a national and international basis while considering the needs and obligations of upstream and downstream communities. The incorporation of regulatory approaches and market-based incentives are also necessary for the development of sustainable water quality management plans.

Acknowledgement of uncertainty in the guideline derivation and implementation process is essential. Maintaining awareness of uncertainty is a pragmatic approach and encourages continual improvement of management objectives and goals (ANZECC, 2000). It is also critical to note, however, that water quality criteria do not represent 'magic' numbers that, if achieved, will ensure sufficient protection and resilience of aquatic water bodies. Ecosystems, at their most basic level, are multi-faceted, complex, and constantly evolving; thus, management approaches must be flexible and adaptive when deriving and applying criteria.

In general, the development of water quality guidelines for aquatic ecosystems is important to effectively monitor and regulate anthropogenic impacts, as well as to help safeguard the overall health and functionality of these dynamic and complex systems.

6.2 Existing Water Quality Guidelines

6.2.1 International

UNEP **International Water Quality Guidelines for Ecosystems (IWQGES)**

It is increasingly recognized that international water quality guidelines for ecosystems are needed to guide water resource management initiatives and policies. The International Water Quality Guidelines for Ecosystems (IWQGES) project was first launched by UNEP during the 2013 Budapest Water Summit, as part of the UN-Water TPA on Water Quality. A final draft of the IWQGES was released in March 2016 for use in regional consultations.

The IWQGES are science-based, advisory guidelines developed with the purpose to assess and safeguard the health of freshwater ecosystems. The guidelines do not cover specific qualities, but focus on the processes of securing water of an acceptable quality for ecosystems within a specific socioecological system. The IWQGES were created to provide governments and other water management authorities with a framework to develop context-specific, national water quality guidelines for freshwater ecosystems (UNEP, 2016). The guidelines advocate an adaptive water quality assessment and management approach to ensure that policies and activities are continually revised and modified towards the achievement of set objectives (UNEP, 2016). The precautionary principle was applied in the development of the IWQGES to account for uncertainties in data and in our current understanding of ecosystem processes.

The proposed IWQGES modular approach shown in figure 13 consists of four phases subdivided into nine steps, with further subdivisions included for certain steps. The framework illustrates a cyclical step-by-step process which includes agreeing on a vision and setting objectives, assessing ecosystems, formulating guidelines, monitoring, reporting, evaluating successes and weaknesses, and identifying future management goals, before the cycle begins anew (UNEP, 2016). Specific action points to be completed to support the overall process are provided for each step. Further included in the IWQGES are various sets of physical, chemical, biological, and hydro-morphological indicators applicable to different freshwater ecosystem types, and methods to define context-appropriate water quality target and threshold values. The IWQGES are not legally enforceable at the international level; however, they can be tailored by local governments to create potentially binding standards applicable within their respective jurisdictions.

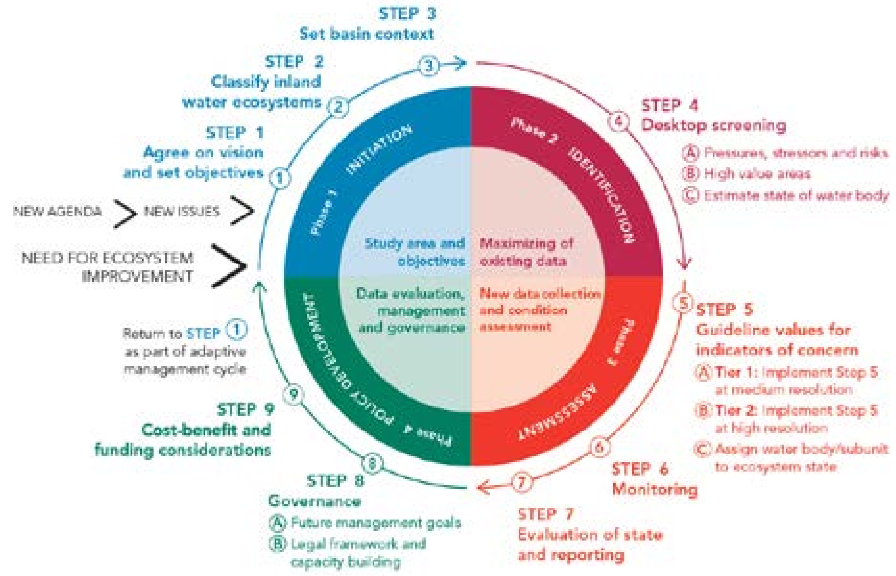
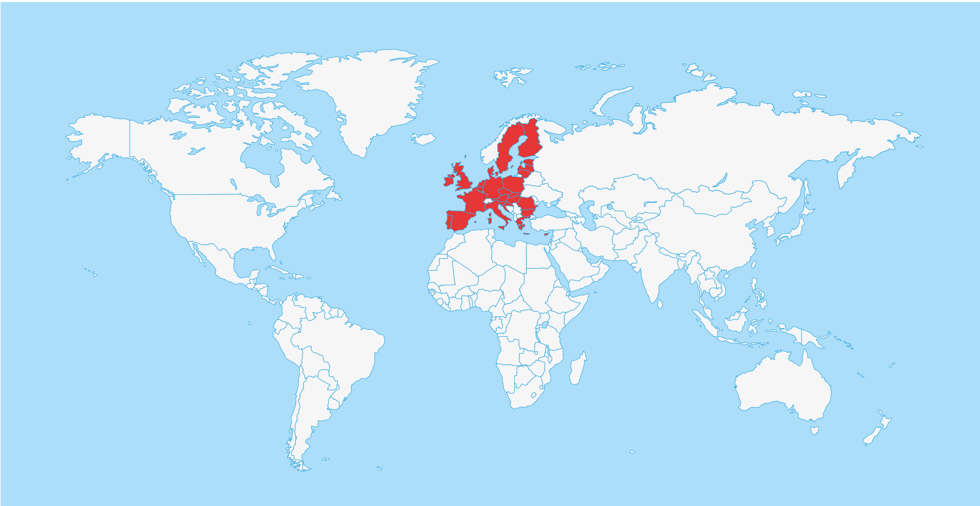


Figure 13: Overview of the 4 phases / 9 steps approach of IWQGES.Source: UNEP, 2016.

6.2.2 Regional

EUROPE



[Water Framework Directive (2000/60/EC)]

The introduction of the Water Framework Directive (WFD) in 2000 represents a substantial piece of regional environmental guidance and legislation and a shift in the approach to water management in Europe. This shift is from a traditional sectorial approach focused primarily on pollutants to a more holistic ecosystem based approach incorporating biological indicators as the primary criteria and management centered around river basins (Apitz et al., 2006, Hering et. al. 2010, European Commission, 2016).

The WFD, incorporating inland surface waters, transitional waters, coastal waters and groundwater, was established to protect and prevent deterioration of aquatic ecosystems, water bodies and associated terrestrial ecosystems and wetlands. Targets are developed specifically for the protection and enhancement of ecological status, with overall water quality status designated from five classification levels – high, good, moderate, poor and bad - defined according to the level of human disturbance imposed on water bodies and resulting judgment of ecological health. An overall aim to achieve 'good' ecological status for all waters by 2015, later adapted to 2027, has been set as a precedent to ensure sustainable and long-term protection. Good ecological status is defined as "the values of the biological quality elements for the surface water body type show low levels of distortion resulting from human activity but deviate only slightly from those normally associated with the surface water body type under undisturbed conditions" (European Commission, 2015).

The results of this high level guidance for European countries have been the increase in healthy aquatic ecosystems in certain places, and a standardisation of assessment and monitoring techniques for water quality across the continent. Since the introduction of the WFD, huge amounts of data were being collected on aquatic water bodies in Europe, however this data is not centrally stored or recorded, and so comprehensive region-wide assessments are difficult to conduct (Hering et al., 2010). Furthermore, the goal of achieving good ecological status in all ecological water bodies in Europe by 2027 has been acknowledged as over-ambitious, hence the date has already been pushed forward from 2015. As of 2017, more than half of EU water bodies still have not reached a 'good' level of ecological status (European Commission, 2015). Some researchers have assessed that the WFD was not able to meet its potential and objectives because of a misunderstanding by member states as to the systems based approach that the WFD is grounded in, and a focus on the symptoms rather than the cause of poor water quality (Vouvoulis et al., 2017).

6.2.3 National

Case studies for Australia, New Zealand, Canada and South Africa are outlined and reviewed below. These represent key national examples with well-established water quality guidelines centered on the specific intention to safeguard aquatic ecosystems.

AUSTRALIA AND NEW ZEALAND

Australian and New Zealand Guidelines for Fresh and Marine Water Quality

Over the past 200 years, aquatic ecosystems in Australia and New Zealand have been subject to profound changes and degradation as a result of increased human settlement and activities. This has contributed to the continuous deterioration of water qualities nationally, in some cases, to levels below those thought necessary to maintain the ecological health of aquatic ecosystems.

To address this, the National Water Quality Management Strategy (NWQMS) was first developed in 1992 by the Agriculture and Resource Management Council of Australia and New Zealand and the Australian and New Zealand Environment and Conservation Council, with the aim to improve water resource qualities throughout Australia and New Zealand. The NWQMS is divided into three sections – policies, processes, and guidelines – which together provide a framework for water quality management at the national level. Included in the Water Quality Guidelines section are the Australian and New Zealand Guidelines for Fresh and Marine Water Quality.

First released in 1992 for only Australia, the Australian and New Zealand Guidelines for Fresh and Marine Water Quality was later revised and updated in 2000 to incorporate New Zealand's water resources, and to reflect current scientific findings and national and international water management trends. These guidelines were created and revised based on the philosophy of ecologically sustainable development set out in the Australian National Strategy for Sustainable Development and in the New Zealand Resource Management Act, and have the specific objective to

> "provide an authoritative guide for setting water quality objectives required to sustain current, or likely future, environmental values for natural and semi-natural water resources in Australia and New Zealand" (ANZECC & ARMCANZ, 2000).

Box 12: Lessons from the Australian Guidelines

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To illustrate the nation's progress in improving water qualities at the national, regional, and local scales through the use of these guidelines, the Australian Government compiled twelve case studies for different regions. A reoccurring lesson learned in many of the case studies presented is the importance of identifying and engaging relevant stakeholders and interested community members at early stages of the project implementation process. This is pivotal to improving water quality and ecosystem health as it enhances transparency at an early stage of the project, promotes trust-building through effective communication (of knowledge, successes, challenges, setbacks, and experiences), and facilitates the sharing of resources (Australian Government, 2012). Moreover, it enables water authorities to identify environmental values based on local needs, preferences, and aspirations, and subsequently, to develop relevant, locally-adapted water quality objectives.

Another key lesson learned is the importance of using an adaptive management approach in improving water resource quality and ecosystem health. Adaptive management is integral to the NWQMS as it enables water authorities to adjust their approach to water quality and ecosystem management over time, in light of recent discoveries, monitoring results, or obstacles (Australian Government, 2012). Related to this is an increased need to improve and expand the current knowledge base and understanding of water resources, to better inform and improve water quality planning and decision-making processes (Australian Government, 2012). Thus, more research is required to better understand how ecosystems are affected or influenced by water quality. Finally, most of the case studies reiterate how the realization of significant improvements in water resource quality and ecosystem health is a long-term process. As such, the implementation of monitoring programs is critical to maintain long-term stakeholder engagement, and regular reporting intervals are necessary to effectively document issues, improvements, and progress made in achieving these long-term goals.

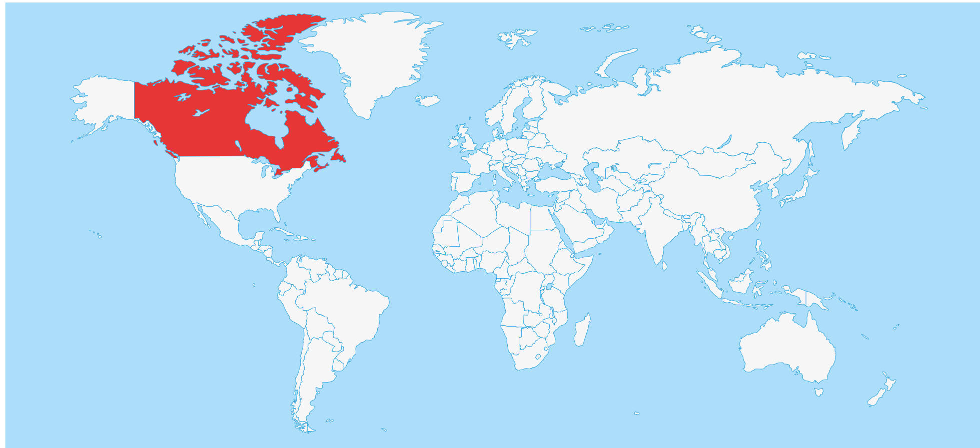
They were updated again more recently in 2018 to reflect up-to-date scientific information and methodology. The guidelines provide governments and other water authorities in the two countries with a set of regulatory tools to better assess and manage ambient water qualities in various national waterways. In order to accomplish this, the guidelines consider the protection of six diverse ecosystem types – upland rivers, lowland rivers, freshwater lakes and reservoirs, wetlands, estuaries, and coastal and marine – and account for various factors that could influence the effects of diverse contaminants.

The *Australian and New Zealand Guidelines for Fresh and Marine Water Quality* primarily advocate an ecosystem-based, issue-based, and risk-based approach to water quality management, rather than the management of individual parameters. They provide various physico-chemical stressors and biological indicator values to monitor and enhance water and sediment qualities as well as ensure adequate protection of Australia and New Zealand's freshwater and marine aquatic ecosystems. It is recommended that these guidelines be viewed as trigger values[1] to be refined into regional, local or site-specific objectives, depending on the internal and external factors affecting the ecosystem. Finally, the guidelines also provide advice on how to effectively develop and establish water quality monitoring and assessment programs, necessary to measure the progress made relative to set water quality objectives.

Due to significant complexities and uncertainties associated with the development of national water quality guidelines for diverse aquatic ecosystems, the Australian and New Zealand Guidelines for Fresh and Marine Water Quality are not mandatory and therefore not legally enforceable at the national scale.

Since the development of the National Water Quality Management Strategy in 1992 and the subsequent revision of the Australian and New Zealand Guidelines for Fresh and Marine Water Quality in 2000, there have been a number of significant changes and advances in the way Australia and New Zealand manage their water resources. Box 12 outlines some of the changes and lessons learned from case studies in the region. Specifically, an increased number of policy initiatives at the federal and state levels have shifted or narrowed their focus towards the ecologically sustainable management of water resources. The development of a Water Reform Framework, the introduction of State of the Environment reporting, and the revision and implementation of the New Zealand Resource Management Act, are a few examples that depict this shift in focus (Australian Government, 2012). In addition, an increased trend in favour of a more holistic approach to the management of water resources and related aquatic ecosystems has also been observed since the introduction of the national water quality guidelines (Australian Government, 2012).

CANADA



Canadian Environmental Quality Guidelines

Canada was the first country to collaboratively develop national, science-based environmental quality guidelines amongst provincial, territorial, and federal jurisdictions. The Canadian Water Quality Guidelines, first implemented by the Canadian Council of Resource and Environment Ministers (CCREM) in 1987, initially encompassed the protection of freshwater biota, raw water for drinking water supplies, agricultural water uses for irrigation and livestock, recreational

1. Trigger values represent concentration levels that, if exceeded, indicate a potential environmental problem, which therefore 'trigger' a management response.

water quality and aesthetics, and industrial water supplies (CCREM, 1987). They were designed to provide water management authorities with basic scientific information concerning the effects of water quality on different water uses, to better assess water quality issues and to facilitate the development of site-specific water quality objectives (CCREM, 1987).

To address growing concerns regarding human-caused and emerging threats to ecosystem health and integrity, these guidelines subsequently evolved in 1999 to encompass the protection of aquatic, terrestrial, and atmospheric resources such as air quality, marine water quality, wildlife tissue quality, marine and freshwater sediment quality, and soil quality for various land use changes (CCME, 2001a). The result of this evolution is the Canadian Environmental Quality Guidelines (CEQG); internationally endorsed, science-based goals developed to enhance the quality of Canada's aquatic, terrestrial, and atmospheric ecosystems (CCME, 2001a). They provide recommended limits for qualitative and quantitative disturbance and contamination levels, which if respected, should minimize risk to biota, their functions, and the interactions necessary to sustain and protect the health of Canadian ecosystems, as well as the many services they provide (CCME, 2001a).

Although the CEQGs are not legally enforceable at the national scale, they do support several national and international legislation acts, agreements, and conventions. Moreover, the CEQGs form the scientific basis for the development of environmental quality standards (enforceable by law) in Canada's provincial and territorial jurisdictions.

At the federal level, the CEQGs support various legislative acts, including the Canadian Environmental Protection Act established in 1999. This act recognizes that environmental protection is essential for human health and well-being, and aims to "contribute to sustainable development through pollution prevention" (Government of Canada, 1999). The CEQGs also support international conventions like the Great Lakes Water Quality Agreement, adopted by Canada and the United States in 2012, and the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, adopted in 1972 (CCME, 2001a). Finally, the CEQGs have been widely endorsed at the international level by the United Nations and the World Health Organization.

