Water quality monitoring strategies for Metro Vancouver

A framework that informs source identification and drainage system performance

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This report was prepared on the lands of the xʷməθkʷəy̓əm (Musqueam), Sḵwx̱wú7mesh (Squamish), and səlilwətaɬ (Tsleil-Waututh) Nations.

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List of acronyms

Abbreviation	Meaning
ACE	Acetaminophen
AMF	Adaptive Management Framework
APE	Alkylphenol ethoxylates
AS	Artificial sweetener
BC EMA	British Columbia Environmental Management Act
BC ENV	BC Ministry of Environment and Parks
CBZ	Carbamazepine
CCME	Canadian Council of Ministers of the Environment
CCTV	Closed circuit television
CEC	Contaminants of Emerging Concern
CEPA	Canadian Environmental Protection Act
Chl	Chlorophyl
COP	Coprostanol
CSO	Combined sewer overflows
CST	Chemical Source Tracking
CUP	Current-use pesticide
DO	Dissolved oxygen
dPCR	Digital polymerase chain reaction
DRIPA	Declaration on the Rights of Indigenous Peoples Act
ECCC	Environment and Climate Change Canada

FEAST	Fast expectation-maximization microbial source tracking
FIB	Fecal indicator bacteria
FTIR	Fourier Transform Infrared spectrometry
ILWRMP	Integrated Liquid Waste and Resource Management Plan
IPPP	Isopropylated triphenyl phosphate
IRMP	Integrated Rainwater Management Plan
ISMP	Integrated Stormwater Management Plan
LWMP	Liquid Waste Management Plan
MCA	Microbial community analysis
MIQE	Minimum Information for Publication of Quantitative Real-time PCR Experiments
MOE	Ministry of Environment
MP	Microplastic
MST	Microbial Source Tracking
MV	Metro Vancouver
NGS	Next generation DNA sequencing
NP	Nonylphenol
OPFR	Organophosphate ester flame retardants
ORP	Oxidation-reduction potential
PAH	Polycyclic aromatic hydrocarbons
PBDE	Polybrominated diphenyl ether
PCB	Polychlorinated biphenyls
PCR	Polymerase chain reaction
PFAS	Polyfluoroalkyl substances

PFOA	Perfluorooctanoic acid
PFOS	Perfluorooctane sulfonate
POP	Persistent organic pollutant
PPCP	Pharmaceuticals and personal care products
PVC	Polyvinyl chloride
qPCR	Quantitative polymerase chain reaction
TDS	Total dissolved solids
TLF	Tryptophan-like fluorescence
TOC	Total organic carbon
TSS	Total suspended solids
TWP	Tire wear particle
UN CBD	United Nations Convention on Biological Diversity
UNDRIP	United Nations Declaration on the Rights of Indigenous Peoples
WQGs	Water Quality Guidelines
WQI	Water Quality Index
WWTP	Wastewater treatment plant

Executive summary

Clean water is vital to people and wildlife in the Metro Vancouver (MV) region, providing safe drinking water, clean habitat for fish and wildlife, an abundance of recreational opportunities, and traditional food sources central to the way of life of First Nations.

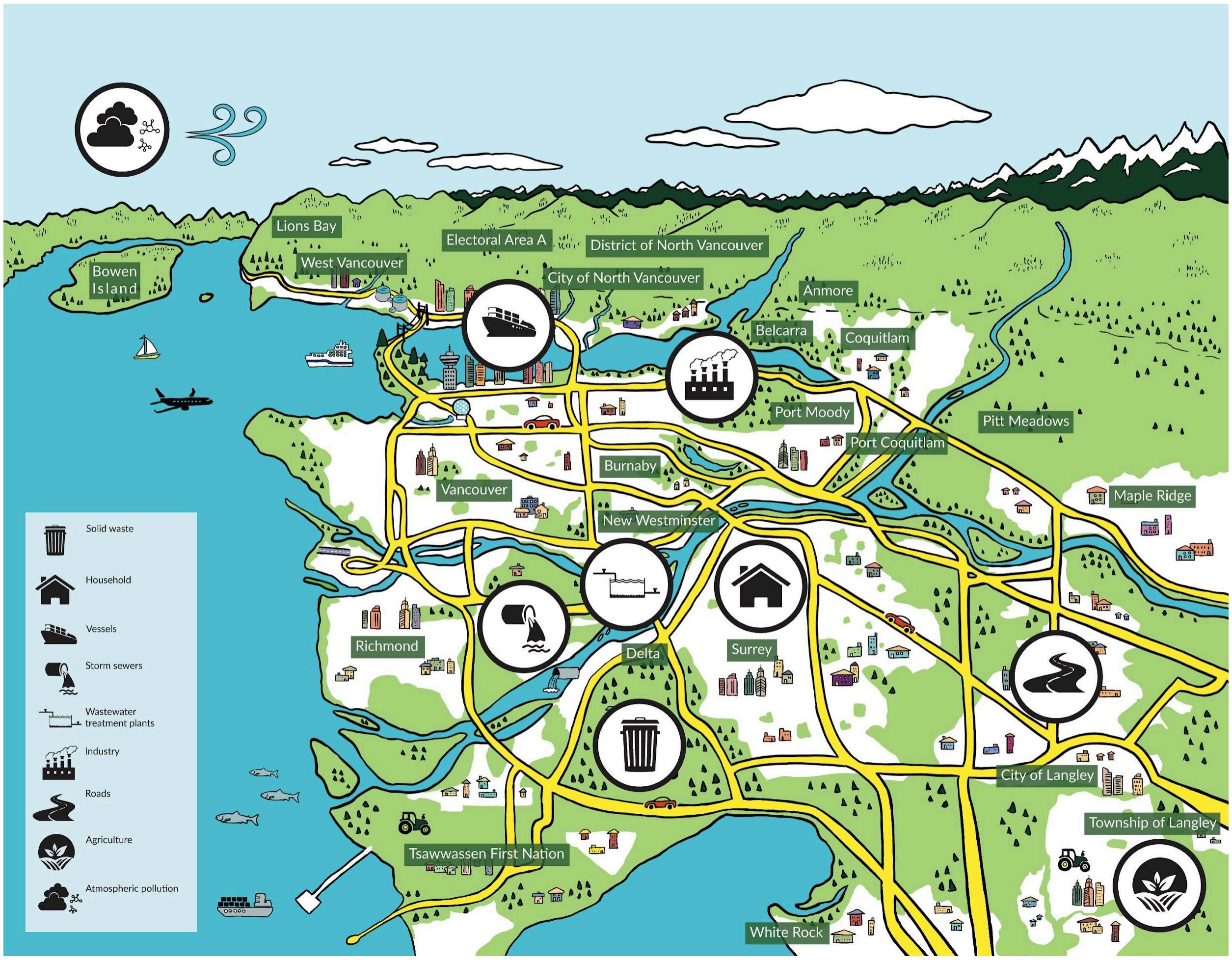
Despite its importance, clean water faces pressure from contaminants, urban developments, and floods, droughts, and fires associated with climate change.

Metro Vancouver and its 23 member jurisdictions (Figure 1) are developing the next Liquid Waste Management Plan (LWMP), which will guide the management of liquid waste in the region and influence the health of urban waters. This plan provides MV and its members with an opportunity to modernize its approach to managing the quality of receiving waters, build on the successes of the previous LWMPs, and protect urban waterways for people and wildlife. This new plan also provides an opportunity to consider environmental, scientific, social and regulatory developments since the inception of the previous Integrated Liquid Waste and Resource Management Plan (ILWRMP) in 2011, and to consider new tools that can help communities meet future operational and environmental performance goals. One important aspect of this future performance pertains to sanitary and stormwater separation and management.

Protecting water quality is everyone's business. Contaminants from households, farms, industry and roads enter the region's sewer and storm sewer systems, and infiltrate urban waterways. Poor water quality degrades fish habitat, reduces recreational opportunities and impedes Indigenous uses of aquatic ecosystems. A critical element of ensuring healthy urban waters in Metro Vancouver is an understanding of the threats to water quality, to document the sources of these threats, and to apply management approaches to protect the region's waters. A modernized approach to liquid waste management in the region will allow Metro Vancouver and its members to contribute to partnerships, knowledge sharing, and capacity-building with First Nations through the BC *Declaration of Rights for Indigenous Peoples Act (DRIPA).*

This report considers the emerging issues facing Metro Vancouver and its member jurisdictions, and proposes a water quality management roadmap for the coming decade. Important considerations herein are i) measures for drainage system performance that illustrate the value of engineering investments, ii) forensic tools to identify sanitary infiltration in stormwater and urban waters, and iii) the importance of a collaborative approach to water quality monitoring that helps to deliver healthy urban waters to the MV community and beyond.