Canadian Water Quality Guidelines for the Protection of Aquatic Life

The Canadian Water Quality Guidelines for the Protection of Aquatic Life (CWQG-PAL) were established in 1999 as a chapter of the Canadian Environmental Quality Guidelines. These revised water quality guidelines were prepared by the Canadian Council of Ministers of the Environment (CCME) to protect marine and freshwater biota from anthropogenic stressors such as chemical inputs or physical alterations to aquatic ecosystems (CCME, 1999).

The CWQG-PAL provide numerical limits or narrative statements for various water quality parameters based on the most up-to-date, scientifically defensible physical or toxicological data (CCME, 1999). All fresh and marine water quality guidelines for the protection of aquatic life in Canada are compiled in an interactive summary table, see Table 15, available on the CCME website. The goal of these recommended values is to ensure the protection of all aquatic life forms, including all aspects or stages of aquatic life cycles over the long-term (CCME, 1999). However, as Table 15 shows, there is still insufficient data and information for many chemicals in aquatic environments, and updates on the summary table are needed. In short, the CWQG-PAL provide the national benchmark for a consistent level of protection for aquatic ecosystems across Canada.

Developing a Global Compendium on Water Quality Guidelines
Ecological Water Quality Guidelines

Table 15: A portion of chemical summary tables under the CWQG-PAL, showing the recommended short and long term concentration levels in both freshwater and marine environments for a range of chemicals. Source: CCME, 1999.

Water Quality Guidelines for the Protection of Aquatic Life							
		Freshwater			Marine		
		Concentration (µg/L)	Concentration (µg/L)	Date	Concentration (µg/L)	Concentration (µg/L)	Date
Chemical name	Chemical groups	Short Term	Long Term		Short Term	Long Term	
1,1,1-Trichloroethane CASRN 71556	Organic Halogenated aliphatic coumpounds Chlorinated ethanes	No data	Insufficient data	1991	No data	Insufficient data	1991
1,1,2,2- Tetrachloroethene PCE (Tetrachoroethylene) CASRN 127184	Organic Halogenated aliphatic compounds Chlorinated ethenes	No data	110	1993	No Data	Insufficient data	1993
1,1,2,2-Tetrachlorethane CASRN 79345	Organic Halogenated aliphatic coumpounds Chlorinated ethanes	No data	Insufficient data	1991	No data	Insufficient data	1991
1,1,2-Trichloroethene TCE (Tricloroethylene) CASRN 79-01-6	Organic Halogenated aliphatic compounds Chlorinated ethenes	No data	21	1991	No data	Insufficient data	1991
1,2,3,4-Tetrachlorobenzene CASRN 634662	Organic Halogenated aliphatic compounds Chlorinated benzenes	No data	1.8	1997	No data	Insufficient data	1997
1,2,3,5-Tetrachlorobenzene	Organic Halogenated aliphatic compounds Chlorinated benzenes	Na data	Insufficient data	1997	No data	Insufficient data	1997
1,2,3-Trichchlorobenzene CASRN 87616	Organic Halogenated aliphatic compounds Chlorinated benzenes	No data	8	1997	No data	Insufficient data	1997

The CWQG-PAL chapter of the CEQGs consists of an introductory document describing the origin, purpose, and content of the CWQG-PAL, followed by 87 guideline factsheets for the various physical (e.g. salinity, temperature, pH, etc.) and chemical (e.g. heavy metals, hydrocarbons, pesticides, etc.) water quality stressors applicable to Canadian aquatic environments. These factsheets are a critical component of the CWQG-PAL as they provide water quality managers and other users with key scientific information for targeted physical and chemical stressors, a summary of the water quality guideline derivation process, and the rationale for each guideline value published (CCME, 1999). Species-specific information is also included in the factsheets and addressed in greater detail in supporting documents (CCME, 1999). Furthermore, CWQG-PAL includes a manual for site-specific applications of the CWQG-PAL. This manual identifies the approaches, procedures and recommended methods for deriving site-specific water quality guidelines in Canada, as well as the tools and evaluation criteria necessary for developing water quality objectives (CCME, 2003). Lastly, the manual features a case study on the derivation of water quality objectives for zinc in the South McQuesten River Basin in the Yukon.

Another interesting component of the CWQG-PAL chapter is the 2007 Protocol for the Derivation of Water Quality Guidelines for the Protection of Aquatic Life. Part I of the Protocol provides a general overview of the water quality guideline derivation process; the CCME guiding principles and the guideline derivation steps. Part II of the Protocol focuses on the methodological details of the guideline derivation process, sub-divided into three sections (CCME, 2007):

1. The general approach for appropriate data collection, the data evaluation and categorization process, the exposure periods, and the minimum data set requirements (CCME, 2007); the minimum data set requirements for the derivation of short- and long-term exposure guidelines for freshwater and marine environments are summarized in the form of detailed tables.
2. Discussion on the importance of incorporating exposure and toxicity-modifying factors into the guideline derivation process, where applicable.
3. The various water quality guideline derivation processes, depending on the quantity and quality of toxicological data available.

The CCME Water Quality Index is the final component of the CWQG-PAL and consists of a water quality index calculator through an Excel macro, user's manual, and technical report (CCME, 2001b). The CCME Water Quality Index was created based on a formula developed by the British Columbia Ministry of Environment, Lands and Parks, and subsequently revised by Alberta Environment and Parks; it is a simplification tool used in water quality data reporting. The Index calculation is shown in Figure 14 and consists of three elements:

1. F_1*: Scope*, referring to the number of variables whose objectives are not met;
2. F_2 *Frequency*, referring to the number of times these objectives are not met;
3. *F3: Amplitude,* referring to the amount by which the objectives are not met.

$$CCMEWQI = 100 - \left(\frac{\sqrt{F_1^2 + F_2^2 + F_3^2}}{1.732} \right)$$

Figure 14: The CCME Water Quality Index equation, with separate calculations for F_1, F_2, and F_3 not shown here. Source; CCME, 2001b.

Application of the Water Quality Index should yield a number between 0 (worst water quality) and 100 (best water quality) and these numbers can be categorized into five descriptive water quality categories, ranging from poor to excellent (CCME, 2001b). All information related to the application and calculation of the Water Quality Index is included in the user's manual which also provides an example calculation.

Following the implementation of the Canadian Water Quality Guidelines for the Protection of Aquatic Life in 1999, the CCME subsequently endorsed the Canada-wide strategic vision for water in October 2009, entitled Setting Strategic Directions for Water. This vision provides a strategic framework to guide CCME in future water-related actions, activities and decision-making processes, to help ensure that all "Canadians have access to clean, safe, and sufficient water to meet their needs in ways that also maintain the integrity of ecosystems" (CCME, 2010). The framework outlines five goals to be achieved under this vision, and the first goal states "aquatic ecosystems are protected on a sustainable watershed basis" (CCME, 2010). This goal lends support to the CWQG-PAL, which aim to protect aquatic life in Canada.

SOUTH AFRICA

South African Water Quality Guidelines for Aquatic Ecosystems

The 1996 South African Water Quality Guidelines (SAWQG) serve as the nation's overall guidance on water quality for all uses and as a common basis for the development of Resource Water Quality Objectives under the National Water Act (NWA). Volume 7 of these guidelines, entitled South African Water Quality Guidelines for Aquatic Ecosystems, specifically addresses the water quality requirements of aquatic ecosystems with the aim of safeguarding freshwater ecosystems in South Africa (DWAF, 1996). The guidelines are meant to serve as the primary source of reference information and decision support required for the management and protection of aquatic ecosystems. USA Quality Criteria (USEPA 1986), Australian and New Zealand Water Quality Guidelines, and Canadian Water Quality Guidelines were used as background and supplementary information in the development of South Africa's guidelines (DWAF, 1996). USEPA databases (ASTER and AQUIRE) were also used extensively in the development of numerical criteria for toxic substances.

The South Africa Department of Water Affairs and Forestry (DWAF) took a precautionary approach in the development of guidelines, recognizing that there is often significant uncertainty and complexity associated with water quality criteria for aquatic ecosystems, because the criteria are often derived from known effects on a very limited number of aquatic organisms. DWAF instead designed guidelines to protect the most sensitive species in each trophic group. Constituents covered by the guidelines include toxic constituents, which cover inorganic metals (mercury, cadmium, arsenic, lead, etc.) and organic constituents (atrazine, endosulfan and phenol); system variables, which cover temperature, pH, DO and TSS; non-toxic inorganic constituents, which covers TDS and nutrients. For each constituent, the guidelines include background information (introduction, occurrence, interactions, measurement, data interpretation), effects and criteria (norms, effects, criteria, modifications) and sources of information. The guidelines also establish the Target Water Quality Range, which defines the fitness of water for particular uses and acts as a management objective that describes conditions that should ensure the protection of aquatic ecosystems (DWA, 2011). As a matter of policy, the DWAF indicates that it will strive to meet the Target Water Quality Range to sustain water resources.

The guidelines are significant in that they are an implementation and guiding tool of South Africa's 1998 National Water Act (NWA), which has been recognized as one of the most progressive pieces of water legislation among the international community, in part, due to its translation of Integrated Water Resources Management (IWRM) into practice (Schreiner, 2013). The NWA mandates the establishment of a national aquatic ecosystem health monitoring system as well as the establishment of an ecological Reserve, ensuring there is enough water of an adequate quality to preserve aquatic ecosystem services (DWA, 2011). For aquatic ecosystems, the NWA is significant in that it mandates that water is reserved for the environment, prior to being allocated for other uses. Fundamentally, the act defines a Water Resource as an ecosystem, so protecting water resources means leaving enough water of an adequate quality to preserve ecological functions in aquatic ecosystems.

Despite the fact that the NWA was recognized as one of the most progressive pieces of legislation by the international water community, implementation has been only partially successful at best (Schreiner, 2013). Schreiner (2013), who worked within the DWAF from 2003-2007, outlines how many of the ways in which implementation has been less than optimal. Water quality data also suggests that the implementation of the NWA hasn't lived up to expectations. The Department of Water Affairs (DWA), which was formerly part of the DWAF and is now known as the Department of Water and Sanitation, conducted a planning level review of water quality in 2011 to help support sustainable use and the integrity of aquatic ecosystems. Only 29% of sites monitored complied with prescribed RWQO ranges for nutrients, so eutrophication is a major threat for aquatic ecosystems (DWA, 2011). DWA suggests that an effective enforcement body is needed to deal with water pollution incidents, as even when deteriorations in water quality are recorded, actions are currently not taken against polluters.

6.3 Discussion

Biophysical conditions and human activities have increased the rate of change to aquatic ecosystems, altering water quality and thus disturbing species and ecosystem balance and functions. In order to prevent substantial damage to these environments, governments and industries must consider the water quality required to meet ecological needs when setting the rules and conditions for allowing emission of effluent or other compounds into natural water systems.

Water quality guidelines for aquatic ecosystems are necessary to define water management objectives according to ecosystem values and use, and to help water management authorities select appropriate criteria to measure progress toward these predetermined water quality objectives. The examples provided in this review, from UNEP, the EU, Australia, New Zealand, Canada and South Africa, showcase good starting points for guiding documents to protect ecosystem water use, however most of the national guidelines are outdated and should be updated to account for new scientific findings and methods.

Water allocation and the management of environmental flows within freshwater systems is an important consideration in integrated river basin management plans and, as a management approach, contributes to water quality values within a catchment. The current scope of work focuses predominantly on administering flows according to the requirements of physical environment and habitats. Considerable scope exists for better integration of water quality considerations, an essential component of environmental flows for ecosystems.

To measure risk, guidelines should provide sets of physical and chemical stressors covering nutrients, organic matter, dissolved oxygen, turbidity, suspended particulate matter, temperature, salinity, pH and changes in flow regime. The guidelines should also incorporate sediment quality and maximum stressor indicators for various toxicants (heavy metals, organic alcohols, pesticides, herbicides, fungicides, etc.). Most of these components are guided

through indicator levels as well as descriptions of the process for managing water quality in the showcased examples in this chapter.

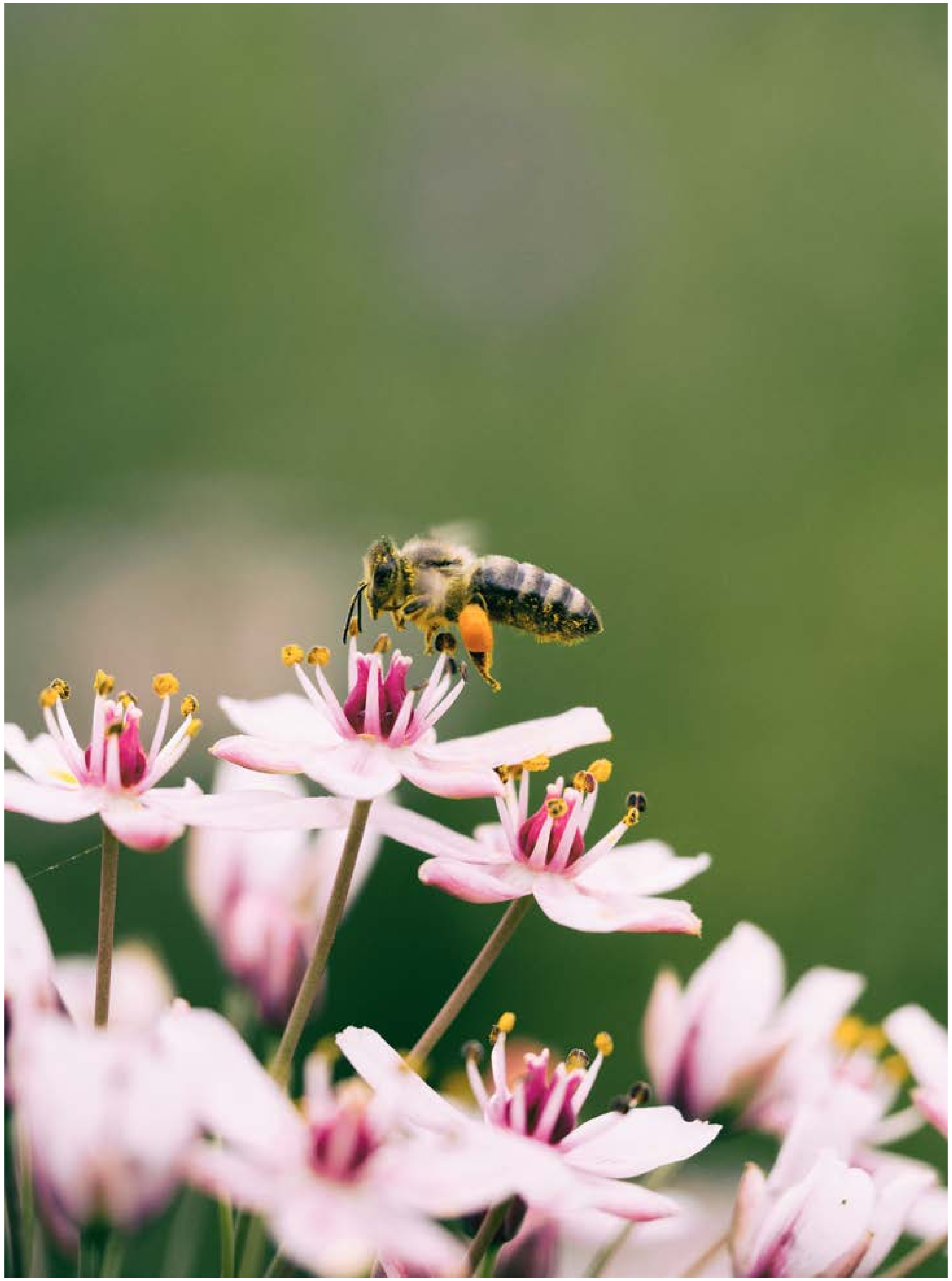
It is increasingly recognized that an integrated, more holistic approach to water quality management in aquatic ecosystems is necessary to effectively account for their inherent complexities and dynamic natures. Current water quality guidelines relevant to aquatic ecosystems are largely limited to physico-chemical indicators, single-species dose response assays, and broad water quality objectives. Expansion of biological indicators and the incorporation of concepts such as community effects and measures of ecosystem integrity are essential to enhance the protection and resilience of aquatic ecosystems moving forward (Hart, Maher & Lawrence, 1999). Guidelines such as the *Australian and New Zealand Guidelines for Fresh and Marine Water Quality* use such biological indicators covering species richness, abundance, distribution, and community composition. However, techniques for monitoring water quality for ecosystems that attempt to capture ecosystem health or biotic integrity, rather than just measuring chemical or physical parameters tend to be relatively time consuming to implement. This may make it difficult or infeasible to monitor broadly across a landscape

Ecosystems can vary significantly across space and time, so it is important to consider local conditions during the implementation of any guideline, be it international or national. Water quality standards for indicator stressors and management processes for ecosystems may need to be established on a very local scale, while remaining flexible to changes that occur in these ecosystems over time. Considering that not all local institutions have the time or funding to acquire the needed ecological data for developing policies sensitive to the changing needs of aquatic ecosystems, larger institutions are more likely to be involved with the development of policies. The development of site-specific criteria, objectives, or standards is both recommended and highly encouraged within each of Canada's various provincial and territorial jurisdictions through the *Canadian Water Quality Guidelines for the Protection of Aquatic Life*. This should also be applied to all guidelines that cover large geographical regions.

There are several challenges associated with ecological water quality. First, there are often economic constraints and a lack of incentives for performing water quality monitoring and maintenance, especially in poor or developing regions. It is difficult to economically value the importance of ecological water quality and can be viewed as less important compared to human water uses, especially where social needs compete with environmental needs. For example, in places with inadequate sanitation, communities may rely upon rivers for sewage disposal despite the impairment of aquatic ecosystems. Reconciling social and environmental needs will likely be particularly challenging in the developing world, where the needs of ecosystems will be considered secondary to meeting the basic human needs of impoverished populations with economic constraints.

Where legislation or guidelines exist for ecological water quality, it may be difficult to legally enforce associated laws and policies. Given the complexity associated with ecosystems, establishing causality between a decline in water quality and the decline of a species or altered ecosystem structure and function is often not straightforward. Further to this issue, transboundary aquatic ecosystems may be particularly vulnerable if water quality standards for ecosystem uses are not as rigorous within all jurisdictions.

Finally, we still have an incomplete understanding of the relationship between water quality and ecosystem health. Ecosystems do not always respond in predictable ways to changes in water quality, so more research is needed to better understand the subtle ways that water quality can impact ecosystem structure and function. Further, this relationship will likely vary from place to place.



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CHAPTER 7

Proposal for an Online Compendium

The first part of the report outlined a selection of water quality guidelines according to water use; however it is acknowledged that there are many more available guidelines and regulatory frameworks for directing management behaviour according to water quality. Furthermore, the printed version of this report is by definition static and limited in scope. Following on from this report, and in order to increase its impact, an online compilation of the provided material, as well as a more comprehensive list or database of similar guidelines should be created. This would provide a more dynamic and larger version of the information as well as a more complete picture of the water quality guidelines available at national, regional and international scales. The full compendium would include regulations as an additional category of content. The format used in this report, providing background information on specific water uses, showcasing relevant examples and then conducting a short analysis, is recommended for a future comprehensive compendium of water quality guidelines and regulations.

It is proposed that this information be stored and available on an online website, in a format that is user-friendly, easily accessible and easily updated as new guidelines emerge. The added benefit of an online compendium is the facility of access of information and analysis. This will contribute to increased availability and sharing of data and tools, which in turn can help lead to sustainable development.

There are several recent examples of such databases, including the AQUACROSS Information Platform released in July 2018 by the Intergovernmental Oceanographic Commission of UNESCO. This platform acts as a central access point for all information related to aquatic ecosystems, biodiversity and related management (Wahlen, 2018). Information platforms such as the AQUACROSS Platform and the proposed online compendium of water quality guidelines, contribute to increased access and sharing of data and tools, which in turn helps lead to sustainable development.

While there are several possible ways of creating and structuring an online database, the proposal outlined here has been identified by IWRA as a structure that would be able to meet the outcomes set for easy information retrieval for water quality guidelines and regulatory frameworks.

Objective

The overall objective of the online compendium is to determine and review the current existence and scope of water quality guidelines and regulations according to uses. The compendium should build on this report and the 2015 UN-Water IWA *Compendium of Water Quality Frameworks*. Specifically, the compendium's content should include water quality guidelines, regulations and methods (tools and mechanisms) of implementation in reference to at least the five main categories of water use from this report: domestic, agriculture, industry, energy and ecosystems.

The users of this compendium would be national and international organisations working on water quality issues who wish to support water management decision/policy-makers and regulators in both the public and private spheres. This includes those who manage water in primary and secondary industries, as well as those monitoring and regulating drinking water and environmental water. A wider user groups would be academia and water law, which may also find this compendium useful, as well as students who wish to learn more on the subject of water quality guidelines that are fit for purpose.

The compendium should be hosted on the internet, as this is the main means of dispersing information and communicating at an international, broad level. This is strategic to reach the target audience. To do so, the information outlined above, otherwise known as 'content', needs to be managed on webpages that have access for multiple collaborators to create and edit digital content. Such a digital environment is referred to as a content management system (CMS). The aims of the CMS are to:

- **promote the compendium,**
- **provide an effective searchable interface;**
- **facilitate broad access to water quality management guidelines and methods;**
- **provide users with pertinent information, links, documents, activities, publications, and other related issues;**
- **provide a forum for user interactions between administrative personnel and other users.**

Functions

Key considerations for the proposed database development and structure are presented here, to guide and assist its development. For sufficient functionality of the online database, there are several recommended best practices outlined below.

As a minimum functionality, the online database of water quality guidelines and regulatory frameworks should include an appropriate, current and comprehensive content base of guidelines and regulations covering each water use sector, and a broad range of geographical regions. Further to listing the guidelines and regulations themselves, there should be a brief summary of each document as well as sector analysis, such as the example key findings and recommendations given in this report. Figure 15 displays all of the potential components that could be added to such an online compendium of water quality guidelines and regulations.

Additional functions of the online compendium would be to hold reference documents. The system should give direct access to a summary of reference documents on water quality and use, in easy to find locations. One such reference to be included is a glossary of related terms and abbreviations to enable full comprehension for users. Beyond the minimum functional requirements, useful tools to be included in the online compendium are a discussion forum for users and administration/experts as well as access to the latest news and events in the field. An electronic message board would facilitate ongoing conversations on the topic between users, while also hosting a space for direct communication between administrators and users. This space would allow users to share additional material for the mangers of the system to consider for incorporation. This would act to create an online community and go-to-place for all water quality guidance. While not all necessary, these components would add further value to the compendium.

Key functional requirements for the structure of the public interface include:

- **convenient search tools to find the content needed,**
- **a responsive website (display adapts to different supports: screens, mobile phones),**
- **various paths to obtain data from the system.**

As shown in Figure 16, there are various paths that can lead the user to the water quality information they are seeking, and thus data can be accessed through multiple search requests. The foremost input request is through water use type using the five categories from this report, but building on this to include others such as recreational water use and with main uses delineated into sub-uses for a more precise result. Other input requests include water source (well, deep well, tap water, groundwater, etc.), water quality, organisation or institution, or geography. The drivers or influences on water quality and guidelines, such as economic and technical considerations, could be another search category. Applicable data lists are displayed and can be searched through each of these categories and input criterion can also be crossed to other criterion.

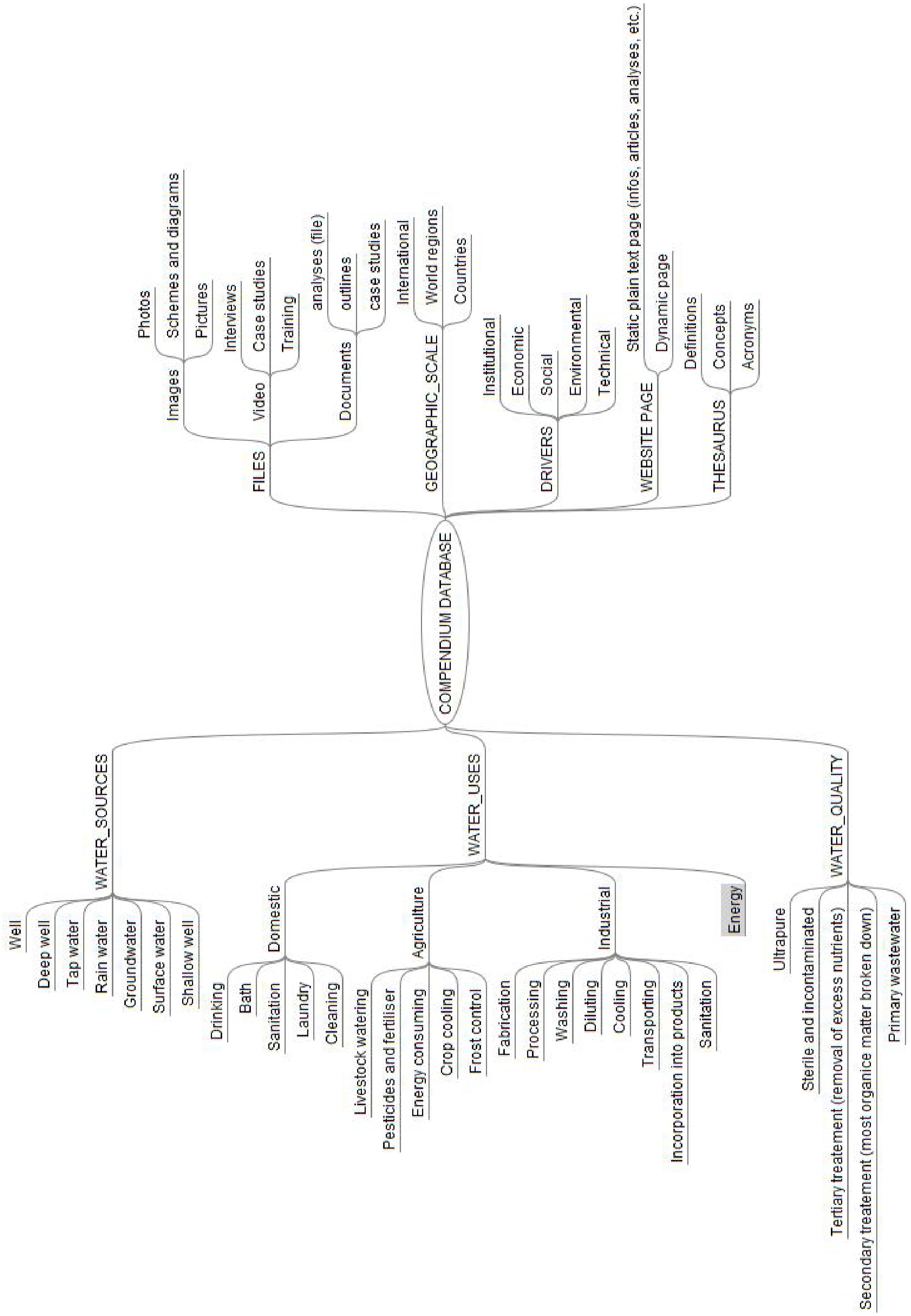

Figure 15: The elements of the proposed online compendium database.

Developing a Global Compendium
on Water Quality Guidelines

Proposal for an Online Compendium

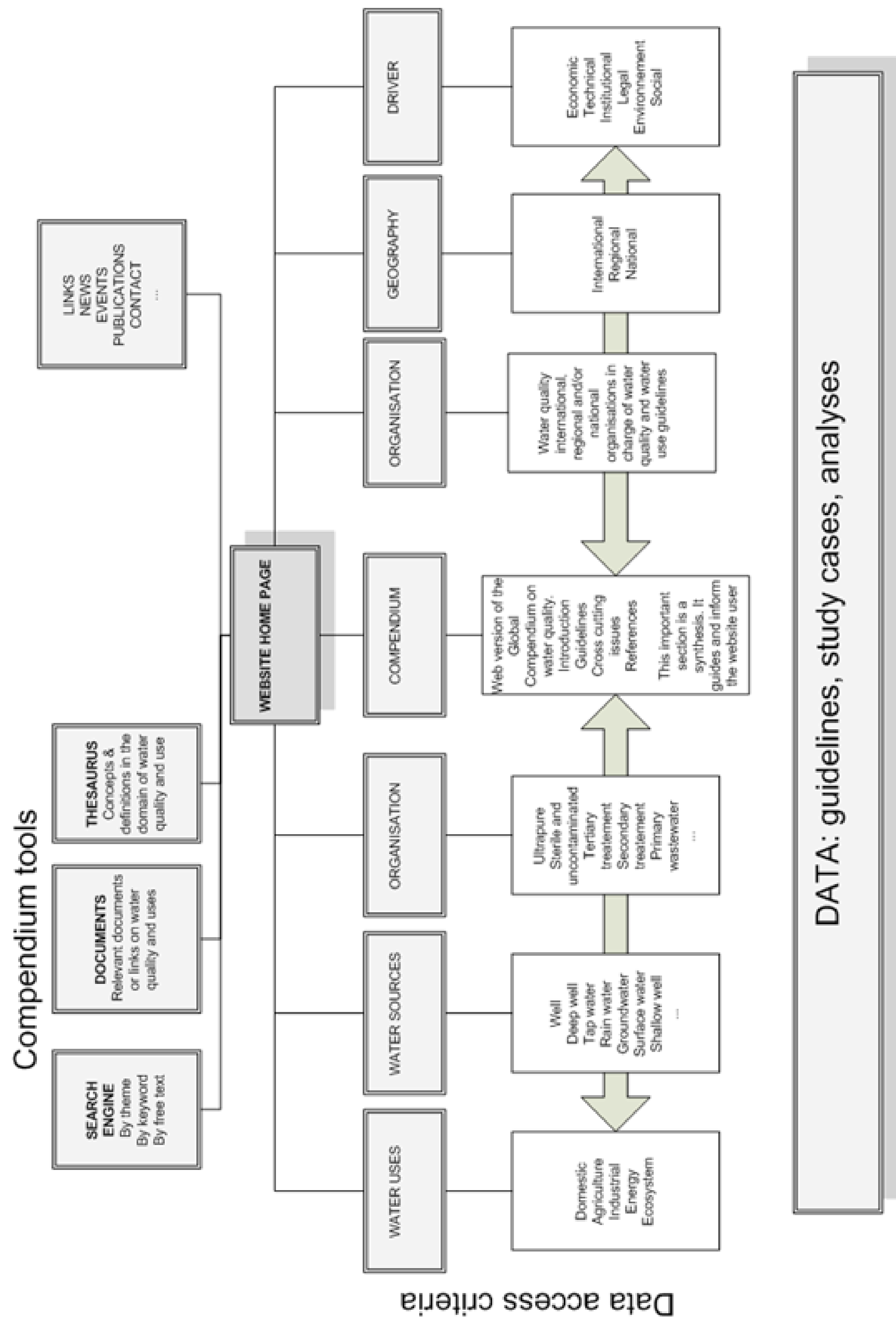

Figure 16: Proposed database structure for an online compendium of water quality guidelines and regulations.

In order to allow continual updates and maintenance of the online compendium, there needs to be a sufficient content management/administrative interface. This interface allows the content manager to edit data and enter new data after an authorised identification login. A full list of potential abilities for the manager include modifying, adding or deleting the content from any page of the website as necessary, manually creating and editing plain text pages or special pages with specific functionalities, managing user accounts, sending emails, producing reports, and checking information.

Challenges

One must acknowledge key challenges that should be addressed in order to overcome potential limitations to an online database. First, funding arrangements need to be made for the creation and upkeep of the proposed database. These costs need to cover a web developer to create the website, a project officer to compile and write the information as well as basic editing and oversight to ensure data is correct. It is important to also recognise the long-term costs of maintaining a living document, rather than only the start-up costs. The funding could come from the public or private sector grants or from users of the database through subscription.

Proper maintenance is essential for any database to remain relevant and classified as a "living document". As such, it is recommended that the database be managed on a regular basis (at least annually) through review of previous examples and hyperlinks to ensure they are still accurate and up-to-date, followed by scanning for new guidelines and regulations, and subsequently adding commentary and analysis. Using feedback from users to improve the online compendium is also advised.

Another challenge is ensuring the available compendium and analysis cover a broad linguistic scope and is accessible to a large number of people. This means having the data within the compendium cover more than the Anglophone region. While this report uses mostly guidelines in English, it is acknowledged that a full compendium of water quality guidelines and regulations should include regulations and guidance from other languages. This would add diversity and value to the database as there are lessons to be learned from all regions of the world but also increase the cost both of creating the website and maintaining it. A further linguistic consideration is in making the compendium available in more than one language to allow greater access to non-English speaking users.

CHAPTER 8

Discussion

CHAPTER 8
Discussion

This report focuses on scoping available water quality guidelines for different water uses. Such guidelines exist at international, regional (especially European Union) and national scales for domestic, agricultural, specific industries, energy production and ecosystems uses (see Table 16).

Table 16: The guidelines assessed in this report.