Figure 1: Metro Vancouver provides leadership on water quality management throughout its 23 member jurisdictions, collectively serving over 2.6 million residents



As the climate changes and priorities evolve, Metro Vancouver continues to build on its 2018 Ecological Health Framework (Metro Vancouver, 2018), with a vision of a beautiful, healthy, and resilient environment for current and future generations. Metro Vancouver operates five WWTPs including: Annacis Island (identified in Figure 1), Iona Island, Lulu Island, Lions Gate, and Northwest Langley.

Context

Capsule

The strength in water quality monitoring programs lies in the generation of high quality data that are comparable over time and space. Historically limited scientific information regarding Contaminants of Emerging Concern (CECs) in the environment has constrained an understanding of urban water health. This has impacted the ability of communities to protect or improve fish habitat in Metro Vancouver. New knowledge, legislation, and guidelines regarding CECs have emerged over the past 10 years, along with evidence of increasing impacts associated with climate change. This has led to new challenges - as well as opportunities - for the 23 MV members as they enter the next LWMP cycle. One thing is clear: water is vital to all, and its protection requires a strong understanding of the activities that threaten its health.

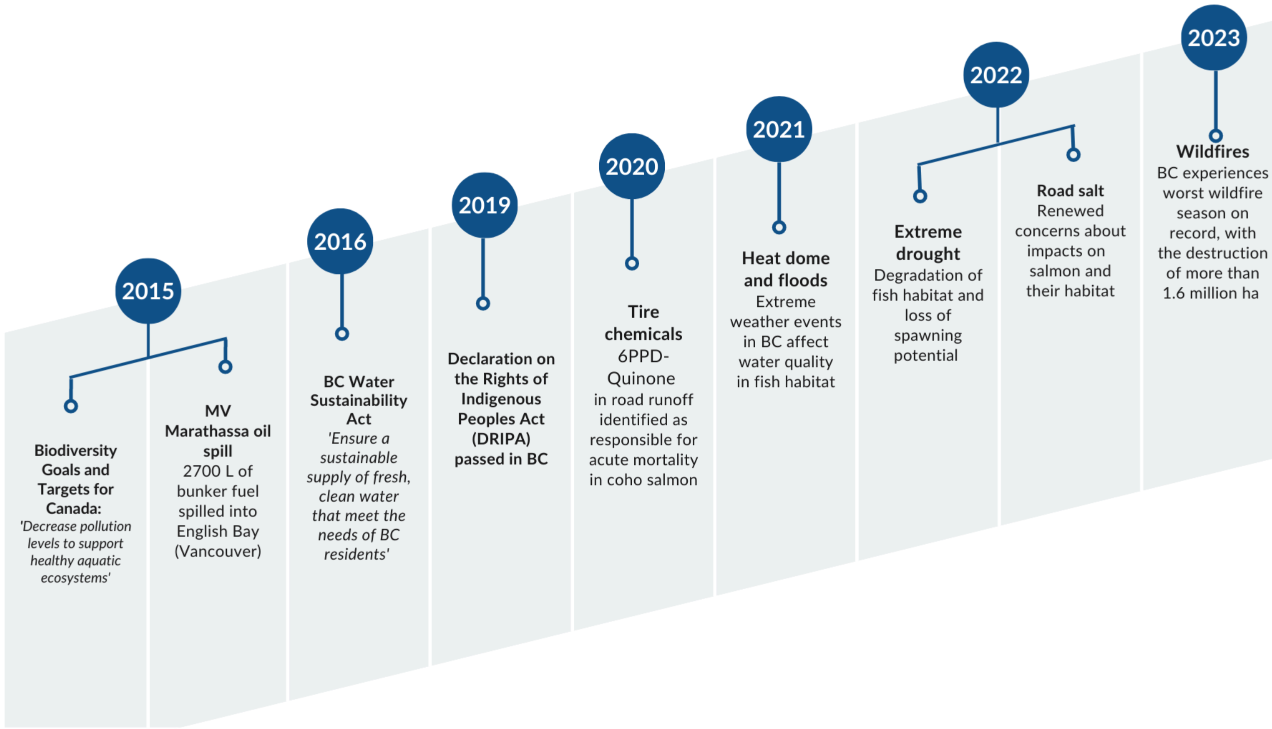
Introduction

A constant and reliable source of freshwater is featured among the 17 goals established by the United Nations Sustainable Development Goals for people and wildlife (SDG 6: Clean water and sanitation and SDG 14: Life below water). Freshwater ecosystems provide many services such as water for drinking, recreation, irrigation, power generation and support to industries. Aquatic environments face tremendous pressures from human activities, and concerted efforts around the world are needed to protect them (United Nations Environment program (UNEP), 2015). Urban stormwater runoff has been identified as a critical source of degradation in aquatic ecosystems, and the management of urban drainage is seen as essential to protect watershed health (Walsh et al., 2016).

Under the British Columbia Environmental Management Act (EMA), local governments develop Liquid Waste Management Plans (LWMPs) for approval by the Ministry of Environment and Parks (BC ENV)). Legislation requires that these plans provide for the management, resource recovery and disposal of treated waste for existing or future developments in order to protect public health and the environment.

Since the design and implementation of the ILWRMP, several developments have taken place, including new legislation, guidelines, scientific knowledge about Contaminants of Emerging Concern (CECs), and notable climate change-related impacts. These all have relevance for water, fish habitat, and stormwater performance (Figure 2). The fulsome consideration of all of these developments as a new monitoring framework is operationalised will strengthen stewardship opportunities and ensure better protections for the region's waterways.

Figure 2. Timeline of legal, scientific, and environmental developments since the approval of the Metro Vancouver ILWRMP in 2011



A number of developments since the approval of the Integrated Liquid Waste and Resource Management Plan in 2011 provide an opportunity for a revitalized approach to monitoring stormwater impact on urban waterways in Metro Vancouver. New contaminants of concern, new legislation, strong public interest in healthy urban waterways, and a distinct need for reconciliation with Indigenous Nations underscore the need for a fresh approach. [1] https://www.cbd.int/countries/targets/?country=ca; [2]Morales-Caselles et al., 2017; [3]https://www.bclaws.gov.bc.ca/civix/document/id/complete/statreg/14015; [4]https://www.bclaws.gov.bc.ca/civix/document/id/complete/statreg/19044; [5]Tian et al., 2022; [6]Ross et al., 2022; [7]https://www.cbc.ca/news/canada/british-columbia/salmon-dead-drought-bella-bella-1.6606418; [8]https://news.ubc.ca/2022/11/07/is-road-salt-killing-salmon/; [9]https://www.cbc.ca/news/canada/british-columbia/bc-wildfire-july-18-1.6909596

New legislation

BC Water Sustainability Act

The British Columbia Water Sustainability Act (WSA) came into force in 2016 with the aim to "*ensure a sustainable supply of fresh, clean water that meets the needs of BC residents today and in the future*". This act brings changes in the way water is managed in BC in order to sustain water quality and quantity to not only support specified uses of water but also sustain healthy aquatic ecosystems (https://www.bclaws.gov.bc.ca/civix/document/id/complete/statreg/14015#part3).

For example, the WSA Section 46 (1) states that "*a person must not (a) introduce debris, refuse, carcasses, human or animal waste, pesticides, fertilizers, contaminants or another matter or substance into a stream, a stream channel or an area adjacent to a stream, or (b) cause or allow debris, refuse, carcasses, human or animal waste, pesticides, fertilizers, contaminants or* *another matter or substance to be introduced into a stream, a stream channel or an area adjacent to a stream*".

2020 Biodiversity Goals and Targets for Canada

Biological resources are important to economic and social development but the threats to species and ecosystems caused by human activities have never been so great. As a result, the United Nations Convention on Biological Diversity (UN CBD) first entered into force in 1993, having been inspired by the world community's growing commitment to sustainable development. Canada then developed the first Canadian Biodiversity Strategy in 1995 (https://www.cbd.int/).

Canada, in response to the UN CBD Strategic Plan for Biodiversity 2011-2020, released the 2020 Biodiversity Goals and Targets for Canada in 2015, a document designed collaboratively by federal, provincial and territorial governments. Overall, the goals and targets encourage better land use planning management, environmentally sustainable management across sectors, improving information about biodiversity ecosystem services and raising awareness of biodiversity and encouraging participation in conservation (https://www.biodivcanada.ca).

In addition, Goal B, Target 10, is highly relevant to water quality monitoring at a local scale, such as in Metro Vancouver:

> "By 2020, pollution levels in Canadian waters, including pollution from excess nutrients, are reduced or maintained at levels that support healthy aquatic ecosystems."