Scale	Name	Date	Location
DOMESTIC WATER QUALITY GUIDELINES			
International	WHO Guidelines for Drinking Water Quality (GDWQ) - fourth edition incorporating the first addendum	2017	All
International	Global Drinking Water Quality Index (GDWQI)	2007	All
International	RAIN Water Quality Guidelines: Guidelines and Practical Tools on Rainwater Quality	2008	All
Regional	EU Drinking Water Directive (with latest amendments)	2015	European Union
Regional	UNECE Protocol on Water and Health	2005	Europe
	Taking policy action to improve small-scale water supply and sanitation systems. Tools and good practices from the pan-European Region	2016	
	Guidelines on the Setting of Targets, Evaluation of Progress and Reporting	2010	
National	Guidelines for Canadian Drinking Water Quality (GCDWQ) (updated version)	2017	Canada
National	Code of Practice on Piped Drinking Water Sampling and Safety Plans	2008	Singapore
National	Australian Drinking Water Guidelines (ADWG)	2011	Australia
AGRICULTURAL WATER QUALITY GUIDELINES			
International	FAO Water Quality for Agriculture	1994	All
International	WHO-FAO Guidelines for the Safe Use of Wastewater, Excreta and Greywater Volume 2: Wastewater use in Agriculture	2006	All
International	ISO Guidelines for Treated Wastewater use for Irrigation Projects	2015	All
International	Codex Alimentarius Code of Hygiene Practice for Fresh Fruits and Vegetables	2003	All
National	Guidelines for Water Reuse	2012	U.S.A.
National	Canadian Water Quality Guidelines for the Protection of Agricultural Water Uses	1999	Canada
	Protocols for Deriving Water Quality Guidelines for the Protection of Agricultural Water Uses (Irrigation and Livestock Water)		
National	Guidelines on the Procedures and Technical Requirements for the Issuance of a Certification allowing the Safe Re-Use of Wastewater for Purposes of Irrigation and Other Agricultural Uses	2007	Philippines
INDUSTRIAL WATER QUALITY GUIDELINES			
International	WHO-FAO General Principles of Food Hygiene	2009	All
International	WHO Good Manufacturing Practices: Water for Pharmaceutical Use	2012	All
Regional	Water Quality Demands in Paper, Chemical, Food and Textile Companies	2010	EU
National	South African Water Quality Guidelines Volume 3	1996	South Africa
National	Canadian Water Quality Guidelines (Chapter 5)	1987	Canada
ENERGY WATER QUALITY GUIDELINES			
International	Efficient Water Management in Water Cooled Reactors	2012	All
National	Cooling Water Options for the New Generation of Nuclear Power Stations in the UK	2010	United Kingdom
ENVIRONMENTAL WATER QUALITY GUIDELINES			
International	UNEP International Water Quality Guidelines for Ecosystems (IWQGES)	2016	All
Regional	EU Water Framework Directive	2000	European Union
National	Australian and New Zealand Guidelines for Fresh and Marine Water Quality	2000	Australia, New Zealand
National	Canadian Water Quality Guidelines for the Protection of Aquatic Life (CWQG-PAL)	1999	Canada
National	South African Water Quality Guidelines for Aquatic Ecosystems	1996	South Africa

The following sections discuss the use of guidelines to direct water of different qualities to their most appropriate use; cross cutting issues that emerge from the review of these guidelines; innovative applications and management styles; and the limitations of this report.

8.1 Using Guidelines to Manage Water Quality

Water quality guidelines are a form of policy recommendations for water quality management, in contrast to binding regulations that often provide direct requirements on how to manage water quality monitoring or management processes. Guidelines are either non-binding or, as in the case of the EU *Water Framework Directive* which we include here as a guideline, they are binding but provide flexibility for the national legal frameworks regarding the means of meeting the objectives.

This report has showcased a range of different types of water quality guidelines. Indices such as the *Global Drinking Water Quality Index* are useful in reducing large amounts of data into a simple expression describing the quality compared to ideal or normal values, which is also easy to interpret for non-experts. While there may be little guidance on the procedures and processes for how to meet certain water quality levels, indices can be useful for forming broad judgments of water quality or when comparing and communicating water quality status across geographies and time.

Another form of water quality guidance needed to assist water users in reaching certain objectives such as a regulation is an implementation guideline, which describes recommended procedures and management. An example of this is the Philippine *Guidelines on the Procedures and Technical Requirements for the Issuance of a Certification allowing the Safe Re-Use of Wastewater for Purposes of Irrigation and Other Agricultural Uses*. Implementation guidelines are useful where legislation or technical guidelines are set for water quality, but it is unclear how water users can optimally meet the prescribed quality levels. While there is more incentive for users to read implementation guidelines when they are required to meet a regulation, it can also be helpful for encouraging users trying to minimize costs or waste water disposal costs.

The more common form of guideline recommended technical parameters for various chemicals and biological factors. *Volume 3: Industrial Use from the South African Water Quality Guidelines* provides recommendations for water quality levels for several chemical constituents such as chloride, iron, silica and total hardness. This is what is typically expected in traditional water quality guidelines or regulations, as it is indeed a key component of insuring the water is fit for a specific use and will not harm the intended user or damage equipment.

This report identifies several examples of comprehensive guidelines at international and national levels, such as the *WHO Guidelines for Drinking Water Quality (GDWQ) and the Canadian Environmental Quality Guidelines*. These guidelines demonstrate a mixture of the above forms of guidelines: indices, technical parameters, and implementation tools, using several overlapping documents. While these documents undoubtedly require the most effort to design, they are also the most beneficial for users who can find all necessary and useful information on the subject from one source.

Strengths & Weaknesses of Guidelines

As has been shown, there is a diversity of guideline structures, distinct from regulations, and any management structure needs to consider the use of tools on a scale from strict regulation to voluntary guidelines.

A distinct disadvantage of guidelines is that they are voluntary, and so can usually not be enforced on the target population. Hence, their recommendations or best practices may often not be implemented. Where there is very clear health or environmental risk to society, enforceable legislation is a better option, such as the *US Safe Drinking Water Act*.

While strict regulations, or command-and-control techniques, help guarantee defined results, they also require strong monitoring and enforcement to be completely effective. Traditional regulation can be costly to governments or other regulatory bodies, and can stifle potential innovation and force companies to act reactively, suffering adverse financial performance (Ramanathan et al., 2017). Guidelines, as presented in this report, offer an option to address the pitfalls of traditional regulatory frameworks. Looser regulations or guidelines allow for more options, innovation and choice of methods for how to achieve an objective. This is sometimes referred to as a target-based approach. Allowing for sufficient flexibility in guidelines and regulation improves innovation and productivity (Ramanathan et al., 2017).

On an international scale, guidelines such as the *WHO GDWQ* and *FAO Water Quality for Agriculture*, offer the best source of instruction for nations and water managers. The *WHO GDWQ* have provided a global baseline that has been adopted by most national and regional governing bodies. This approach also functions for federal countries like Canada and Australia, where national guidelines assist states or smaller localities in creating their own guidance or regulations relevant to their local context.

There are a couple of further benefits to the use of guidelines over regulations. Guidelines can be written and published by any organization or potentially even a knowledgeable individual in the field, not just the governing body of the country or region, offering diversity of voice. They are often the first type of guidance document for users when new technologies or sources of water are emerging, and regulations can later be built on preliminary guidelines. Additionally, guidelines are often more appropriate where there is unclear risk and/or it does not impact the public, such as input water quality in industrial settings.

8.2 Cross Cutting Issues

Current knowledge of water quality parameters is extensive; for example, the *Australian Drinking Water Guidelines* demonstrates considerable scope by incorporating more than 200 criteria. However, the body of knowledge remains largely incomplete in view of the extensive range of potential users that could benefit from using water of different qualities.

Measurement and determination of water quality is complicated by data gaps, primarily in regards to what is relevant to provide an adequate assessment of criteria for specific uses. Additionally, due to the large number of chemical, physical and biological variables contributing to water quality, assessments are often too expensive or incapable of providing a complete summary of overall water quality (UNEP, 2010). The type of data also presents challenges due to variance over time, geographical region, and according to contaminant characteristics (source, variability in residence time, potential impacts on humans and ecosystems). This complicates data collection, monitoring and application within guidelines and is a reason why many guidelines, particularly on an international scale, are presented simply as guidance. As with the *WHO's GDWQ*, it is stressed that criteria and objectives are presented merely as a guide and that objectives intended for direct implementation and regulatory purposes should be adapted according to local conditions and considerations (WHO, 2011).

Another threat to water supply for all purposes is climate change, which is anticipated to create shifts and variability in hydrological regimes that may have significant effects on water supply and quality. These effects are predicted to include changes in the seasonal timing of rainfall and snowpack melt, shift precipitation from less snow to more rain and produce a higher incidence of floods and droughts (OECD, 2008a). It is generally accepted that achieving water quality objectives will become more difficult with the effects of climate change, due in part to the unpredictability of extreme weather events and overall increase in temperatures and water scarcity (OECD, 2008b), which may necessitate shifts from rain-fed agriculture to irrigated agriculture. Possible adaptation strategies to the effects imposed by climate change on water quality include extension of water quality standards, discharge limits, wastewater charges, ecosystem-based approaches (e.g. installation, of riparian barriers, restoring/ protecting wetlands) and improved water treatment capabilities (OECD, 2013). However, overall, linkages between climate change and water qualities required for various uses are still not fully understood.

A recurring theme in this report is the use of recycled or reclaimed water to address water shortages. Water reuse offers an option for using lower quality water for other purposes, addressing the problems of wastewater disposal and water shortage. As described by Molle et al. (2012), a waste output from one use has the potential to be the input for another use. A multi-sectorial view and shift in thinking is required as wastewater is often treated to remove pollutants for adequate water quality to be released, rather than for the purpose of recycling for purposes such as irrigation. Further, the precautionary principle can make regulations for water reuse too constricting (Molle et al., 2012). It is important not to overlook the health dangers associated with improper use of wastewater in agricultural applications and guidelines can help protect land, animals and people from the risks of using untreated wastewater for irrigation and livestock. Once health risks are accounted for, guidelines on safe use can promote the widespread use of recycled wastewater and greywater rather than high-quality surface water and groundwater. While only volume 2 was explored in this report, the full four volume *WHO-FAO Guidelines for the Safe Use of Wastewater, Excreta and Greywater* offers an excellent resource for promoting the use of this resource in a responsible manner, particularly in agricultural settings. It is recommended to refine the quality of outflow from treatment facilities to match the needs of uses such as agriculture, industry, landscapes, recreational areas and sports grounds.

A limitation of most of the listed guidelines across all sectors is the omission of contaminants of emerging concern (CECs) such as pharmaceuticals and personal care product residuals. As these are an increasing component of domestic wastewater that can cause problems in the environment and to humans, further water quality guidance including these constituents is needed.

8.3 Multi-disciplinary Perspectives

Table 17 provides a comprehensive overview of considerations relevant to water quality from a multidisciplinary approach, including economic, technical, legal, institutional, environmental and social. These represent preliminary considerations and could be built upon as work on a comprehensive compendium of water quality guidelines is developed.

Table 17: Cross-cutting considerations and perspectives for the creation and maintenance of guidelines directing water quality for a specific purpose.

Sector	Consideration	Perspective
Economic	• Cost recovery and affordability	• Developing economies often lack expertise and resources to implement guidelines
	• Economic mechanisms	• Useful to determine future demand and supply
	• Investments in water supply and sanitation	• Net economic benefits for private organisations and government bodies with further effects to the public
	• Technology and infrastructure investments	• Investments can be prohibitive in some situations especially for large scale technology such as desalination
	• Cost savings from the use of natural infrastructure (e.g. Constructed wetlands)	• These savings are likely to outweigh rehabilitation costs in the long run and help improve surface water quality in a cost-effective way
	• Economic development leads to increased standards of living, increasing water demand	• Must be taken into consideration when projecting future demand, especially regarding developing countries
	• Costs related to disease burden of drinking unsafe water	• These often undocumented costs may outweigh implementation of drinking water and sanitation guidelines in long run
	• The pursuit of cost savings drives privately operated industries and farms	• These water users may need further incentives to use grey-water or wastewater. Governments could provide economic incentives through cost-sharing programmes or through providing technical assistance
	• Economic constraints in developing world	• These constraints may preclude maintaining environmental water quality such as monitoring and enforcement activities
	• Clustering industries to economise water treatment	•

Sector	Consideration	Perspective
Technical	• Source of water or its initial quality is important for dictating its use	• Major ramifications on level and cost of treatment required
	• Emergence of new pollutants such as certain pharmaceuticals	• Find new technology to detect and remove new pollutants however it will be difficult to determine impacts of each contaminant on aquatic ecosystems; impacts of some contaminants may be compounded over time and different species may have different thresholds of tolerance to these contaminants
	• Improvements in detection levels	• Need to uncover which contaminants are relevant for water quality per use (greater detection powers do not necessarily mean more criteria are needed)
	• Design and infrastructure associated with dual distribution system to enable the use of greywater in homes and businesses	• Should this be driven by public or private sector? What are the needs for guidelines (eg. greywater, rainwater)?
	• Development of new water treatment technologies and techniques	• Low-tech biologically based water treatment systems are developing that could enhance the ability of farmers to re-use water safely
	• Quality control and harmonization of sampling and analytical techniques	• Ensure data is comparable between regions and countries
	• Measuring sustainability and long-term resident pollutants	• Add a 'sustainability criterion' to guidelines to account for pollutants with long residence times that can accumulate in the environment (Jensen et al., 2001)
	• There is a great need for more and updated data on global wastewater (generation, treatment, components, use)	• A fuller data set would assist global wastewater use, improve assessments and contribute to more effective and targeted water quality guidelines (Sato et al., 2013)
	• Consequences of a lack of data	• Greater unknowns encourage the use of the precautionary principle, hence less water re-use implementation (Molle et al., 2012)
	• Bioassessments are an optimal technique to measure and track ecological health, biotic integrity	• Biological monitoring of ecosystems tend to be relatively time consuming and may make it difficult or infeasible to monitor broadly across a landscape
Legal	• Access to water as a human right (UNESCO, 2009)	• How does this alter the agenda moving forward?
	• There is power behind legal statutes in pushing progress	• Requirements or legally binding objectives, as opposed to just guidelines in criteria frameworks, greatly improve the chances of meeting that objective
	• Prohibitive laws can make it difficult to use alternative water sources	• Water re-use or rainwater may be regulated, limiting its potential use. Farmers may not have legal ability to use water from alternative sources (eg. Western U.S. states law states that all precipitation is owned by state or existing water right owner (NSCL, 2018))
	• Restrictions imposed by overzealous risk aversion	• Precautionary principle's role in prevention of wastewater reuse
	• Ability to legally enforce laws and policies associated with water quality for ecosystem uses	• Due to complexity of ecosystems, it is often difficult to establish causality between a decline in water quality and altered ecosystem structure and function

Sector	Consideration	Perspective
Institutional & Business	• Horizontal and vertical integration (data sharing, inter-ministerial and inter-agency committees, policy linkages)	• Vital in dissemination of information and efficiency, required for concerted effort to improve access to drinking water and reduce burden of disease
	• International cooperation is essential	• Transboundary nature of water resources dictates this requirement and underlines the need for thinking at larger scales, both geographically and politically
	• Lack of institutional awareness, especially in developing country settings	• Difficult to oversee safe and cross-sectoral water use
	• Repercussions of government inability to assist populations with adequate water quality management measures	• What happens when management is left to the responsibility of a community? What steps towards education and empowerment can be taken?
	• Expanding the role of private sector and public-private partnerships	• Decentralising and shifting components of financial infrastructure and maintenance can place burdens on private institutions
	• Potential reputational risk for food and beverage companies	• Unwilling to undertake reputational risk, companies may put blanket bans on wastewater use for food production
	• Different institutions utilize different methods for monitoring ecological water quality	• Methods may not always be directly comparable, which can present challenges in the development of guidelines and water quality standards
	• Not all local institutions have time or funding to acquire ecological data for developing policies sensitive to local aquatic ecosystems	• Larger institutions are more likely to be involved with developing ecological water policies, they will not consider specific local concerns
Environmental	• A major driver impacting the hydrological cycle and water quality are changes in land use associated with human settlement and development	• Deforestation & impervious surface of cities can lead to serious effects on downstream water quality and recharge of groundwater supplies
	• Importance of ecosystem services	• Essential for water cycling and purification
	• Input water to agriculture/industry will affect output quality flowing to the environment	• Use of low-tech applications such as riparian buffer strips, constructed wetlands to mitigate environmental impacts
	• Connectivity of aquatic ecosystems, especially rivers	• Degraded water quality in one part of a stream or river spreads downstream into other aquatic ecosystems

Sector	Consideration	Perspective
Social	• Education, empowerment and public participation	• Community awareness and public opinion pushes formulation and implementation of water quality management policies and programmes
	• Population growth	• Implications for greater water needs and wastewater production
	• Urbanisation and urban agriculture (per-urban, urban and rooftop)	• Where will water be sourced? Can a cycling system be used with wastewater from buildings to harness these resources
	• Conventional public attitudes about water 'aesthetics' and high quality of water quality	• Expectations of water quality focused on qualitative criteria (taste, appearance, smell)
	• Public perception influences the public agenda (acceptance of standards and new practices)	• Conventional attitudes may prevent adoption of new schemes (eg. linking industry to environmental degradation, wastewater reuse deemed unacceptable for drinking water), effective education and branding are needed to overcome this issue
	• Social needs may not always be compatible with environmental needs	• Reconciling social and environmental needs will likely be particularly challenging in the developing world
	• Sharing water quality knowledge	• Create global knowledge portals online as well as local partnerships between scientists and farmers in order to share best practices

8.4 Emerging Applications & Management Options

With globalisation and new water quality challenges, there is a need to address water scarcity and water quality problems from innovative approaches. Structuring this report around examining water quality for a specific use demonstrates one such approach of quality that is fit for use. Further management approaches and new techniques are explored below to showcase the innovative of water quality management and thus the potential for guidelines content. This intends to help nudge the field into sustainable and efficient styles of management in order to help address water scarcity and general water quality issues from around the world.

Adaptive Management

As described in section 8.1, there are different formats for guiding information on water quality; parameters, indices, standards. Further to different types of guiding documents, there are other forms of water quality management that may be more suitable than strict regulations or targets. Adaptive management provides one such option for flexible style of water management when uncertainty is high.

Adaptive management is primarily concerned with the management of uncertainty through formalized experimentation and process-based learning (Huitema et al., 2009); it is a six-step process in which management aims are identified, an environmental assessment is conducted, management actions or policies are designed, implemented, and monitored, and the subsequent outcomes are evaluated (Rist et al., 2013). Figure 17 depicts this cyclical learning process. The primary objective of adaptive management is to enhance scientific knowledge and

reduce ecological uncertainty (Rist et al., 2013), where ecological uncertainty may stem from the natural variability and stochastic behaviour of ecosystems, misinterpretation of data, lack of data, or changes in social and economic events that affect ecosystems (National Research Council, 2004).

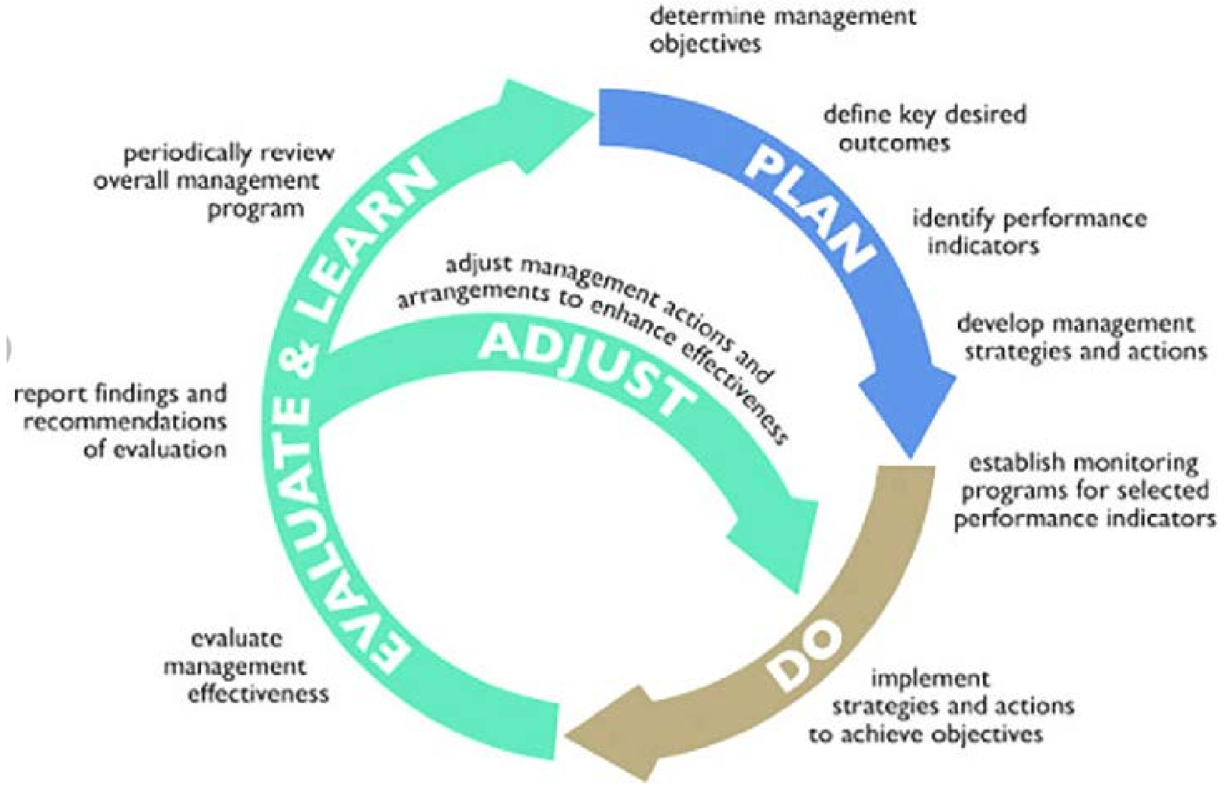

Figure 17: A conceptual plan of the key steps within adaptive management, from planning implanting, evaluating then learning and adjusting. Source: https://www.researchgate.net/figure/The-adaptive-management-cycle-DPIPWE-2014-Jones-2005-2009-Reprinted-with-kind_fig1_320934215

Adaptive management promotes an iterative, social learning process within which ecologically-oriented policies are designed to be more flexible to change. This is particularly important in the context of ecosystems, where climate change, rapid urbanization rates, and industrialization have already caused severe environmental degradation, including water quality deterioration in countless waterways, and whose future impacts are uncertain or poorly understood. For the successful implementation of adaptive management, a shift in management culture to one that acknowledges uncertainty, encourages risks, and accepts failure as part of the learning process may be required (Rist et al., 2013). To increase the overall effectiveness of adaptive ecosystem management, future management actions or policies must be viewed as experiments in which active learning is encouraged, and management strategies are adaptable to change.

All water uses can benefit from the inclusion of essences of adaptive management to address uncertainty, especially in the face of climate change. Of particular note, ecosystems are multi-faceted, complex, and constantly evolving, and as such ecological water quality management should be flexible and adaptive through such management techniques as described above.

Effect Based Monitoring

Another novel and flexible water quality management approach that is emerging as a suitable alternative to traditional monitoring is effect-based water quality monitoring. Traditionally, substance-based monitoring has been the norm, with water managers tracking specific priority substances and determining quality based on their levels. A problem with this method is that there are continually new substances emerging in aquatic settings, and it often takes years before they are recognised and methods of monitoring are determined and widely instructed. Furthermore, this approach only measures the level of each substance which does not account for the effects of pollutant mixtures or interactions which are often not predictable on the basis of chemical analyses. While substances are an indicator of water quality, it is not the presence of a pollutant that is important, but rather its effect on the water setting.

To address these shortcomings, as well as to assess water quality in a larger perspective with an overview of both chemical concentrations and ecological responses, effect-based water quality monitoring is recommended. This does not need to replace substance-based monitoring, but could compliment it using biological effect tests like bioassays or biomarkers to better understand water quality as well as the structural composition of aquatic communities. Several large institutions are acknowledging its advantages to integrated water quality management, and a report by the European Commission outlines how effect-based monitoring tools can fit into the context of the *EU Water Framework Directive and the Regional Seas Conventions and the Marine Strategy Framework Directive* (European Commission, 2014). While thus far these tools are used for ecological water uses, different monitoring approaches can be used to detect and assess effects of hazardous substances and quality for other uses such as domestic or agricultural water.

Blockchain Technology

As seen throughout this report, data is key to assessing water quality for all uses, and usually the more data one can acquire and analyse, the better the understanding of the quality level. This information includes better temporal data (long term monitoring), more parameters and techniques, as well as greater geographical reach, often requiring international or at least regional communication and cooperation (especially important for ecological monitoring). One way to increase data communication across nations, but also across institutions (public, private), is through providing it as open source for others to view and use from other regions or companies.

The emerging technology of blockchain, while so far mostly used for financial data and as a cryptocurrency, has the potential to greatly increase access and communication of water quality data and best practices.

> **"Blockchain is a decentralised record of information."** Weisbord, 2018

There are many benefits to its use for water quality information. Blockchain is openly accessible and secure, with recorded information not centralised in one database but rather data is copied and sits in a network on top of the internet in blocks of similar information (Weisbord, 2018). The decentralised, open source system holds immutable information that all interested parties can contribute to and access. These features mean that blockchain could address the problems of limited stakeholder access to data and high costs associated with maintaining long-term information, communicating and collaborating between stakeholders. Furthermore, it can help empower communities in addressing local water quality management through its decentralised and democratised approach.

In this digital age and the shift to using smart water management techniques, blockchain can provide an integrated foundation that is more efficient, secure and cost-effective for future water quality monitoring and management in the future.

Citizen Science

Water quality management can benefit from drawing on a broader set of stakeholders than traditional researchers and policymakers, but rather engaging the public and involving communities in data collection, management and decision making activities. Such public involvement in information gathering and decision-making helps ensure that the appropriate path is chosen and is more widely accepted. Community members are not only an added resource for project managers, but their involvement in projects through quality public engagement helps contribute to stakeholder learning, and the success of such projects (Bernhardt et al., 2007). Community engagement is an iterative process that involves continual and open communication between staff and the public, working towards broad societal and ecological goals. This approach could be especially helpful in the use of unconventional water sources such as wastewater or rainwater, where a lack of understanding from the public contributes to perceived distrust.

> **"Citizen science: the collection and analysis of data relating to the natural world by members of the general public, typically as part of a collaborative project with professional scientists."** Oxford Dictionary, 2018

Citizen-led monitoring or citizen science is able to generate new information and knowledge from non-scientists and is a growing trend in conservation and the science community. Especially in aquatic ecology settings, communities can participate in collecting data and water monitoring to contribute a more extensive database and a better understanding of freshwater ecosystems. This is directly relevant to addressing the water quality data gap, and addressing the issue that many government and custodian agencies lack the institutional structures and coordination to organise the appropriate personnel and gather data (United Nations, 2018).

FreshWater Watch is a global citizen science programme from Earthwatch that has more than 20 000 data sets of water quality samples from around the world as of mid-2018 (see figure 18). It features several projects within its scope, all of which are consistent around measurement methodologies, data upload and educational approaches. These elements have proven effective as a global citizen science platform with quality control, comparable data, and reduced costs (Thornhill et al. 2016).

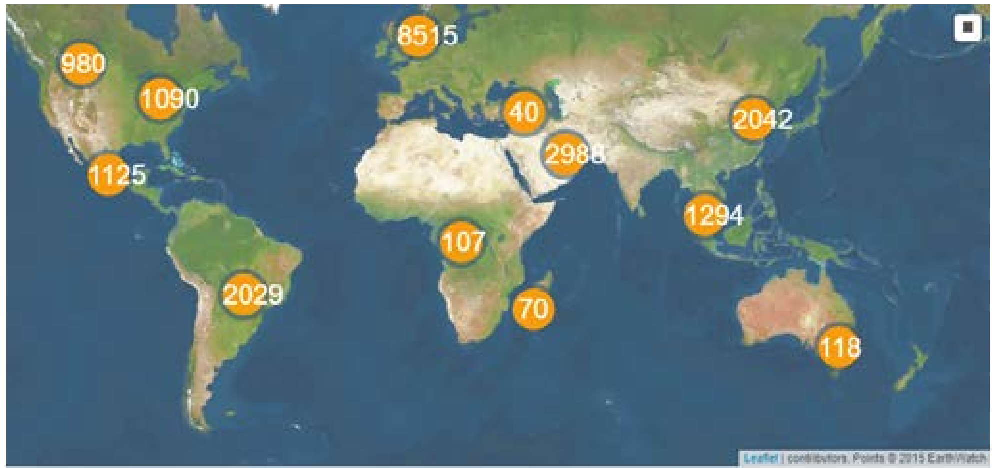

Figure 18: The global distribution of citizen collected data sets within the FreshWater Watch programme as of mid-2018. Source: EarthWatch Institute, 2018.

While there are concerns that volunteer collected data is unreliable, a comparison study of volunteer and regional council staff water samples at stream sites in New Zealand revealed that there was close agreement between the results of samples (Storey et al. 2016). Additional benefits in the study included increased public awareness and understanding of local freshwater ecosystems, as well as increased interest in local issues and commitment to personal action. Few national governments agencies are currently utilising data collected by volunteer community members, however increasing results of credible data collection such as Storey et al. 2016, demonstrate that volunteer collected data is a compatible addition to professionally collected data and also increases the knowledge, skills and interest of the community. Key to the competence of volunteer collected data is ensuring appropriate training around robust protocols and resources availability. If these conditions are met, the acquisition of greater knowledge can be achieved while shaping more-informed and empowered citizens.

8.5 Challenges and Limitations

Maintenance
A challenge for guidelines and frameworks is in administering the appropriate maintenance to ensure it stays up-to-date and relevant. For guidelines themselves, this means staying up-to-date with recent research findings, technology and other available guidance relating to water quality parameters, monitoring and water use. For compilations of regulatory instruments and guidelines such as this report, the proposed compendium and the 2015 UN-Water *Compendium of Water Quality Frameworks*, regular maintenance is also necessary as new editions to guidelines are released, hyperlinks must be verified as functional and new documents or regulations must be added. Furthermore, including and discussing current water quality issues is important for pushing the future improvements in the sector. An example of this in this 2018 report is the importance of considering contaminants of emerging concern such as pharmaceuticals in water quality monitoring and standard setting. Any plans for establishing such a comprehensive guideline must include funding and consideration not only for its establishment but also for on-going and long term maintenance of the system.

English Bias
As the working language of IWRA is English, the majority of national case studies in this report are from Anglophone countries. Water quality guidelines exist all over the world, so it is acknowledged that there is a bias of English case studies and perspectives in this report. Future work should attempt to cross language and cultural boundaries to explore water quality guidelines from non-English speaking countries in order to bring more diversity to the international review. While the analysis would still be in English, the actual guidelines could be in any language. Translations of such guidelines might be useful but are expensive to provide. Any proposal to establish and maintain such a comprehensive guideline must consider this aspect when resourcing the system.

Other Water Uses
This report focused on five distinct water uses, however this is not a comprehensive account of all water uses. The following is a list of other water uses that should be considered when compiling water quality guidelines or regulations in a future compendium:

- Municipal watering of parks, sports fields and other public areas
- Private watering of golf courses
- Recreational uses (e.g. Water parks, fishing)
- Transportation
- Waste disposal

These water uses are broad in nature and scope, and thus more difficult to guide, nonetheless, they should not be ignored as many of these water users have considerable potential for benefitting from using water quality fit for their purpose.

Within the water uses that are explored in this report, there is a wide diversity of applications. While domestic water quality guidelines were addressed, they mainly focused on potable water quality, whereas more attention and guidelines are needed for non-potable domestic uses, such as for flushing toilets, filling private pools and ponds as well as gardening. This is an important distinction as non-potable water in domestic settings can and should have a lower quality of water compared to potable uses, although in developed countries they are often the same.

The diversity of water uses is the most extreme in the industry and energy sectors. There was limited time and technical capabilities in the creation of this report to adequately examine each sub-section of the industry and energy sector, and their corresponding water needs. Even those sectors and guidelines that were discussed, more analysis such as comparing methods and substance target values across guidelines would be useful for understanding the sector's water quality and how it is so far being guided. Thus, it is recommended for future work such as a comprehensive compendium, a thorough examination of water quality guidance across all water uses and a comparison among uses be conducted, to provide a nuanced view of the needs and guidance of water for each industry type.

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CHAPTER 9
Conclusion

Water quality remains a key consideration for global water management, not only for addressing low quality discharges that affect other uses and have environmental impacts, but also for examining the most efficient water quality for a specific purpose. The expansion of water quality criteria and references to more adequately consider five central applications of domestic, ecosystem, agriculture, energy and industry water uses has been reviewed and identified as an essential component of future management practices. This report identifies a number of existing guidelines directing water quality on an international, regional and national scale. Defining water quality requirements based on both application and geographical setting will help allow water resources to be applied more effectively.

Due to its significant and direct impact on human health, water quality for domestic purposes is the most heavily regulated and guided of all the water uses, while other sectors have very limited guidance on input water quality. For example, while the energy sector in many countries has considerable guidelines and regulations surrounding water emitted from processes (particularly concerning thermal pollution), the water quality requirements of water consumed by many sectors of this industry are not readily defined (WWAP, 2012). Where they do exist, guidelines are specific to one energy sub-sector, often the cooling systems of thermoelectric generation of fossil fuel and nuclear plants. Furthermore, the emphasis of guidelines for managers of these facilities is mainly on water quantity rather than quality, or on the quality of discharged water from the facility. Given the innovations and requirements for the energy sector in biofuel, tidal power generation, hydropower, nuclear, solar and wind, as well as the continued use of non-renewable sources, we recommend the development of guidelines for water quality for these purposes.

A key takeaway from this report is that wastewater and grey-water offer alternative options for water sources, and appropriate guidance could encourage its use and ensure it meets health related values for all water uses. The private ownership structure of industry is unique compared with centralised water management, allowing for this sector to undergo fast change when opportunities exist to use alternative and potentially cost-effective water sources. We suggest the production of more guiding documents on water quality across all industrial and energy sectors, particularly for processes that require low quality water where little guidance is available, to encourage and assist companies to use water of the appropriate quality.

This report represents a sectoral analysis of water qualities; however, it is clear that a nexus exists between water and all the main sectors explored. Decision-makers must collaborate with other sectors for an integrated and broader approach. We encourage refining the quality of outflow from treatment facilities to match the needs of uses such as agriculture, landscapes, recreational areas and sports grounds.