Environment and Climate Change Canada (ECCC) is currently leading the development of Canada's 2030 National Biodiversity Strategy to align with the recently adopted Kunming-Montreal Global Biodiversity Framework (2022), with a draft delivered at the end of 2023 (https://www.canada.ca/).

Declaration on the Rights of Indigenous Peoples Act (DRIPA)

In 2007, the United Nations Declaration on the Rights of Indigenous Peoples (UNDRIP) was adopted and set out the minimum standards for the survival, dignity and well-being of Indigenous Peoples. Canada endorsed UNDRIP in 2016, and in 2019, the BC government passed the Declaration on the Rights of Indigenous Peoples Act (DRIPA) and established UNDRIP as the Province's framework for reconciliation. The Province released the Declaration Act Action Plan in 2022 to support the implementation of the Declaration.

UNDRIP affirms Indigenous Peoples' rights to the "conservation and protection of the environment and the productive capacity of their lands or territories and resources" (Article 29). It establishes Indigenous knowledge and environmental stewardship as a core part of Indigenous rights and well-being, recognizing that caring for the environment is essential to their cultures, survival, and self-determination. Indigenous Knowledge was used to guide recent environmental policies such as Bill C-69 in 2019 that states the requirement of early and regular engagement with Indigenous peoples during federal environmental impact assessments (https://indigenousclimatehub.ca). The United Nations describes Indigenous Knowledge as

" The understandings, skills and philosophies developed by Indigenous nations with long histories of interaction with their natural surroundings. This local knowledge informs decision-making about fundamental aspects of day-to-day life. This knowledge is integral to a cultural complex that also encompasses language, systems of classification, resource use practices, social interactions, ritual and spirituality. These unique ways of knowing are important facets of the world's cultural diversity and provide a foundation for locally-appropriate sustainable development." (UNDRIP, 2007).

Environmental Quality Guidelines and Water Quality Objectives

One of the key means of evaluating water quality is to be able to compare measurements to Environmental Quality Guidelines (EQGs). Available guidelines include those from the Canadian Council of Ministers of the Environment (CCME) and the Province of BC (BC Ministry of Water, Land and Resource Stewardship, WLRS).

The CCME defines water quality guidelines as "intended to protect all forms of aquatic life and all aspects of aquatic life cycles, including the most sensitive life stage of the most sensitive species over the long term from anthropogenic stressors such as chemical inputs or changes to physical components. They provide the science-based benchmark for a nationally consistent level of protection for aquatic life in Canada" (https://ccme.ca/en/current-activities/canadian-environmental-quality-guidelines).

Appendix A summarizes EQGs available, as of August 2023, for some of the parameters discussed in this document. As guidelines are being developed or updated on a regular basis, care should be taken to ensure that the most up-to-date guidelines are being used by consulting both the BC and the CCME Guidelines (https://www2.gov.bc.ca/gov/content/environment/air-land-water/water/water-quality/water-quality-guidelines/approved-water-quality-guidelines ; https://ccme.ca/en/resources/water-aquatic-life).

In addition to the BC water quality guidelines, water quality objectives (WQOs) are developed for specific waterbodies that hold regional, provincial, or Indigenous significance. The WQOs define the levels for substances in waterbodies necessary to protect water values and are used to inform land and resource management decisions and support stewardship. In the region, WQOs exist for the Fraser River (https://www2.gov.bc.ca/gov/content/environment/air-land-water/water/water-quality/water-quality-objectives). WQOs for Burrard Inlet were initially developed in 1990 by the Province but had not been updated to reflect the current health of the Inlet and address data gaps. Tsleil-Waututh Nation led the update of the WQOs for Burrard Inlet (*səl̓ilw̓ət*), in partnership with the Province of British Columbia (BC ENV and TWN, 2024). The updated objectives integrate Tsleil-Waututh Indigenous science and knowledge with improved western science, a better understanding of contaminants of concern and the fate and transport of contaminants, and more recent monitoring data. The objectives lay the foundation for continued efforts to improve water quality and protect the ecological, social, economic, health and First Nation values in Burrard Inlet. The WQOs include a wide range of contaminant categories including contaminants of emerging concern, metals, microbiological parameters, microplastics, oil and grease, persistent organic pollutants, pesticides, pharmaceuticals and personal care products, physical parameters, polybrominated diphenyl ethers, and polycyclic aromatic hydrocarbons (BC ENV and TWN, 2024; Braig et al., 2019).

It is important to note that for the Tsleil-Waututh Nation: "*The absence of a specific water quality parameter in the WQOs does not imply its irrelevance to Burrard Inlet; reducing contamination of any kind in Burrard Inlet stands as an overarching objective*."

Contaminants of Emerging Concern

As new chemicals are coming onto the market, some will enter waterways directly or indirectly, and present risks to the health of aquatic biota. A detailed evaluation of current CECs is provided in Section 2, but regular updates will be needed in order to be relevant to the current contaminant concerns in urban waters.

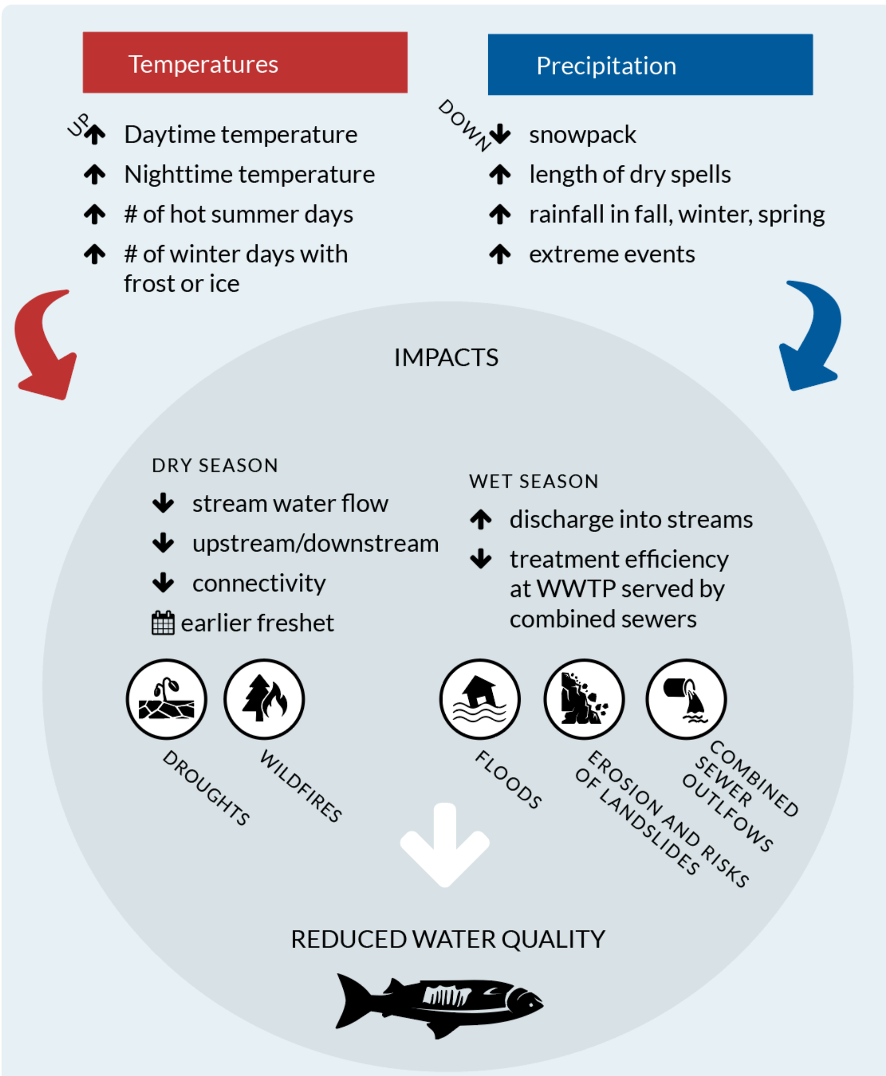
Climate change

Climate change is contributing to weather extremes across the globe, and causing losses and damage to nature and property (Intergovernmental Panel on Climate Change (IPCC), 2023). Canada is warming at more than twice the global rate with the Canadian Arctic warming even faster (Bush and Lemmen, 2019). In their Climate Projections Report, Metro Vancouver highlights the following changes expected for the region (Metro Vancouver, 2016):

- warmer temperatures throughout the year with more hot summer days and fewer winter days with frost or ice;
- 50% decrease in snowpack by 2050;
- longer dry spells in summer months;
- more precipitation in fall, winter, and spring;
- more extreme precipitation events, with more rain falling during the wettest days of the year and an increase in the frequency of extreme rainfall events.