In order to prevent substantial damage to aquatic environments, governments and industries must consider the water quality required to meet ecological needs when setting the rules and conditions for allowing emission of effluent or other compounds into natural water systems. The review of national water quality guidelines for ecosystems demonstrates that most are outdated and would benefit from updates to account for new scientific findings and methods, such as effect-based monitoring and adaptive management.

Building on this report, it is recommended that future work should include the creation and ongoing long-term maintenance of a full online compendium of water quality guidance according to water use in order to improve the ease of access and sharing of information. This should consider further water uses as well as the inclusion of regulations and guidelines from a diverse range of countries. The format used in this report of listed guidelines according to water use with short summaries and analyses is recommended for a future comprehensive compendium of water quality guidelines and regulations. It is proposed that this information be stored and available on an online website, in a layout that is user-friendly, easily accessible and

easily updated as new guidelines emerge. Other recommended functional requirements for the public interface include convenient search tools to find the content needed, a responsive website with displays that adapt to different supports (screens, mobile phones), discussion platforms and various paths to obtain data from the system.

As the global community works towards meeting the Sustainable Development Goals for 2030, further widespread use of the guidelines compiled within this report as well as the recommendations for future work, will contribute to meeting the key performance indicators:

- **6.3.2** Proportion of bodies of water with good ambient water quality
- **6.4.1** Change in water-use efficiency over time
- **6.4.2** Level of water stress: freshwater withdrawal as a proportion of available freshwater resources
- **6.5.1** Degree of integrated water resources management implementation
- **6.6.1** Change in the extent of water-related ecosystems over time

Promoting the integrated use of water quality guidelines, while acknowledging the water cycle as a whole and that all outputs are eventually released to the environment, will contribute to more efficient water management. Directing water more appropriately across all sectors based on water quality needs could ultimately improve water use efficiencies, health outcomes, decision making, and management processes. Furthermore, it could help relieve stress on water scarce resources and ensure adequate water quality inputs to various applications, with the end goal of contributing to water security.

List of Acronyms

ADWG	Australian Drinking Water Guidelines
AFEID	French National Committee of the International Commission on Irrigation and Drainage
BOD	Biological Oxygen Demand
CCME	Canadian Council of Ministers of the Environment
CCREM	Canadian Council of Resource and Environment Ministers
CECs	Contaminants of emerging concern
CEQG	Canadian Environmental Quality Guidelines
CKDu	chronic kidney disease of unknown etiology
CMS	Content management system
COD	Chemical Oxygen Demand
CW	Constructed Wetland
CWQG	Canadian Water Quality Guidelines
CWQG-PAL	Canadian Water Quality Guidelines for the Protection of Aquatic Life
DO	Dissolved Oxygen
DWA	Department of Water Affairs (South Africa)
DWAF	South Africa Department of Water Affairs and Forestry
EEA	European Environment Agency
EPRI	Electric Power Research Institute, Inc.
ES	Ecosystem Services
EU	European Union
EV	Ecosystem values
FAO	United Nations' Food and Agricultural Organization
GCDWQ	Guidelines for Canadian Drinking Water Quality
GDWQ	Guidelines for Drinking-Water Quality (WHO)
GDWQI	Global Drinking Water Quality Index
GEMS	Global Environmental Monitoring System
IAEA	International Atomic Energy Agency
IBI	Index for Biotic Integrity
IEA	International Energy Agency
ISO	International Organisation for Standardisation
IWA	International Water Association
IWQGES	International Water Quality Guidelines for Ecosystems
IWRA	International Water Resources Association
IWRM	Integrated Water Resources Management
NEA	National Environment Agency (Singapore)
NTU	Nephelometric Turbidity Unit
NWQMS	National Water Quality Management Strategy
P&P	Pulp and Paper
PES	Payment for ecosystem services
RWH	South African Water Quality Guidelines
SAWQG	rainwater harvesting
SDGs	Sustainable Development Goals
TDS	Total Dissolved Solids
TPA	UN Thematic Priority Area
UN	United Nations
UNECE	United Nations Economic Commission for Europe
UNEP	United Nations Environment Programme
UNESCO	UN Educational, Scientific and Cultural Organization
UNU-EHS	United Nations University - Institute for Environment & Human Security
US EIA	United States Energy Information Association
US EPA	United States Environmental Protection Agency
WFD	Water Framework Directive (EU)
WHO	World Health Organization
WQI	Water Quality Index
WQS	water quality standards
WWAP	World Water Assessment Programme

References

Addington, L., Fitz, C., Lunsford, K., Lyddon, L., & Siwek, M. (2011). Sour water: where it comes from and how to handle it. In *GPA Europe Annual Conference*, Praga (pp. 21-23).

AFEID (L'Association Française pour l'Eau l'Irrigation et le Drainage) Office Association. (2012). *Which quality for which use? A regulators' and practitioners' perspective*. AFEID, Académie de l'Eau, SHF, ASTEE and ONEMA.

ANZECC (Australian and New Zealand Environment and Conservation Council). (2000). *Australian and New Zealand Guidelines for Fresh and Marine Water Quality: The Guidelines. Volume 1.* Canberra: Australian and New Zealand Environment and Conservation Council/Agriculture and Resource Management Council of Australia and New Zealand, 1-103.

Apitz, S.E., Elliott, M., Fountain, M., & Galloway, T.S. (2006). European Environmental Management: Moving to an Ecosystem Approach. *Integrated Environmental Assessment and Management*, 2(1): 80-85.

AquaFit4Use (2010). *Water Quality Demands in Paper, Chemical, Food and Textile Companies*. Brussels: European Union 7th Framework Programme.

Australian Government. (2012). *Improving water quality: Stories of progress and success from across Australia.* Canberra: Department of Agriculture and Water Resources.

AXEON Water Technologies. (n.d.). *Ultra Pure Water*. Temecula, CA: AXEON. Retrieved from: http://www.axeonwater.com/pdf/TA Ultra Pure Water.pdf

Ayers, R.S., & Westcot, D.W. (1985). *Water quality for agriculture* (Vol. 29). Rome: Food and Agriculture Organization of the United Nations.

Barbour, M. T., Gerritsen, J., Snyder, B. D., & Stribling, J. B. (1999). *Rapid bioassessment protocols for use in streams and wadeable rivers: periphyton, benthic macroinvertebrates and fish* (Vol. 339). Washington, DC: US Environmental Protection Agency, Office of Water.

Baumann, J. (2013). *More Crop per Drop: GIS-based water requirement maps optimize water use*. Esri. Retrieved from: http://www.esri.com/esri-news/arcuser/winter-2013/more-crop-per-drop

Bernhardt, E. S., Sudduth, E. B., Palmer, M. A., Allan, J. D., Meyer, J. L., Alexander, G., Follastad-Shah, J., Hassett, B., Jenkinson, R., Lave, R., Rumps, J. & Pagano, L. (2007). Restoring rivers one reach at a time: results from a survey of US river restoration practitioners. *Restoration Ecology*, 15(3): 482-493.

Bernstein, S. (2002). Freshwater and Human Population: An International Perspective. In K. M. Krchnak (Ed.), *Human Population and Freshwater Resources: U.S. Cases and International Perspectives* (Vol. 107, pp. 117). Yale School of Forestry and Environmental Studies: New Haven.

Biswas, A. K., Tortajada, C., & Izquierdo-Avino, R. (Eds.). (2009). *Water management in 2020 and beyond*. Berlin: Springer.

Blumenthal, U.J & Peasey, A. (2002). *Critical review of epidemiological evidence of the health effects of wastewater and excreta use in agriculture*. London: London School of Hygiene and Tropical Medicine.

Bos, R., Carr, R. & Keraita, B. (2010). Assessing and Mitigating Wastewater-Related Health Risks in Low Income Countries: An Introduction. In Dreschel, P., Scott, C.A., Raschid-Sally, L., Redwood, M. & Bahri, A. (Eds.), *Wastewater Irrigation and Health: Assessing and Mitigating Risk in Low-Income Countries*. (pp. 287-302). London: Earthscan.

Bowman, D.D. (2009). *Manure pathogens: Manure management, regulations and water quality protection*. New York, McGraw Hill.

Bradford, S. A., Morales, V. L., Zhang, W., Harvey, R. W., Packman, A. I., Mohanram, A., & Welty, C. (2013). Transport and fate of microbial pathogens in agricultural settings. *Critical Reviews in Environmental Science and Technology*, 43(8): 775-893.

Carlyle, R. (2013). *Why can't seawater be used for fracking? Is there a reason beyond the logistics of location? Is it a chemical issue?* Quora. Retrieved from: http://www.quora.com/Why-cant-seawater-be-used-for-fracking-Is-there-a-reason-beyond-the-logistics-of-location-Is-it-a-chemical-issue

Carr, G.M. & Neary, J.P. (2008). *Water Quality for Ecosystem and Human Health*, 2nd Edition. United Nations Environment Programme Global Environment Monitoring System (GEMS/Water Program), Ontario. Retrieved from http://hdl.handle.net/20.500.11822/12217.

Canadian Council of Ministers of the Environment. (2002). Canadian environmental quality guidelines (Vol. 2). Canadian Council of Ministers of the Environment.

CCME (Canadian Council of Ministers of the Environment). (1999). *Canadian Water Quality Guidelines for the Protection of Agricultural Water Uses.* Winnipeg; CCME Documents.

CCME (Canadian Council of Ministers of the Environment). (1999). Canadian water quality guidelines for the protection of aquatic life: Introduction. *In: Canadian environmental quality guidelines, 1999*. Winnipeg: Canadian Council of Ministers of the Environment.

CCME (Canadian Council of Ministers of the Environment). (2001a). Introduction. Updated. In: *Canadian environmental quality guidelines, 1999.* Winnipeg: Canadian Council of Ministers of the Environment.

CCME (Canadian Council of Ministers of the Environment). (2001b). Canadian water quality guidelines for the protection of aquatic life: CCME Water Quality Index 1.0, User's Manual. In*: Canadian environmental quality guidelines, 1999.* Winnipeg: Canadian Council of Ministers of the Environment.

CCME (Canadian Council of Ministers of the Environment). (2003). Canadian water quality guidelines for the protection of aquatic life: Guidance on the site-specific application of water quality guidelines in Canada: Procedures for Deriving Numerical Water Quality Objectives. In: *Canadian Environmental quality guidelines, 1999.* Winnipeg: Canadian Council of Ministers of the Environment.

CCME (Canadian Council of Ministers of the Environment). (2007). A protocol for the derivation of water quality guidelines for the protection of aquatic life. In: *Canadian Environmental quality guidelines, 1999.* Winnipeg: Canadian Council of Ministers of the Environment.

CCME (Canadian Council of Ministers of the Environment). (2008). Notice to Readers, within *Canadian Water Quality Guidelines.* Ottawa: Environment Canada. Retrieved from: https://www.ccme.ca/files/Resources/supporting_scientific_documents/cwqg_pn_1040.pdf

CCME (Canadian Council of Ministers of the Environment). (2010). *Strategic Directions for Water: Three year action plan,* Canadian Council of Ministers of the Environment, Winnipeg.

CCREM (Canadian Council of Resource and Environment Ministers). (1987). *Canadian water quality guidelines.* Prepared by the Task Force on Water Quality Guidelines.

CDC (Centres for Disease Control and Prevention). (2009*). Agricultural Water*. Retrieved from: http://www.cdc.gov/healthywater/other/agricultural/

Government of Canada. (1999). Canadian Environmental Protection Act. Ottawa. Retrieved from: https://www.canada.ca/en/environment-climate-change/services/canadian-environmental-protection-act-registry/related-documents.html

Commission of the European Communities. (2000). *Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy.* European Union Water Framework Directive. Retrieved from: http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32000L0060

Coombes, P. (2006). *Guidance on the use of rainwater harvesting systems*. Rain Harvesting.

Cross, K., & Latorre, C. (2015). Which water for which use? Exploring water quality instruments in the context of a changing climate. *Aquatic Procedia*, 5: 104-110.

DA (Department of Agriculture – Republic of the Philippines). (2007). Guidelines on the Procedures and Technical Requirements for the Issuance of a Certification allowing the Safe Re-use of Wastewater for Purposes of Irrigation and other Agricultural Uses. BSWM (Bureau of Soils and Water Management) Technical Publication No. 2, ISSN– 1908-9600. Quezon City: Department of Agriculture Office of the Secretary.

Da Costa Silva, G. & Dubé M. (2013). Water quality assessment at global scale: a comparison between world regions. *Water International*: 38 (1): 78-94.

Dale, P. E. R., Dale, M. B., Anorov, J., Knight, J., Minno, M. C., Powell, B., ... and Visser, J. M. (2006). Aspects of adaptive management of coastal wetlands: case studies of processes, conservation, restoration, impacts and assessment. In J. T. A. Verhoeven, B. Beltman, R. Bobbink, and D. F. Whigham (Eds.), *Wetlands: Functioning, Biodiversity Conservation, and Restoration* (pp. 197-222). Berlin: Springer.

Department of Water Affairs and Forestry. (1996). *South African Water Quality Guidelines (second edition), Volume 3: Industrial Use*. Pretoria; The Government Printer.

Dieter, C.A. & Maupin, M.A. (2017). *Public Supply and Domestic Water Use in the United States, 2015.* Reston, Virigina; U.S. Geological Survey (USGS).

Dieter, C.A., Linsey, K.S., Caldwell, R.R., Harris, M.A., Ivahnenko, T.I., Lovelace, J.K., Maupin, M.A., & Barber, N.L. (2017). *Estimated use of water in the United States county-level data for 2015*. Reston, VA: U.S. Geological Survey

Diver, S. (2010). *Aquaponics-Integration of hydroponics with aquaculture*. ATTRA. Retrieved from: https://attra.ncat.org/attra-pub/summaries/summary.php?pub=56

Dodds, W.K., Bouska, W.W., Eitzmann, J.L., Pilger, T.J., Pitts, K.L., Riley. A.J., Schloesser, J.T. & Thornbrugh, D.J. (2009). Eutrophication of U.S. Freshwaters: Analysis of Potential Economic Damages. *Environmental Science & Technology*, 43(1): 12-19.

Duke Energy. (n.d.) *Electricity from Coal.* Duke Energy. Retrieved from: https://www.duke-energy.com/about-energy/generating-electricity/coal-fired-how.asp

Dunn, G., Bakker, K., & Harris, L. (2014). Drinking Water Quality Guidelines across Canadian Provinces and Territories: Jurisdictional Variation in the Context of Decentralized Water Governance. *International Journal of Environmental Research and Public Health*, 11(5): 4634-4651;

DWA (South African Department of Water Affairs). (2011). *Planning Level Review of Water Quality in South Africa*. Pretoria: Department of Water Affairs.

DWAF (South African Department of Water Affairs and Forestry). (1996). *South African Water Quality Guidelines Volume 7: Aquatic Ecosystems (2nd edition).* Pretoria: Department of Water Affairs and Forestry.

EarthWatch Institute. (2018). *FreshWater Watch Results*. Retrieved from: https://freshwaterwatch.thewaterhub.org/content/data-map

EEA (European Environment Agency). (2010). *Forecast of global water demand*. Copenhagen: EEA. Retrieved from http://www.eea.europa.eu/data-and-maps/figures/forecast-of-global-water-demand/forecast-of-global-water-demand/

EEA (European Environment Agency). (2012). *European waters – assessment of status and pressures.* EEA Report (no. 8/2012). Copenhagen: EEA. Retrieved from: http://www.eea.europa.eu/publications/european-waters-assessment-2012

EIA (US Energy Information Administration). (2017). *International Energy Outlook 2017: Highlights*. Washinton, DC: Office of Energy. Retrieved from https://www.eia.gov/outlooks/ieo/

Enderlein, U.S., Enderlein, R.E. & Williams, W.P. (1997). Water Quality Requirements. In: *Water Pollution Control – A guide to the use of Water Quality Management Principles*. London: United Nations Environment Program and World Health Organisation.

Environment Agency. (2010). *Cooling water options for the new generation of nuclear power stations in the UK.* Bristol: Environment Agency Rio House.

EPRI & California Energy Commission. (2003). *Use of Degraded Water Sources as Cooling Water in Power Plants.* Palo Alto, Sacramento, CA: EPRI, California Energy Commission.

European Commission (2016). *Introduction to the new EU Water Framework Directive*. Retrieved from: http://ec.europa.eu/environment/water/water-framework/info/intro_en.htm

European Commission. (2014). *Technical Report on Aquatic Effect-Based Monitoring Tools*. Luxembourg: Office for Official Publications of the European Communities.

European Commission. (2015). 4th Report on the progress in implementation of the Water Framework Directive Programmes of Measures. Brussels: European Commission.

European Commission. (2018). *Legislation: The Directive Review*. Retrieved from: http://ec.europa.eu/environment/water/water-drink/legislation_en.html

ExxonMobil. (n.d.) *Energy in Tomorrow's Global Landscape*. ExxonMobil. Retrieved from: http://corporate.exxonmobil.com/en/energy/energy-outlook/global-landscape/overview

FAO (Food and Agricultural Organisation of the United Nations). (2001). *Integrated Agriculture-Aquaculture: A Primer.* Retrieved from: http://www.fao.org/docrep/005/y1187e/y1187e00.HTM

FAO (Food and Agricultural Organisation of the United Nations). (2011a). *The State of the World's Land and Water Resources for Food and Agriculture, Managing systems at risk*. Rome: FAO.

FAO (Food and Agriculture Organisation of the United Nations). (2011b). *World aquaculture 2010 (FAO Fisheries and Aquaculture Technical Paper 500/1)*. Rome: FAO.

FAO, (Food and Agricultural Organisation of the United Nations). (2013). AQUASTAT database, Food and Agriculture Organization of the United Nations. Retrieved from: http://www.fao.org/nr/water/aquastat/main/index.stm

FAO (Food and Agricultural Organisation of the United Nations). (2016). AQUASTAT database, Food and Agriculture Organization of the United Nations. Retrieved from: http://www.fao.org/nr/water/aquastat/data/query/index.html?lang=en

FAO (Food and Agriculture Organization of the United Nations)- IWMI (International Water Management Institute). (2018). *More People, More Food, Worse Water? A Global Review of Water Pollution from Agriculture.* Colombo, Sri Lanka: CCGIAR Water Land and Ecosystems research program.

Faries, F.C. Jr., Sweeten, J.M., & Reagor, J.C. (1998). *Water Quality: It's Relationship to Livestock (L2374).* Texas, Texas Agricultural Extension Service: Texas A&M University System.

FracFocus. (2015). *What Chemicals Are Used*. GWPC (Ground Water Protection Council) & IOGC (Interstate Oil & Gas Compact Commission). Retrieved from: http://fracfocus.org/chemical-use/what-chemicals-are-used.

Gassert, F., Landis, M., Luck, M., Reig, P., & Shiao, T. (2015). *Aqueduct Global Maps 2.1 Working Paper.* Washington, DC: World Resources Institute. Retrieved from: http://www.wri.org/publication/aqueduct-global-maps-21

GEF (Global Environment Facility). (2014). *GEF investments on payment for ecosystem services schemes.* Retrieved from: https://www.thegef.org/publications/gef-investments-payments-ecosystem-services-schemes

Global Water Intelligence. (2009). *Pure water, semiconductors and the recession*. Global Water Intelligence. Retrieved from: http://www.globalwaterintel.com/archive/10/10/market-insight/pure-water-semiconductors-and-the-recession.html

Great Mining. (n.d.). *Coal*. Retrieved from: http://www.greatmining.com/coal.html

Great Mining. (n.d.). *Hardrock Mining*. Retrieved from: http://www.greatmining.com/Hardrock-mining.html

Greenway, M. (2005). The role of constructed wetlands in secondary effluent treatment and water reuse in subtropical and arid Australia. *Ecological Engineering*, *25*(5), 501-509.

Grey, D. and Sadoff, C.W. (2007). Sink or Swim? Water security for growth and development. *Water Policy*, 9(6): 545-571.

GT Technology. (n.d.). *Sour Water Stripping.* Retrieved from: http://www.gtctech.com/technology-licensing/refining/sour-water-stripping/

Gupta, A. (2013). *Top 10 Open-Pit Mines.* MiningTechnology.com. Retrieved from: http://www.mining-technology.com/features/feature-top-ten-deepest-open-pit-mines-world/

Gunderson, J. (2012). *Water Treatment in the Pulp and Paper Industry*. Industrial WaterWorld, vol. 12(3). Retrieved from: http://www.waterworld.com/articles/iww/print/volume-12/issue-3/feature-editorial/water-treatment-in-the-pulp-and-paper-industry.html

Gwenzi, W., Dunjana, N., Pisa, C., Tauro, T., & Nyamadzawo, G. (2015). Water quality and public health risks associated with roof rainwater harvesting systems for potable supply: Review and perspectives. *Sustainability of Water Quality and Ecology*, 6: 107-118.

Harraz, H. Z. (2011). *Topic 5: Mining Methods: Part1- Surface Mining*. SlideShare LinkedIn Corporation. Retrieved from: http://www.slideshare.net/hzharraz/atud-gold-mine-egypt-9998734.

Hart, B.T., Maher, B., & Lawrence, I. (1999). New generation water quality guidelines for ecosystem protection. *Freshwater Biology,* 41(2): 347-359.

Hartman, H.L., Mutmansky, J.M. (2002). *Introductory Mining Engineering*. 2 ed. Hoboken. NJ: John Wiley & Sons, Inc.

Hasibuzzaman, M.M., Hossain, S., Islam, M.S., Rahman, A., Anjum, A., Hossain, F., et al. (2017). Association between arsenic exposure and soluble thrombomodulin: A cross sectional study in Bangladesh*. PloS one,* 12(4): e0175154.

Health Canada. (2017). *Guidelines for Canadian Drinking Water Quality Summary Table*. Federal-Provincial-Territorial Committee on Drinking Water. Ottawa: Water and Air Quality Bureau, Health Canada.

Heinz, I., Salgot, M., & Mateo-Sagasta Dávila, J. (2011). Evaluating the costs and benefits of water reuse and exchange projects involving cities and farmers. *Water international*, 36(4): 455-466.

Hering, D., Moog, O., Sandin, L., & Verdonschot, P.F. (2004). Overview and application of the AQEM assessment system. *Hydrobiologia*, *516*(1-3): 1-20.

Hering, D., Borja, A., Carstensen, J., Carvalho, L., Elliott, M., Feld, C.K. et al. (2010). The European Water Framework Directive at the age of 10: A critical review of the achievements with recommendations for the future. *Science of the Total Environment*, 408(19): 4007-4019.

Hoekstra, A.Y. (2015). The water footprint: The relation between human consumption and water use. In: Antonelli M., Greco F. (eds) *The Water We Eat* (pp. 35-48). Springer, Cham.

Holling, C.S. (1973). Resilience and stability of ecological systems. *Annual Review of Ecology and Systematics* 4(1): 1–23.

Huibers, F., Redwood, M. & Raschid-Sally, L. (2010). Challenging Conventional Approaches to Managing Wastewater Use in Agriculture. In Dreschel, P., Scott, C.A., Raschid-Sally, L., Redwood, M. & Bahri, A. (Eds.), *Wastewater Irrigation and Health*: *Assessing and Mitigating Risk in Low-Income Countries*. (pp. 287-302). Colombo: IWMI.

Huitema, D., Mostert, E., Egas, W., Moellenkamp, S., Pahl-Wostl, C., & Yalcin, P. (2009). Adaptive water governance: assessing the institutional prescriptions of adaptive (co-) management from a governance perspective and defining a research agenda. *Ecology and Society* 14(1): 26.

IAEA (International Atomic Energy Agency). (2012). *Efficient water management in water cooled reactors.* IAEA Nuclear Energy Series No. NP-T-2.6. Vienna: International Atomic Energy Agency.

IEA (International Energy Agency). (2012). *World Energy Outlook 2012*. Paris: International Energy Agency. Retrieved from: https://webstore.iea.org/world-energy-outlook-2012-2

IEA (International Energy Agency). (2014). *World Energy Outlook 2014*. Paris: International Energy Agency. Retrieved from: https://www.iea.org/newsroom/news/2014/november/world-energy-outlook-2014.html

IISD (International Institute for Sustainable Development). (2018). *Earth Negotiations Bulletin: HLPF 2018 Highlights*. IISD Reporting Services. Retrieved from: http://enb.iisd.org/vol33/enb3338e.html?utm_medium=email&utm_campaign=2018-07-21 - HLPF2018 NYC - ENB - English - Summary SW&utm_content=2018-07-21 - HLPF2018 NYC - ENB - English - Summary SW+CID_8855c08ab4acfbb597f8337e0e469f68&utm_source=cm&utm_term=httpenbiisdorgvol33enb3338ehtml

IPCC (Intergovernmental Panel on Climate Change). (2011). *Special report on Renewable Energy Sources and Climate Change Mitigation (SRREN).* Prepared by Working Group III of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press.

ISO (International Organisation of Standarization). (2015). *Guidelines for treated wastewater use for irrigation projects. ISO 16075.* Retrieved from: https://www.iso.org/obp/ui/#iso:std:iso:16075:-1:ed-1:v1:en

IWMI (International Water Management Institute). (2002). *The Hyderabad Declaration on Wastewater Use in Agriculture*. 14 November 2002. Hyderabad, India: International Water Resources Management Institute.

Jacobson, R. (2016). *Israel Proves the Desalination Era Is Here*. Scientific American, A Division Of Springer Nature America, Inc. Retrieved from: https://www.scientificamerican.com/article/israel-proves-the-desalination-era-is-here/

Jacxsens, I,L, Amoah, P, Law, M, Uyttendaele, & Drechsel, P. (2012). *Irrigation water and waters used for fresh produce production*. Presentation at World Water Week 2012, Stockholm.

Jayasumana, C., Gunatilake, S., & Senanayake, P. (2014). Glyphosate, hard water and nephrotoxic metals: are they the culprits behind the epidemic of chronic kidney disease of unknown etiology in Sri Lanka? *International journal of environmental research and public health*, *11*(2): 2125-2147.

Jouravlev, A. (2009). The Drinking Water Supply and Sanitation in Latin America: Moving toward Sustainability following two decades of Reforms. In C. Coussens (Ed.), *Global Environmental Health: Research Gaps and Barriers for providing Sustainable Water, Sanitation, and Hygiene Services: Workshop Summary*. Washington, D.C.: National Academies Press.

Kagel, A. (2008). *The State of Geothermal Technology: Part II Surface Technology*. Washington, D.C.: Geothermal Energy Association. Retrieved from: http://www.geo-energy.org/reports.aspx.

Karr, J.R., & Dudley, D.R. (1981). Ecological perspective on water quality goals. *Environmental Management*, *5*(1): 55-68.

Karr, J.R. (1991). Biological integrity: a long-neglected aspect of water resource management. *Ecological Applications*, 1(1): 66-84.

Kenessey, Z. (1987). The primary, secondary, tertiary and quaternary sectors of the economy. *Review of Income and Wealth*, *33*(4): 359-385.

Kershner, K. (2012). *How Hydraulic Fracturing Works*. HowStuffWorks. Retrieved from: http://science.howstuffworks.com/environmental/energy/hydraulic-fracking.htm

Kimani-Murage, E.W., & Ngindu, A.M. (2007). Quality of Water the Slum Dwellers Use: The Case of a Kenyan Slum. *Journal of Urban Health: Bulletin of the New York Academy of Medicine*, 84(6): 829-838.

King, G.E. (2011). *Alternate Water Sources for Fracturing*. Apache. GEK Engineering.

Kivaisi, A.K. (2001). The potential for constructed wetlands for wastewater treatment and reuse in developing countries: a review. *Ecological Engineering*, *16*(4): 545-560.

Likens, G.E. (1992). The Ecosystem Approach: Its Use and Abuse. In Kinne O. (Ed.) *Excellence in Ecology.* Oldendorf/Luhe: Ecology Institute.

Likens, G.E., Walker, K.F., Davies, P.E., Brookes, J., Olley, J., Young, W.J., et al. (2009). Ecosystem science: toward a new paradigm for managing Australia's inland aquatic ecosystems. *Marine and Freshwater Research*, 60(3): 271-279.

Lipinski, B., Hanson, C., Lomax, J., Kitinoja, L., Waite, R. & Searchinger, T. (2013). *Installment 2 of "Creating a Sustainable Food Future" Reducing Food Loss and Waste.* Washington, D.C.: World Resources Institute, United Nations Environment Programme.

Lundqvist, J. (1998). Avert Looming Hydrocide. *Ambio*, 29 (6): 428-433.

Manivasakam, N. (2011). *Industrial Water Quality Requirements*. New York City: Chemical Publishing Co Inc.

Mateo-Sagasta, J. & Burke, J. (2010). Agriculture and water quality interactions: a global overview. *SOLAW Background Thematic Report-TR08*. Rome: Food and Agriculture Organization of the United Nations (FAO).

Megdal, S.B. (2012). The role of the public and private sectors in water provision in Arizona, USA. *Water International*, 37(2): 156-168.

Meybeck, M & Helmer, R. (1996). An Introduction to Water Quality. In Chapman, D. (Ed.), *Water Quality Assessments – A Guide to Use of Biota, Sediments and Water in Environmental Monitoring* 2nd Edition (pp. 19-39). London: UNESCO/WHO/UNEP, E&FN Spon.

Meybeck, M. (2004). The global changes of continental aquatic systems: dominant impacts of human activities. *Water Science and Technology*, 49(7): 73-83.

McMurtry, M.R., Sanders, D.C., Cure, J.D., Hodson, R.G., Haning, B.C., & St Amand, E.C. (1997). Efficiency of Water Use of an Integrated Fish/Vegetable Co-Culture System. *Journal of the World Aquaculture Society*, *28*(4): 420-428.

Mielke, E., Anadon, L.D., & Narayanamurti, V. (2010). *Water Consumption of Energy Resource Extraction, Processing, and Conversion.* Cambridge, MA: Belfer Center for Science and International Affairs, Harvard Kennedy School.

Millennium Ecosystem Assessment. (2005). *Ecosystems and human well-being. Synthesis*. Washington, DC: Island Press.

Mobley, R.K. (2001). *Plant Engineer's Handbook*. Woburn, MA: Butterworth-Heinemann.

Molle, B., Brelle, F., Bessy, J. & Gatel, D. (2012). Which water quality for which uses? Overcoming over-zealous use of the precautionary principle to reclaim wastewater for appropriate irrigation uses. *Irrigation and Drainage*, 61(1): 87-94.

Msangi, S., & Rosegrant, M.W. (2011). *Feeding the Future's Changing Diets: Implications for Agricultural Markets, Nutrition, and Policy*. Washington, D.C.: International Food Policy Research Institute (IFPRI). Paper presented at 2020 Conference: Leveraging Agriculture for Improving Nutrition and Health, New Delhi, India.

National Research Council. (2004). *Adaptive Management for Water Resources Project Planning*. Washington, DC: The National Academies Press.

NCSL (National Conference of State Legislatures). (2018). *State rainwater harvesting laws and legislation.* Retrieved from: http://www.ncsl.org/research/environment-and-natural-resources/rainwater-harvesting.aspx

NEA (National Environment Agency). (2008). *Code of Practice on Piped Drinking Water Sampling and Safety Plans*. Singapore: NEA.

NEI (Nuclear Energy Institute). (n.d.) *How Nuclear Reactors Work*. Nuclear Energy Institute. Retrieved from: https://www.nei.org/fundamentals/how-a-nuclear-reactor-works

NHMRC, NRMMC. (2011). *Australian Drinking Water Guidelines Paper 6.* National Water Quality Management Strategy. Canberra: National Health and Medical Research Council (NHMRC), National Resource Management Ministerial Council (NRMMC).

NOAA (National Oceanic and Atmospheric Administration). (2014). *Aquaculture.* Retrieved from: https://www.fisheries.noaa.gov/topic/aquaculture.

Odiyo, J., & Makungo, R. (2012). Water quality problems and management in rural areas of Limpopo Province, South Africa. *WIT Transactions on Ecology and the Environment*, 164: 135-146.

OECD. (2008a). *OECD Glossary of Statistical Terms*. Paris:

Organisation for Economic Cooperation and Development (OECD).

OECD. (2008b). *Water Resources in Agriculture: Outlook and Policy Issues*. Paris: Organisation for Economic Cooperation and Development (OECD). Retrieved from: http://www.oecd.org/agriculture/48498988.pdf

OECD. (2012a). Global water demand: Baseline, 2000 and 2050 In *OECD Environmental Outlook*. Paris: OECD (Organisation for Economic Cooperation and Development) Publishing.

OECD. (2012b). *OECD Environmental Outlook to 2050*. Paris: OECD (Organisation for Economic Cooperation and Development) Publishing.

OECD. (2013). *Water and Climate Change Adaptation: Policies to Navigate Uncharted Waters*. OECD Studies on Water. Paris: OECD (Organisation for Economic Cooperation and Development) Publishing.

Oil & Gas School. (2014). *Oil Drilling: Oil & Gas Animations*. Retrieved from: https://www.youtube.com/watch?v=SfazJ6P_g7w

Oxford Dictionary. (2018). *Citizen Science*. Oxford Dictionary. Retrieved from: https://en.oxforddictionaries.com/definition/citizen_science

Osterath, B. (2017). *Wastewater crop irrigation risks health of nearly a billion people*. Deutsche Welle. Retrieved from: https://www.dw.com/en/wastewater-crop-irrigation-risks-health-of-nearly-a-billion-people/a-39538101

Øvergaard, S. (2008). Issue Paper: Definition of Primary and Secondary Energy. Prepared as input to Chapter 3: Standard International Energy Classification (SIEC) In the *International Recommendation on Energy Statistics* (IRES). Oslo: Oslo Group of Energy Statistics.

PUB. (2016). *Our Water Our Future*. Singapore: PUB Singapore's National Water Agency.