Locally significant increases in drought, water temperatures, floods, erosion, and wildfires, and earlier freshet will impact combined sewer discharge and the treatment efficiency at wastewater treatment plants that are receiving wastewater from combined sewers during the wet season (Figure 3; Metro Vancouver, 2016). While it is clear that water quality and quantity will be affected, the extent of these changes remains unclear. Monitoring is therefore key to establish trends and better understand the impacts of climate change at the local scale.

Figure 3. Climate change is happening now, with large fluctuations in water temperature and volumes threatening municipal and regional infrastructure



Droughts, fires and floods all have strong potential to degrade fish habitat quality, serving as a reminder that investments in resilient infrastructure can help protect both property and fish habitat.

Elements of water quality monitoring in urban waterways: contaminants, technologies and strategies

Capsule

Effective stormwater management is vital to the protection of water quality and the health of aquatic habitats in receiving waters. Data from water quality monitoring in stormwater and local waterways provide a basis of modulating activities that degrade water quality, through enforcement of bylaws and other pertinent laws, education and source control, zoning, green infrastructure projects, and land use practices. Without adequate data, the opportunity to detect, characterise, and mitigate substances of concern in local waterways will not be effective. As part of their ILWRMP, MV was required by the Province of British Columbia to develop a Stormwater and Adaptive Monitoring Framework (SAMF) in 2014 to assess the effectiveness of Integrated Stormwater Management Plans (ISMPs). In light of new legislation, guidelines, CECs, and a changing climate over the past decade, we provide here a review of new and emerging considerations in measuring water quality in urban waterways. These include not only well known contaminants of concern such as polycyclic aromatic hydrocarbons (PAHs), but also CECs such as the tire breakdown chemical 6PPD-Quinone that is highly toxic to coho salmon in urban waterways. Some contaminants are discharged in pulses associated with wet weather events, with this requiring some consideration in designing monitoring initiatives.

Introduction

Contaminants in urban environments originate from numerous sources and enter nearby waterways via discharges, runoff, and atmospheric deposition. Sources may be classified as point or nonpoint, with the former being traced back to a single source. Contaminants from nonpoint sources accumulate on surfaces including roads, buildings, and green spaces during dry days, and may be washed away during rainfall events. Long-range transport can also be a significant source of persistent contaminants to local environments via atmospheric processes (Figure 4).

Figure 4. Point and nonpoint source contaminants enter the many urban waterways of Metro Vancouver by way of stormwater infrastructure, wastewater effluent and other discharge points

Documenting the presence and trends of historical and emerging contaminant concerns in this historical salmon habitat provides an opportunity to develop, track and share performance measures for land use practices, green infrastructure, source control, and regulations. Since each of these sectors can release harmful contaminants into salmon habitat, performance measures can speak to priorities, targeted solutions, and conservation and restoration initiatives.

Water quality monitoring is key to identifying contaminant sources and the impact of point-source discharges, supporting decision-making for mitigation measures and evaluating the effectiveness of measures that are implemented. Since water quality monitoring is a multifaceted endeavour, selecting appropriate sampling, analysis, and interpretative tools is critical to effective performance measures and successful source identification. We present here the key components needed to design an effective water quality monitoring program in this context.

Land use information

Land use plays an important role in the generation of pollution, and is directly linked to adjacent water quality (Yu et al., 2013). Land use changes when population increases due to 1) housing needs, 2) demand for agricultural products and other goods, and 3) the development of infrastructure for transportation. Urbanization typically results in an increase in impervious surfaces such as parking lots, roof tops, roads, and sidewalks, thereby leading to an increase in runoff containing a variety of contaminants (Wilson and Weng, 2010). Agricultural activities generally lead to the release of fertilizers and pesticides into adjacent water bodies.

Flow monitoring

Stream flow, or discharge, is the volume of water that moves over a designated site during a fixed period of time. Stream flow is affected by weather, snowpack properties, and precipitation events, but also changes throughout the year with lower flow during summer as a result of lack of rain and evaporation. Urbanization also affects waterways by altering surface water dynamics, groundwater recharge, stream geomorphology, biogeochemistry and ecology and ultimately water quantity and quality (O'Driscoll et al., 2010; Sun and Caldwell, 2015). The loss of natural riparian zones also renders streams more vulnerable to increased flow and to contaminants washed into waterways.

Water properties

The determination of eight basic - yet relevant - water properties lays the foundation for water quality monitoring in urban streams and fish habitat:

- Temperature: aquatic animals struggle to survive in warm water, and temperature directly affects metabolic rates and biological activity of aquatic organisms. Temperature can alter the physical and chemical properties of water (DataStream Initiative, 2021).
- Dissolved oxygen (DO): aquatic animals need oxygen to survive. DO is therefore a direct indicator of a waterway's ability to support aquatic life, and can be influenced by water flow, stream geomorphology, temperature and depth (EPA, 2018), as well as excess nutrients.
- pH: provides an indication of how acidic or basic the water is. Aquatic organisms function at an optimal pH range (EPA, 2018). pH can be altered by geology, point- and nonpoint discharges and acid rain.
- Conductivity: is the ability of water to pass an electric current, and is influenced by the amount of dissolved substances and minerals in the water. Significant changes in conductivity can indicate that contaminants are entering the waterway (EPA, 2018), including metals and road salt.

- Hardness: is measured as calcium carbonate and indicates the dissolved content of calcium and magnesium in the water. Hardness can alter the interactions of various substances and can alter the toxicity of some metals (DataStream Initiative, 2021).
- Total Suspended Solids (TSS): directly impact the turbidity of the water (i.e how clear it is) and how much light can penetrate the water column. TSS consists of silt, clay, fine particles of organic and inorganic matter, plankton and other microscopic organisms. TSS can impact the diversity and productivity of aquatic life, and is driven by a number of chemical, physical and biological factors associated with natural geology and land use (EPA, 2018).
- Total Dissolved Solids (TDS): while TSS is a measure of the amount of particulate matter retained by the filter during analysis, TDS refers to smaller particles going through the filter and includes inorganic salts and small amounts of organic matter dissolved in water. TDS is related to conductivity, salinity and hardness (Datastream Initiative, 2021).
- Total Organic Carbon (TOC): TOC includes living material, waste materials and some wastewater constituents. Organic carbon can affect water chemistry and is a useful indicator of the degree of pollution in a waterway. TOC can be impacted by snowmelt, runoff from agricultural lands, municipal and industrial wastewater discharges and stormwater overflows (Ministry of Water, Land and Air Protection, 2001).

Nutrients

Nitrogen

Nitrogen is an essential nutrient for all life. Nitrogen is present in several forms in freshwater including nitrate (NO_3^-), nitrite (NO_2^-), ammonia (NH_3) and ammonium (NH_4^+). Nitrogen supports the growth of algae and aquatic plants in fish habitat. While nitrogen is an essential nutrient, high concentrations of nitrate, nitrite and ammonia can be toxic to organisms. Excess nitrogen can contribute to dead zones, i.e water with little to no oxygen, where aquatic life is no longer supported. The primary sources of excess nitrogen in urban waterways include agriculture (animal manure and fertilizer), stormwater, wastewater, and households (pet waste, fertilizer, soaps and detergents containing nitrogen) (US Environmental Protection Agency (USEPA), 2023).

Phosphorus

Together with nitrogen, phosphorus is an essential nutrient for plants and animals. It is usually in short supply in most freshwaters so that even a slight increase can, under specific conditions, lead to a series of negative impacts in a stream including algae blooms, accelerated plant growth, low dissolved oxygen, and ultimately the death of fish, invertebrates and other aquatic species (US EPA, 2012).

Phosphorus can be of both natural (soil and rocks) and anthropogenic origin (wastewater treatment plants, fertilized lawns and cropland, failing septic systems, animal manure, disturbed lands, drained wetlands, water treatment, and commercial cleaning preparations) (US EPA, 2012). Phosphorus is not only found in wastewater and fertilizers, it is also linked to areas undergoing development since phosphorus from the soil can wash away from construction sites.

While the measurement of phosphorus can be challenging due to its low concentrations, it remains an important parameter of many water quality monitoring programs.

Metals

Metals can be of both natural and anthropogenic origin. Some metals are essential at trace concentrations for biochemical functions in biota, but elevated concentrations can cause acute or chronic toxicity (Tchounwou et al., 2012). Stormwater can contain metals from sources such as car brakes, tire wear, vehicle exhaust, commercial and industrial activities, building facades, structures and paved surfaces. Studies have shown that metal concentrations in stormwater are influenced by traffic volume (Ma et al., 2016). High concentrations of metals can be toxic, cause disruptions to aquatic ecosystems and decrease the suitability of a water body to support aquatic life or supply water for domestic uses.

Iron, copper, lead, zinc and cadmium are frequently detected in stormwater, and tend to be targeted in water quality monitoring programs, but data on additional metals may be of interest. Chromium, manganese, vanadium, cobalt and aluminum are indeed commonly found in stormwater (Sansalone and Buchberger, 1997; McKenzie et al., 2009). In addition, Rao et al. (2021) identified stormwater runoff as a significant source of nickel to local Burrard Inlet.

Microbiology

E. coli and fecal coliforms are the most widely used parameters when investigating water quality at the microbiology level. Even though fecal coliforms continue to be used as an indicator of microbiological contamination, they are no longer a preferred microbiological indicator for Canadian monitoring programs given that their presence does not always correlate with the incidence of diseases (Health Canada, 2021, Tallon et al., 2005; Scott et al., 2002). For example, basic counts of fecal coliforms are no longer measured as part of the surface water quality monitoring in Toronto (TRCA, 2017). Health Canada is recommending more specific indicators such as *E. coli* and enterococci, which are good indicators of gastrointestinal disease, and *Pseudomonas aeruginosa* which correlates with ear and skin infections (Health Canada, 2021).

Pinpointing fecal sources, especially human, in complex watersheds, has been a high priority for water quality managers and advanced microbial source tracking methods are increasingly being sought (see Section 3).

High concern contaminants

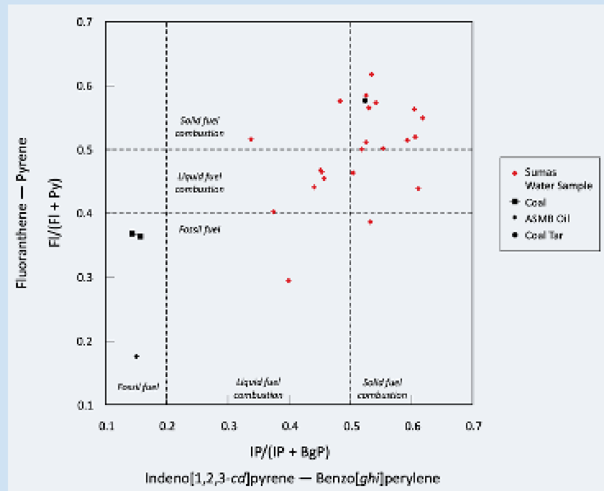
Polychlorinated biphenyls (PCBs)

PCBs are Persistent Organic Pollutants (POPs). They were introduced in the 1930s and heavily used as coolants, insulators, lubricants in transformers, capacitors and other electrical equipment (Agency for Toxic Substances and Disease Registry (ATSDR), 2000) as well as in paints, hydraulic fluids, heat exchange fluids, printing inks, sealants, plasticizers, and fire retardants (ECCC, 1997). Due to their persistence, bioaccumulative nature, and toxicity, PCBs were banned in the 1970s in Canada, and were among the first 12 POPs (the 'Dirty dozen') listed under the Stockholm Convention (2001).

The *Canadian Environmental Protection Act* (CEPA) prohibits the manufacture, use, importation, and release of PCBs, and manages their storage and destruction (CEPA, 1999). Despite regulations, PCBs continue to be a high concern contaminant due to their persistence and bioaccumulation in the aquatic environment. PCBs also continued to be used in some closed applications, with phase out scheduled for 2029.

Southern Resident killer whales were found to be among the most PCB-contaminated marine mammals in the world (Ross et al., 2000), and PCBs are cited by the Southern Resident Killer Whale Contaminants Technical Working Group as one of the primary contaminants of concern for the recovery of the Southern Resident Killer Whale population as well as Chinook salmon populations (Hickie et al., 2007; Buckman et al., 2011, Desforges et al., 2018; Holbert et al., 2023). As early as 1985, combined sewer overflows and stormwater discharges were

Case study: From the catastrophic BC floods of 2021: Polycyclic Aromatic Hydrocarbon (PAH) fingerprinting can identify sources



Forest fires, wood fires, vehicle use, and industrial sources dominate PAH emissions in Canada.[1]

High Resolution analysis of PAHs for 75 different hydrocarbons creates a unique "fingerprint".

The ratio of certain PAHs in water samples can distinguish between solid fuel (e.g. wood) and petroleum sources.

Surface water analysed after the Sumas floods revealed a domination of PAHs from the combustion of solid fuels.

[1]Ross, P.S., Walters, K.E., Yunker, M. and B. Lo. 2022. A lake re-emerges: Analysis of contaminants in the *Sema:th_Xo:tsa* (Sumas Lake) region following the BC floods of 2021. Raincoast Conservation Foundation. Sidney BC Canada. ISBN 978-1-9993892-6-0
www.raincoast.org/reports/flood-water/

identified as sources of PCBs to the Fraser River (Nijman and Swain, 1990). In addition, PCBs are detected at levels of concern in Burrard Inlet (Rao et al., 2019; Ocean Wise, 2018).

Polycyclic Aromatic Hydrocarbons (PAHs)

PAHs can be of both natural (crude oil seeps, coal and shale deposits, and forest fires) and anthropogenic (combustion of fossil fuels, spills and discharges from vessels, industry, stormwater outfalls and wastewater treatment plants) origin. In their report on Burrard Inlet Water Quality, Braig et al. (2019) also point out that sealcoat applied to many parking lots and driveways can release PAHs (Mahler et al., 2005). In some cases, runoff from sealed parking lots can account for the majority of nearby stream PAH loadings (Mahler et al., 2005). Runoff from coal tar sealcoated pavement sampled more than three months after application was acutely toxic to fathead minnows and water fleas, two species commonly used to assess toxicity to aquatic life (Mahler, 2016). In the MV area, coal tar based sealcoats are available to consumers through local retailers (Braig et al., 2019).

PAH fingerprinting has allowed for the evaluation of the relative contribution of natural vs anthropogenic sources along the BC coast (Yunker et al., 2002; 2015), as well as confirm the grain carrier *MV Marathassa* as the source of the oil that affected beach and mussel samples in Burrard Inlet and English Bay following the 2015 spill (Morales-Caselles et al., 2017).

Pesticides

There are numerous pesticides (herbicides, insecticides, fungicides, and vertebrate pest toxicants) which are designed to target specific classes of biota (ECCC, 2011) but may impact non-target biota. Current-use pesticides (CUPs) were developed to replace highly persistent and toxic legacy pesticides, and generally have lower persistence and bioaccumulative potential, as well as a higher water solubility (Kannan et al., 2005). However, some current use pesticides can bioaccumulate and harm biota, while others may affect olfaction, behaviour and osmoregulation through direct contact in water. Current use pesticides have been identified as a priority contaminant class of concern for some populations of salmon (ECCC, 2020; Harris et al., 2008).

Urban runoff may contain a mixture of different pesticides, released through precipitation and canopy throughfall from landscaping trees, garden runoff, roof runoff and road runoff. Pesticides may also be applied for structural pest control such as the protection of buildings from pests using the neonicotinoid pesticide imidacloprid against ants and termites, and are frequently detected in urban stormwater (Burant et al., 2018; Esminger et al., 2013). In addition, agricultural practices in proximity to urban areas can also contaminate runoff and compromise water quality.

As part of their water quality assessment and water quality objective development for Burrard Inlet, Braig et al. (2024)[1] selected 10 CUP of particular interest based on their levels detected in the local marine environment (Table 1).

Table 1: Current use pesticides of concern for the local marine environment

Name	Class	Use	Regulation
Atrazine	Triazine	Herbicide	In use[2]
Carbaryl	Carbamate	Insecticide; currently registered to control a wide range of arthropod pests	In use[3]
Chlorophenols	Chlorophenols	Used in pesticides and wood preservatives	No longer manufactured in Canada. As of 2022, penta products are being phased out within a year[4]
Chlorpyrifos	Organophosphate	Insecticide in agricultural, residential and commercial settings	Chlorpyrifos products in Canada are being phased out by the end of 2023[5]
Imidacloprid	Neonicotinoid	One of the most widely used insecticides to control sucking, chewing and soil insects as well as fleas on pets	Certain restrictions and risk-reduction measures apply but Neonicotinoids are not banned[6]
Hexachlocyclohexane	Organochlorine	Insecticide	Control of head lice and scabies only[7]; other uses banned in 1990s
Malathion	Organophosphate	Insecticide in agricultural and domestic sectors	In use[8]
Permethrin	Pyrethroid	Insecticide in agricultural and domestic sectors	In use[9]
Simazine	Triazine	Herbicide	In use[10]
Trifluralin	Dinitroaniline	Herbicide	In use[11]

[1]Braig et al., 2024; [2]Health Canada, 2014; [3]Health Canada, 2016; [4]Health Canada PMRA, 2022; [5]Health Canada, 2021; [6]Health Canada, 2021b; [7]ECCC, 2015; [8]CAREX, 2023; [9]Health Canada, 2020; [10]Health Canada, 2016b; [11]Health Canada, 2015

Surfactants

Alkylphenol ethoxylates (APEs) are chemicals used as surfactants in commercial detergents and cleaners, but they can also be used in textile and leather products, agriculture, paints, metal industries, oilfield chemicals and electrical and optical equipment (Markets and Markets, 2016). The physico-chemical properties of APEs reduce the surface tension of water against a surface, such as soiled laundry, facilitating the wetting of the surface and spreading of the cleaning solution (Ying, 2006).