Qadir, M., Wichelns, D., Raschid-Sally, L., McCornick, P.G., Drechsel, P., Bahri, A., & Minhas, P.S. (2010). The challenges of wastewater irrigation in developing countries. *Agricultural Water Management*, 97(4): 561-568.

RAIN. (2008). *RAIN Water Quality Guidelines: Guidelines and Practical Tools on Rainwater Quality*. Amsterdam: Rain Foundation.

Rakocy, J.E., Bailey, D.S., Shultz, R.C., & Thoman, E.S. (2004). Update on tilapia and vegetable production in the UVI aquaponic system. In *New Dimensions on Farmed Tilapia: Proceedings of the Sixth International Symposium on Tilapia in Aquaculture*.

Ramanathan, R., He, Q., Black, A., Ghobadian, A., & Gallear, D. (2017). Environmental regulations, innovation and firm performance: a revisit of the Porter hypothesis. *Journal of Cleaner Production*, *155*: 79-92.

Raschid-Sally, L., & Jayakody, P. (2008). *Drivers and Characteristics of Wastewater Agriculture in Developing Countries: Results from a Global Assessment* (IWMI Research Report 127). Colombo, Sri Lanka: International Water Management Institute (IWMI).

Rigzone. (n.d.). *What is EOR, and How Does It Work*? Rigzone.com Inc. Retrieved from: http://www.rigzone.com/training/insight.asp?i_id=313

Rist, L., Felton, A., Samuelsson, L., Sandström, C., & Rosvall, O. (2013). A new paradigm for adaptive management. *Ecology and Society,* 18(4): 63.

Rodriguez, D. J., Delgado, A., DeLaquil, P., & Sohns, A. (2013). *Thirsty Energy.* Water Papers, Water Partnership Program. Washington D.C.: World Bank.

Rommelmann, D.W., Duranceau, S.J., Stahl, M.W., Kamnikar, C., & Ganzales, R.M. (2003). *Industrial Water Quality for Reclaimed Water*. Denver: AWWA RF Report no. 90979F. AWWA Research Foundation.

Roychowdhury, T., Tokunaga, H., Uchino, T., & Ando, M. (2005). Effect of arsenic-contaminated irrigation water on agricultural land soil and plants in West Bengal, India. *Chemosphere*, 58(6): 799-810.

Rutkowski, T., Raschid-Sally, L., & Buechler, S. (2007). Wastewater irrigation in the developing world—two case studies from the Kathmandu Valley in Nepal. *Agricultural Water Management*, 88(1-3): 83-91.

Sato, T., Qadir, M., Yamamoto, S., Endo, T., & Zahoor, A. (2013). Global, regional, and country level need for data on wastewater generation, treatment and use. *Agricultural Water Management*, 130: 1-13.

Scheierling, S. M., Bartone, C. R., Mara, D. D., & Drechsel, P. (2011). Towards an agenda for improving wastewater use in agriculture. *Water International*, *36*(4): 420-440.

Schreiner, B. (2013). Viewpoint- Why has the South African National Water Act been so difficult to implement? *Water Alternatives,* 6(2):239-245.

Sclar, E.D., Garau, P. & Carolini, G. (2005). The 21st Century health challenge of slums and cities. *The Lancet*, 365(9462): 901-903.

Scott, C.A., Drechsel, P., Raschid-Sally, L., Bahri, A., Mara, D., Redwood, M., & Jimenez, B. (2010). Wastewater irrigation and health: challenges and outlook for mitigating risks in low-income countries. In: P. Drechsel, et al., eds. *Wastewater irrigation and health: assessing and mitigating risk in low-income countries.* London: Earthscan-IDRC-IWMI.

SDCWA (San Diego County Water Authority). (2009). *Technical Information for Cooling Towers Using Recycled Water*. San Diego: SDCWA.

Siebert, S., Burke, J., Faures, J.M., Frenken, K., Hoogeveen, J., Döll, P., & Portmann, F.T. (2010). Groundwater use for irrigation – a global inventory. *Hydrology and Earth System Sciences*, 14(10): 1863-1880.

Smedley, P.L., & Kinniburgh, D.G. (2002). A review of the source, behaviour and distribution of arsenic in natural waters. *Applied Geochemistry*, 17(5): 517-568.

Smedley, T. (2013). *'Energy for Water' May Have A Greater Impact on the Nexus*. Guardian News and Media Limited. Retrieved from: http://www.theguardian.com/sustainable-business/energy-water-greater-impact-nexus

Soifer, S.Y. (1987). Irrigation Water Quality Requirements. *Water International*, 12(1-2): 15-18.

Solomon, E.B., Pang, H.J., & Matthews, K.R. (2003). Persistence of *Escherichia coli* O157:H7 on Lettuce Plants following Spray Irrigation with Contaminated Water. *Journal of Food Protection*, 66(12): 2198-2202.

Statistics Canada. (2009). *Industrial Water Use 2009: Updated*. Ottawa: Government of Canada. Retrieved from: https://www150.statcan.gc.ca/n1/en/catalogue/16-401-X

Steffen, J., Jensen, M., Pomeroy, C.A., & Burian, S.J. (2013). Water supply and stormwater management benefits of residential rainwater harvesting in US cities. *JAWRA Journal of the American Water Resources Association*, 49(4): 810-824.

Storey, R.G., Wright-Stow, A., Kin, E., Davies-Colley, R.J., & Stott, R. (2016). Volunteer stream monitoring: Do the data quality and monitoring experience support increased community involvement in freshwater decision making? *Ecology and Society*, 21(4).

Tan, Y.S., Lee, T.J., & Tan, K. (2009). *Clean, Green and Blue: Singapore's Journey towards Environmental and Water Sustainability*. Singapore: Institute of Southeast Asian Studies.

Tansley, A.G. (1935). The use and abuse of vegetational terms and concepts. *Ecology,* 16(3): 284–307.

Tchounwou, P. B., Yedjou, C. G., Patlolla, A. K., & Sutton, D. J. (2012). Heavy metal toxicity and the environment. In A. Luch, (Ed.) *Molecular, Clinical and Environmental Toxicology*. Basel: Springer Science and Business Media.

Thornhill, I., Loiselle, S., Lind, K., & Ophof, D. (2016). The citizen science opportunity for researchers and agencies. *BioScience*, 66(9): 720-721.

Tyrrel, S.F., & Quinton, J.N. (2003). Overland flow transport of pathogens from agricultural land receiving faecal wastes. *Journal of Applied Microbiology*, 94: 87-93.

Udmale, P., Ichikawa, Y., Nakamura, T., Shaowei, N., Ishidaira, H., & Kazama, F. (2016). Rural drinking water issues in India's drought-prone area: a case of Maharashtra state. *Environmental Research Letters*, 11(7): 074013.

UN (United Nations). (2015). *Sustainable Development Goals: 17 Goals to Transform our World*. United Nations. Retrieved from: http://www.un.org/sustainabledevelopment/

UN (United Nations). (2018). *Sustainable Development Goal 6: Synthesis Report 2018 on Water and Sanitation.* New York: United Nations Publications.

UNECE (United Nations Economic Commission for Europe). (1999). *Protocol on Water and Health to the 1992 Convention on the Protection and Use of Transboundary Watercourses and International Lakes*. London 1999: Third Ministerial Conference on Environment and Health.

UNECE (United Nations Economic Commission for Europe). (2010). *Guidelines on the Setting of Targets, Evaluation of Progress and Reporting.* Geneva: UNECE Secretariat.

UNEP (United Nations Environment Programme), GEMS (Global Environment Monitoring System). (2007). *Global Drinking Water Quality Index Development and Sensitivity Analysis Report*. Burlington, Ontario: UNEP/GEMS Water Programme Office.

UNEP (United Nations Environment Programme). (2008). *Payment for ecosystem services: Getting started. A Primer*. Washington, D.C.: Forest Trends, The Katoomba Group.

UNEP (United Nations Environment Programme). (2010). *Clearing the Waters: A focus on water quality solutions.* Nairobi: UNEP Pacific Institute.

UNEP IETC (United Nations Environment Program International Environmental Technology Center). (2002). *Rainwater Harvesting and Utilisation: An Environmentally Sound Approach for Sustainable Urban Water Management: An Introductory Guide for Decision Makers*. Osaka: UNEP International Environmental Technology Centre.

UNEP (United Nations Environment Programme) & UNU-EHS (United Nations University and Institute for Environment and Human security). (2016). *International Water Quality Guidelines for Ecosystems*. Nairobi: UNEP.

UNESCO. (2017). *The United Nations World Water Development Report 2017: Wastewater The Untapped Resource*. Paris: UNESCO Headquarters.

UN-Habitat (United Nations Human Settlements Program). (2003a). *The Challenge of Slums – Global Report on Human Settlements 2003*. Nairobi: UN-Habitat.

UN-Habitat (United Nations Human Settlements Program). (2003b). *Improving the Lives of 100 Million Slum Dwellers: Guide to Monitoring Target 11.* Nairobi : UN-Habitat.

UN Water. (2006). *Coping with Water Scarcity: a strategic issue and priority for system-wide action.* Geneva: United Nations.

UN Water. (2015). *Compendium of Water Quality Regulatory Frameworks: Which Water for Which Use?* UNEP, IWA. Retrieved from: http://www.unwater.org/publications/compendium-water-quality-regulatory-frameworks-water-use/

US EPA (United States Environmental Protection Agency). (2012). *2012 Guidelines for Water Reuse.* (EPA/600/R-12/618). Washington, D.C.: US EPA Office of Research and Development.

USGS (United States Geological Service). (n.d.). *Industrial Water Use*. USGS. Retrieved from: http://water.usgs.gov/edu/wuin.html.

USGS FAQs. (n.d.). *Hydraulic Fracturing ("Fracking") FAQs*. Reston, VA: USGS. Retrieved from: https://www.usgs.gov/faqs/what-hydraulic-fracturing?qt-news_science_ products=0#qt-news_science_products

Valente-Campos, S., Nascimento, E.D.S., & Umbuzeiro, G.D.A. (2014). Water quality criteria for livestock watering: a comparison among different regulations. *Acta Scientiarum. Animal Sciences*, *36*(1): 1-10.

Voulvoulis, N., Arpon, K.D., & Giakoumis, T. (2017). The EU Water Framework Directive: From great expectations to problems with implementation. *Science of the Total Environment*, 575: 358-366.

Wahlen, C. (2018). UNESCO Platform Supports Data Sharing for EU Biodiversity Targets. IISD: SDG Knowledge Hub. Retrieved from: http://sdg.iisd.org/news/unesco-platform-supports-data-sharing-for-eu-biodiversity-targets/?utm_medium=email&utm_campaign=2018-07-20 - SDG Weekly Update AE&utm_content=2018-07-20 - SDG Weekly Update AE+CID_4e4cf8e63b42afedbe7f71c59651c02c&utm_source=cm&utm_term=UNESCO Platform Supports Data Sharing for EU Biodiversity Targets

Water Education Foundation. (2018). *Water Recycling and Title 22.* Retrieved from: https://www.watereducation.org/aquapedia/water-recycling-and-title-22

Water in the West. (2013). *Water-Energy Nexus: A Literature Review*. Stanford Woods Institute for the Environment. Retrieved from: http://waterinthewest.stanford.edu/news-events/news-press-releases/water-energy-literature-review

WEF (World Economic Forum). (2015). *Global Risks 2015: Introduction*. Geneva: World Economic Forum. Retrieved from: http://reports.weforum.org/global-risks-2015/part-1-global-risks-2015/introduction/.

WEF (World Economic Forum). (2016). *The Global Risks Report 2016* (11th Edition). Geneva: World Economic Forum.

Weisbord, E. (2018). *Demystifying Blockchain for Water Professionals: Part 1*. International Water Association (IWA). Retrieved from: http://www.iwa-network.org/demystifying-blockchain-for-water-professionals-part-1/

WHO (World Health Organisation). (2011). *Guidelines for drinking-water quality (4th Edition).* Geneva: World Health Organisation Press.

WHO (World Health Organisation) & UNICEF (2013). *Progress in sanitation and drinking water – 2013 update*. Geneva: World Health Organisation Press.

WHO (World Health Organization). (2016). *Taking policy action to improve small-scale water supply and sanitation systems. Tools and good practices from the pan-European Region*. Copenhagen: WHO Regional Office.

WHO (World Health Organization). (2017). *Guidelines for drinking-water quality*: first addendum to the fourth edition. Geneva: World Health Organization.

WHO (World Health Organisation). (2018). *Drinking-water.* WHO. Retrieved from: http://www.who.int/news-room/fact-sheets/detail/drinking-water

WHO-FAO (World Health Organisation, Food and Agriculture Organisation of the UN). (2006). *Guidelines for the Safe Use of Wastewater, Excreta and Greywater*, vols. 1-4. Geneva: World Health Organisation Press.

WHO-FAO (World Health Organisation, Food and Agriculture Organisation of the UN). (2009). Recommended international code of practice general principles of food hygiene. Codex Alimentarius Commission. *CAC/RCP, Rev*, *4*, 1-1969.

WHO (World Health Organisation) & UNICEF (United Nations Children's Fund). (2017). *Progress on drinking water, sanitation and hygiene: 2017 Update and SDG Baselines*. Geneva: WHO, UNICEF.

WHO Expert Committee. (2011). Specifications for Pharmaceutical Preparations - WHO Technical Report Series, No. 970 - Forty-sixth Report (Geneva, 10–14 October 2011).

Wichelns, D., Owaygen, M., & Redwood, M. (2011). Developing country farmers need more than financial incentives to reduce the risks of wastewater irrigation. *Water international*, 36(4): 467-475.

Withanachchi, S.S., Ghambashidze, G., Kunchulia, I., Urushadze, T., & Ploeger, A. (2018). Water Quality in Surface Water: A Preliminary Assessment of Heavy Metal Contamination of the Mashavera River, Georgia. *International Journal of Environmental* Research and Public Health, *15(4)*: 621.

WMO (World Meteorological Organisation). (2013). *Planning of Water Quality Monitoring Systems.* Technical Report Series No. 3; WMO-No. 1113. Geneva: World Meteorological Organisation.

WWAP (World Water Assessment Programme). (2012). *The United Nations World Water Development Report 4: Managing Water under Uncertainty and Risk*. Paris: UNESCO Headquarters.

WWAP (World Water Assessment Programme). (2014). *The United Nations World Water Development Report 2014: Water and Energy: Facts and Figures*. Paris: UNESCO Headquarters.

WWAP (World Water Assessment Programme). (2015). The United Nations World Water Development Report 2015: Water for a Sustainable World Executive Summary. Paris: UNESCO Headquarters.

WWAP (United Nations World Water Assessment Programme). 2017. *The United Nations World Water Development Report 2017. Wastewater: The Untapped Resource*. Paris: UNESCO Headquarters.

WWAP (World Water Assessment Programme). (n.d.). *Facts and Figures.* UNESCO. Retrieved from: http://www.unesco.org/new/en/natural-sciences/environment/water/wwap/facts-and-figures/all-facts-wwdr3/fact-22-water-biofuels/

Yillia, P.T. (2012*). Scoping Study – International Water Quality Guidelines for Aquatic Ecosystems* (Project No. 2011-CPL-5060-3B41-1131-2201). Vienna: Vienna University of

Technology, Institute for Water Quality, Resources and Waste Management.

Zammit, K. (2012) *Water Conservation Options for Power Generation Facilities*. Power. Retrieved from: http://www.powermag.com/water-conservation-options-for-power-generation-facilities/

Zhang, H.H., & Brown, D.F. (2005). Understanding urban residential water use in Beijing and Tianjin, China. *Habitat International*, *29*(3): 469-491.

Zweig, R.D., Morton, J.D. & Stewart, M.M. (1999). *Source Water Quality for Aquaculture: A Guide for Assessment*. Washington D.C.: The World Bank.

IWRA

The International Water Resources Association (IWRA) is a non-profit, non-governmental, educational organisation established in 1971. It provides a global knowledge based forum for bridging disciplines and geographies by connecting professionals, students, individuals, corporations and institutions who are concerned with the sustainable use of the world's water resources. The aims of IWRA to facilitate knowledge generation and sharing are accomplished through publications, events and networking.

ONEMA/AFB

ONEMA, the French National Office of Water and Aquatic Environments, is a reference institution under the French Ministry of Ecology, Sustainable Development and Energy, initiated in 2007. ONEMA conducts research and knowledge distribution of public policies relating to water, as well as promoting the preservation of biodiversity. In 2017, AFB, the French Agency for Biodiversity was created, bringing together four existing organisations including ONEMA. It has a similar, yet expanded role, as ONEMA, supporting the implementation of public policies concerning biodiversity of terrestrial and aquatic environments.

World Water Council

The World Water Council (WWC) is an international multi-stakeholder platform, established in 1996 in response to an increasing concern about world water issues from the global community. It addresses the political dimensions of water issues at all levels, including the highest decision-making level. The three main activities of the WWC are in conducting hydro-politics to increase awareness of water security and sustainability on the political agenda, tackling emerging challenges in this field and co-organising the triennial World Water Forum. This is the world's largest event on water.