Nonylphenols ethoxylates (NPEs) are a class of APEs that have received considerable attention due to the endocrine-disrupting properties of their degradation product, nonylphenol (NP). NP and NPEs include a large number of compounds (ECCC, 2022). These compounds mimic estrogen, a sex hormone, and have been associated with feminization of aquatic organisms, reduced male fertility and other estrogenic effects in bivalves, nematodes, fish and frogs (De la Parra-Guerra and Olivero-Verbel, 2020; De la Parra-Guerra et al., 2020). Other adverse effects associated with NPs include altered growth and development, neurotoxicity, liver toxicity and immunotoxicity (review in Hong et al., 2020). In addition, surfactants usually increase the solubility of contaminants and facilitate eutrophication (Zanoletti et al., 2017).

Studies have shown that effluent from wastewater treatment plants, urban run-off and stormwater discharges are significant sources of NP to aquatic environments (Shang et al. 1999; review in Priac et al., 2017). Seasonal variations in NP levels in rivers have been linked to increased microbial activity in warmer summer temperatures leading to enhanced degradation of APEs (Priac et al., 2017).

NP and NPEs were added to the Canadian List of Toxic Substances as per Schedule 1 of CEPA in 2002. In 2022, the government of Canada released the *Performance Measurement Evaluation for Risk Management of Nonylphenol and its Ethoxylates, eco-component,* and concluded that the risk management strategy in place was meeting its intended objectives with lower reported NP and NPE levels, but recommended continued monitoring to expand the available dataset and monitor trends over time (ECCC, 2022).

Contaminants of Emerging Concern (CECs)

Contaminants of Emerging Concern can be defined as substances that are increasingly detected in the environment, have uncertain environmental and human health impacts and are not taken into account (or only recently) in environmental legislation around the world (Deblonde et al., 2011; EPA, 2008). CECs are contaminants that are not typically considered in routine monitoring programs, and are generally under review by regulators. In light of the potential negative consequences for urban waterways, there has been a global push for more comprehensive stormwater monitoring that would include a broader spectrum of contaminants including many CECs (Suits et al., 2023). Examples of CECs in Canada are outlined in Table 2.

Table 2: Select Contaminants of Emerging Concern (CECs) in urban waters

Contaminants	Common sources in urban environments	Canadian regulations	Previously detected in the MV environment?
6PPD - Quinone	Oxidative product of tire additive	New BC Short Term WQG of 10 ng/L; Under federal re-review as of August 2025	Yes – Water from Lost Lagoon in Stanley Park[1]
Per- and polyfluoroalkyl substances (PFAS)	Leaching from industrial applications such as aqueous firefighting foams (AFFFs), and consumer goods such as non-stick cookware and textiles	PFOS and PFOA listed under CEPA Toxic Substances List (recommendation to add PFAS as a class); Stockholm Convention; FEQG available (PFOS)	Yes – sediment and mussels from Burrard Inlet[2]
Microplastics	Tire wear, city dust, synthetic turf fields, microfibers from textiles	Microbeads (primary microplastics) listed under CEPA Toxic Substances List	Yes – sediment and mussels from Burrard Inlet[2,3,4]
Pharmaceuticals and Personal Care Products (PPCPs)	Prescription, over the counter medications for humans, pets and livestock, illicit drugs.	FEQG for a small number	Yes – seawater, sediment and mussels from Burrard Inlet[2,5,6]
Chloride	Road salts	Yes - CCME and BC	Yes - https://www.theroadsaltproject.com/
Organophosphate ester flame retardants (OPFRs)	Insulation materials from building, runoffs from roads	Some recommended to be listed under CEPA	Not to our knowledge (only in house and fire station dust [7,8]

[1]Hwang et al., 2023; [2]pollutiontracker.org; [3]Boucher et al., 2016; [4]Law et al., 2014; [5]EnkonEnv, 2012; [6]Golder, 2013; [7]Shoeib et al., 2019; [8]Gill et al., 2020

6PPD – Quinone

Vehicle tires contain numerous additives, including 6PPD (N-(1,3-dimethylbutyl)-N'-phenyl-p-phenylenediamine), an additive intended to prevent damage to tire rubber from ozone. The breakdown product of 6PPD (6PPD-q) has been directly linked to acute coho salmon mortality events (Tian et al. 2022). Recent lab exposure studies have also shown the high toxicity potential of this compound on various species of fish (Lo et al., 2023; Greer et al., 2023). 6PPD-Quinone was recently detected in water samples collected from Lost Lagoon in Stanley Park (Hwang et al., 2023), as well as upstream of Metro Vancouver during the floods of November 2021 (Ross et al., 2022). A new EQG for 6PPD-q has been adopted at 10 ng/L by BC (British Columbia Ministry of Water, Land and Natural Resource Stewardship, 2025).

Polyfluoroalkyl substances (PFAS)

PFAS are a broad group of thousands of human-made substances with distinct properties. Their ability to repel oil and water have led to many clothing and packaging applications. Estimates of the number of PFAS compounds vary from 4,700 (Health Canada, 2023) to as many as 7 million (Schymanski et al., 2023), with ~17,000 used as a current working estimate (USEPA CompTox Chemicals Dashboard v. 2.2.1, 2025). They are used in firefighting foams, cosmetics, non-stick cookware, food packaging materials, textiles, adhesives, vehicles and electronics (ECCC, 2023).

Perfluorooctane sulfonate (PFOS) and perfluorooctanoic acid (PFOA) are well-studied PFAS. They are persistent, bioaccumulative and toxic. Due to their physico-chemical properties, aquatic environments are expected to be their primary sink in the environment (EC, 2010). They have been frequently detected in both urban and rural stormwater at a wide range of concentrations (Nguyen et al. 2011; Houtz & Sedlak 2012) and several studies have linked elevated PFAS concentrations in stormwater runoff to the transportation sector (Wilkinson et al., 2016; Murakami et al., 2009; Houtz et al., 2012).

PFOA, its salts and PFOA-related compounds have been listed under Annex A (Elimination) of the Stockholm Convention since 2019, while PFOS and its salts are listed under Annex B (Restriction). In Canada, PFOS and PFOA are prohibited through regulations. In addition, due to the similar physico-chemical properties of all PFAS, the government of Canada is considering addressing PFAS as a class rather than as individual substances. In Canada, 3 well-defined subgroups of PFAS have been added to Schedule 1 of CEPA: PFOS and its salts and precursors; PFOA and its salts and precursors and Liquid Chromatography (LC)-PFCAs and their salts and precursors (ECCC, 2025).

Microplastics (MPs)

Microplastics are plastic particles less than 5mm in size; they come from a variety of sources. Primary microplastics designed as abrasives in cosmetics and toothpaste have been banned in

Canada, but many forms of secondary MPs come from virtually any kind of plastic item, including consumer packaging, fishing gear, and clothing. Plastic microfibers have been found to be a dominant form of MP in wastewater and in the world's oceans, with the release of fibers from laundry into the wastewater system providing an important conduit to ocean pollution (Gago et al., 2018; Vassilenko et al., 2021). While the study of one major MV wastewater treatment plant (WWTP) showed that 99% of MPs entering the WWTP were retained, 30 billion particles were nonetheless estimated to be released into receiving waters annually (Gies et al., 2018).

In urban environments, vehicle tires, road markings, and city dust have also been identified as potential sources of microplastics (Lassen et al., 2012; Magnuson et al., 2016; Sundt et al., 2014; Essel et al., 2015), with stormwater increasingly suggested to be a major source of MPs to aquatic habitats. In a recent study in San Francisco Bay, Werbowski et al. (2021) concluded that stormwater may be a more significant pathway than treated wastewater. In the Ottawa River, Forrest et al. (2022) found that a heavy rainfall event in summer or fall with strong stormwater drain overflows increased MPs concentrations by 50 times.

Tire wear is an important source of MPs in the environment. Kole et al (2017) estimated the relative contribution of tire wear to the global amount of MPs ending up in our oceans at 5-10%. In their study, Grbic et al. (2020) found that the concentrations of black particles in stormwater samples were higher in areas of increasing road density in Toronto. Tire wear particles (TWPs) also come from secondary usage when tires are ground up and used as infill in artificial turf grass, playgrounds or running lanes (Kole et al., 2017). MV municipalities such as Vancouver, Burnaby, Coquitlam, North and West Vancouver all have some synthetic turf fields (Vancouver Board of Parks and Recreation, 2016; City of Burnaby, 2018; City of Coquitlam, 2013; North Vancouver District, 2017; District of West Vancouver, 2012). Over time, those surfaces break down into MPs that can be transported to nearby watersheds (Lassen et al., 2012 and Hüffer et al., 2018).

California recently approved the world's first requirements for testing MPs in drinking water with 30 of the State's largest water providers required to test their water quarterly over two years, starting in the fall 2023 (State Water Resources Control Board, 2022).

While methods to quantify MPs have significantly improved over the past decade, it remains a challenging field to generate reliable data even more so when it comes to TWPs due to their range in texture, morphology, density, and highly complex chemical composition (Rodland et al., 2023). Grbic et al. (2020) were not able to identify TWP using Raman spectrometry due to the limitations of this instrument with black particles, however Fourier Transform infrared spectrometry (FTIR) was able to identify some of the rubber particles isolated; the rest was assumed to be from tires based on their rubber-like texture and elongated shape. Regardless of the technical challenges, information on MPs in MV water bodies would be invaluable as synthetic rubber particles from tires and fibers from textiles are expected to significantly contribute to MP contamination in urban environments (Kole et al., 2017; Grbic et al., 2020; Ziajahromi et al., 2020).

Pharmaceutical and Personal Care Products (PPCPs)

PPCPs are frequently detected in stormwater around urban areas (Masoner et al., 2019; Tran et al., 2019). The primary concerns with stormwater-driven PPCP loading in the environment are the potential for bioaccumulation and/or endocrine disruption in humans and animals (Hopkins & Blaney 2016). The European Union Water Framework Directive has identified 33 pollutants, including the PPCPs iopamidol, ibuprofen, bisphenol A, triclosan, and carbamazepine, as priorities to control in stormwater runoff, based on the potential risk to receiving water bodies. A total of 13 PPCP were detected in seawater sampled in Burrard Inlet and Victoria Harbour, including analgesics (acetaminophen, naproxen), antimicrobials (clarithromycin, ciprofloxacin, erythromycin-H20), antihypertensives (desmethyldiltiazem, diltiazem), antihistamines (diphenydramine), recreational drugs (cocaine and its metabolite benzoylecgonine), personal care products (N,N-diethyl-meta-toluamide (DEET)) and stimulants (caffeine, 1,7-dimethylxanthine) (Enkon, 2012; Krogh et al., 2017).

Chloride

Sodium chloride (NaCl) is found in road salts and fertilizers, with the primary source in Canadian urban environments being the application of road salts in winter months. This salt does not readily bind to mineral surfaces, leading to potentially high levels in surface water and shallow aquifers, the latter releasing chloride throughout the year (CCME, 2011). While MV experiences mild winter weather compared to the rest of the country, salt is still applied to roads during the colder times of winter. For example, the City of Vancouver averages nine snowfall days per year and 100 days where icy conditions are possible due to the temperatures going below 3°C (City of Vancouver, 2020). Environment and Climate Change Canada reports that 830,000 tonnes of road salt was applied to BC roads in the winter of 2020-21 (https://www.theroadsaltproject.com/facts).

Chloride can be toxic to aquatic organisms, with acute toxic effects at high concentrations and chronic effects (on growth and reproduction) at lower concentrations (Ontario Ministry of Environment (OMOE), 2003). There are growing concerns that Pacific salmon may be harmed by road salt entering urban streams (University of British Columbia (UBC), 2022).

Organophosphate ester flame retardants (OPFRs)

Flame retardants are added to a variety of products such as textiles, electrical equipment, furniture, hydraulic fluids and vehicles (Kung et al., 2022). They may also be used as plasticizers in consumer products and construction materials including polyvinylchloride (PVC), flexible and rigid polyurethane foams (PUF) and thermoplastic materials to improve their flexibility and durability (Marklund et al., 2005; Blum et al., 2019). After the ban of the well-known polybrominated diphenyl ethers (PBDEs) in Canada, organophosphate ester flame retardants (OPFRs) became widely used on the presumption that they were less persistent (Blum et al., 2019). However, recent studies suggest that chlorinated OPFRs can persist in water and undergo long-range transport via waterborne routes. Evidence of accumulation has also been reported in the remote Arctic and Antarctic environments (Suhring et al., 2016, 2020; Fu et al., 2020). Data from toxicity testing, epidemiological studies and risk assessments all suggest health concerns at current exposure levels for both halogenated and non-halogenated OPFRs (review in Blum et al., 2019).

OPFRs have been detected in municipal wastewater, surface waters, stormwater and urban precipitation (Bika et al., 2022, Zhang et al., 2023; Yao et al., 2021; Yang et al., 2019). Insulation materials in buildings may be a significant source of OPFRs in urban environments. A recent study on urban stormwater in Germany found the highest OPFR levels in commercial areas with large industrial buildings, warehouses and large retail stores followed by other densely built up land use (Wicke et al., 2021). Traffic was also identified as a source of OPFRs related to leakage of transmission and motor oils with higher OPFR levels at road intersections and at an airport in Sweden (Marklund et al., 2005).

In their 2021 screening assessment of 13 flame retardants, ECCC and Health Canada concluded that five OPFRs pose a risk of harm to the environment and concluded that they meet criteria to be listed under CEPA as they are "entering or may enter the environment in a quantity or concentration or under conditions that have or may have an immediate or long-term harmful effect on the environment or its biological diversity". In addition, one of these, isopropylated triphenyl phosphate (IPPP), is suspected of being harmful to human health. One additional OPFR was flagged due to potential concern should environmental exposure increase (Table 3; ECCC and Health Canada, 2021a).

Table 3: Organophosphate ester flame retardants of concern[1]

Name	Class	Use	Persistence (P) or bioaccu-mulation (B)	Harmful
Triphenyl phosphate (TPHP)	Aryl organo-phosphate	Adhesives and sealants, paints, lubricants, plastic and rubber formulation, food packaging, cosmetics, pest control products	P	Environment
Tert-butylphenyl diphenyl phosphate (BPDP)	Aryl organo-phosphate	Paints, lubricants, food packaging	-	Environment
Bis (*tert*-butylphenyl)	Aryl organo-phosphate	Paints, lubricants	B	Environment

phenyl phosphate (BDMEPPP)				
Isodecyl diphenyl phosphate (IDDP)	Aryl organo-phosphate	Paints, lubricants	-	Environment
Isopropylated triphenyl phosphate (IPPP)	Aryl organo-phosphate	Adhesives and sealants, paints, lubricants, plastic and rubber formulation, pest control products	B	Environment and human health
tris(2-butoxyethyl) phosphate (TBOEP)	Alkyl organo-phosphate	Paints, floor coverings, food packaging	-	Environment

[1]Adapted from ECCC and Health Canada, 2021a,b

To our knowledge, OPFR levels have only been quantified in house and fire station dust from the Metro Vancouver area (Shoeib et al., 2019; Gill et al., 2020). Given the risk that some OPFRs pose to the environment and the recent recommendations from the Government of Canada, monitoring of these compounds in urban watersheds would be valuable in establishing a current baseline and evaluating the effectiveness of regulations anticipated in the near future.

Monitoring urban waters

Sampling strategies

There are several strategies to collect water quality samples that depend primarily on the goals of the monitoring program but also budget (Table 4). An efficient sampling strategy should therefore balance available resources and data needs, but would benefit from updates over time based on results and/or new scientific knowledge.

Table 4: Different sampling strategies have different advantages and disadvantages based on the goal of the monitoring program

Sampling strategy	Definition	Pros	Cons
Grab sampling	One sample taken at a specific point and time (can be done monthly, quarterly or yearly)	-Limited number of samples collected so lower cost -Samples suitable for water quality parameters analyses and CECs	-Does not capture min, max concentrations or trends -Difficult to ensure reproducibility
Composite sampling	Multiple grab samples pooled together	-Can capture a number of samples over a desired period -Decrease the number of samples that need to be analyzed so decreased cost -Samples suitable for water quality parameter analyses and CECs	-Does not capture min, max concentrations
Automatic sampling	Devices deployed that collect samples based on predefined criteria such as flow rate, time, and water quality parameters	-Event can trigger automated (remote) sampling -Can capture min, max concentrations and trends	-Mostly useful for basic water quality parameters -Preservation needed for some analyses -Need electricity, shelter -Costly
Passive sampling	Long-term monitoring of various environmental pollutants with a single sample collection	-Reduced number of samples required to be analyzed so reduced cost. -Can include a wide range of contaminants	-Does not capture min, max concentrations or fluctuations
E-monitoring	System comprised of sensors, data storage, analysis and representation that collects real-time data	-Transmit data in real-time to a data platform -High resolution data in space and time -Capture min, max concentrations and trends	-Expensive -Still new so issues with data storage/transmission, sensor accuracy -Mostly useful for basic water quality parameters

Reviewed in Suits et al. 2023.

Water property monitoring devices

Routine water property measurements are typically conducted using spot or semi-continuous (datalogger) approaches as an initial means of characterizing water quality (Table 5). These methods are favoured as they are a relatively low-cost way to gather preliminary data on water quality.

When selecting devices to incorporate into in situ sampling for water quality monitoring, several options exist, each with their own advantages. Here we briefly discuss two types of devices frequently employed by monitoring programs: handheld multi-probe spot samplers, and semi-continuous data loggers.

Handheld multi-probe spot samplers can be equipped with a variety of sensors capable of measuring basic water properties such as dissolved oxygen, pH, temperature, turbidity, and conductivity. There are sensors available from several manufacturers which can measure additional parameters such as chloride, ammonia, ammonium, nitrates, total algae, and oxidation-reduction potential (ORP), Tryptophan-like fluorescence (TLF), TOC, among others (YSI[1], Hobo[2], Eureka Water Probes[3]). Advantages to handheld devices include portability, versatility in the field, ability to be rapidly deployed, and flexibility of use under different scheduling regimes. Drawbacks to these devices include a larger investment in labour to operate, lack of continuity of data which may not capture all factors impacting water quality, and limits to sensor options. Handheld devices typically feature a USB port for data download, and are often paired with a product-specific software which will allow users to download and visualize the data collected by the device.

Data loggers are often deployed by municipal, provincial, and federal agencies at sites where long-term continuous monitoring is of interest – such as immediately downstream of CSOs and WWTP effluent discharges (Toran, 2016). There are a variety of options with respect to data loggers including single parameter and multi-parameter devices. These have similar sensor options to their handheld counterparts and can be customized to suit the needs of a monitoring program depending on the interests and concerns. Data must be downloaded from data loggers on a regular basis by users, the frequency of which will depend on the storage capacity of the individual device deployed. New developments in this field have led to devices which can be accessed remotely by users, allowing access to data in real-time.

Integrated water monitoring systems

Recent developments in water quality monitoring have led to the integration of smart technologies and computer-mediated data acquisition into complex water monitoring systems. Examples of such are systems utilizing the Internet of Things (IoT) (Zainurin, et al. (2022)). IoT

[1] https://www.ysi.com/products/multiparameter-sondes
[2] https://www.onsetcomp.com/
[3] https://www.waterprobes.com/multi-probes-sondes-water-quality-monitoring

describes a system which includes embedded sensors, monitoring software complete with internal processing ability, and a communications component (Rose, et al. (2015)). These systems are widely used in various applications including Smart Home technology, elder care, medical, and industrial settings in the automation and control of various modular components via a central computerized hub. A major strength of IoT is its ability to generate real-time data that is remotely accessible, and which can be made available to the public via online servers. The flexibility of IoT allows for the customization of a system with respect to the needs of a wide range of water quality monitoring programs that can be programmed to include algorithms and run calculations using data-acquired to give relational data such as flow estimates. It is expected that the increasing utilization of this technology will revolutionize the field of environmental monitoring in the near future (Hart & Martinez (2015)).

Table 5: In situ water parameter monitoring for basic monitoring: device overview

Device	Use	Parameters Captured	Data	Notes
Handheld water quality multi-probe	Portable handheld spot-sampler	Basic water properties*	point measurement	can be equipped with sensors that measure nitrates, crude oil, and others.
Data loggers	Installed in situ for continuous monitoring	Basic water properties*		can be equipped with sensors that measure nitrates, crude oil, and others.
ATP Luminometer	Desktop or Handheld	ATP - correlated with presence of fecal coliforms		Measures ATP of all plant, animal, and microbial cells in a sample.
Colourimeter	Desktop or handheld	Various parameters		uses consumable reagent sachets that can be purchased for a wide variety of parameters depending on device and interest
Modular wastewater monitoring systems	Installed in situ	Various parameters including basic water properties*, ammonia and nitrates.	semi-continuous	Large modular system that can be customized to measure parameters of interest. Up to 20 parameters. Designed for use in waste -water facilities.
Internet of Things IOT-equipped monitoring stations	Installed in situ	Basic water properties* plus discharge and other parameters	Real-time semi-continuous	Uses IoT technology and algorithms to assess water quality and to estimate discharge of a system in real-time. Requires connectivity.

Handheld mass spectrometer	Portable handheld	Drugs, pesticides, explosives, and many others	Single sample	There are various portable HPMS (high pressure mass spectrometry) devices on the market, some are capable of detecting trace amounts of drugs and recently utilized in pesticide detection.

*Basic water properties include temperature, pH, dissolved oxygen, turbidity, and conductivity.

Sampling frequency

In order to provide meaningful information, sampling frequency should take into consideration several parameters including the response time of the system, half-life of water quality parameters, seasonal fluctuations and random effects, representativeness under different conditions of flow, duration of pollution events, magnitude of response, and variability of the inputs (US EPA, 1993). Depending on the goal of the monitoring plan, different sampling frequencies have been adopted by different agencies; from weekly to every five years (Table 6). Frequent samples are generally taken when the purpose of a monitoring program is to observe trends, while programs and surveys with the purpose of assessing the general state of many water bodies generally are based on low sampling frequency. It is important to note that a large proportion of the costs of operating a monitoring program is directly related to the sampling frequency.

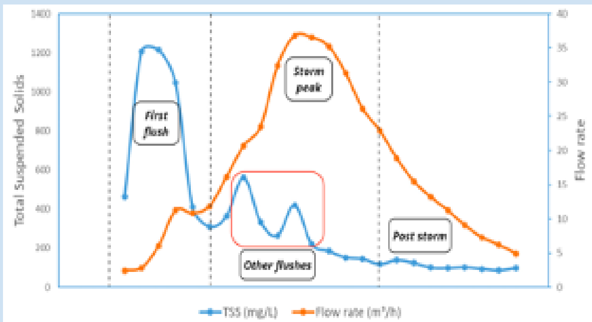
Table 6: Guidance frameworks

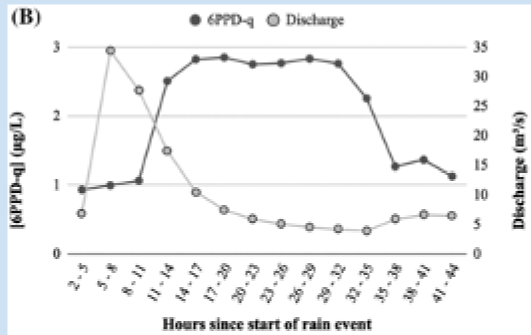
Goal of monitoring	Proposed frequency
Establish a baseline of the condition of wadeable streams and extent of major stressors[1]	Single sample every 5 years
Assess long-term trends; Establish the status of water bodies identified as being at risk of failing to meet their environmental objectives[2]	Monthly for priority substances; every 3 months for other pollutants
Assess current status and long-term trends[3]	Streams: bi-monthly and 8-18 seasonally weighed samples; Agricultural and urban sites: monthly and 12 seasonally weighed samples

Assess current status and long-term trends[4]	Trend monitoring network: monthly; Status monitoring: 1 sample
Evaluate water quality in large urbanized river as defined by the European Water Framework Directive[5]	Weekly for ammonium, nitrogen, phosphorus and Chl *a* Monthly for DO and nitrate
Implementation of the European Water Framework Directive[6]	Monthly
Routine river water quality monitoring[7]	Every 2-3 months
Long-term environmental research monitoring[8]	Every 6 months but continuous measurements are needed for accurate results
Assessment of ambient water quality status[9]	Between 4 and 12 samples per year depending on variables. Biweekly data needed for accurate results
River water quality long-term monitoring[10]	Different frequency depending on the size of the catchment

[1]US EPA, 2020; [2] European Commission, 2003; [3]Gilliom et al., 1995; [4] FDEP, 2020; [5] Vilmin et al., 2018; [6]Naddeo et al., 2007; [7]Liu et al., 2013; [8]Guigues et al., 2013; [9]Khalil et al., 2014; [10]daSilva et al., 2019

Case study: The ‘first flush’ elicits a distinct contaminant signature





Water quality parameters including total suspended solids (Suits et al., 2023) and 6 PPD-quinone (Johannessen et al., 2022) vary over the course of rainfall events with higher levels during the first flush.

In addition, watershed features and land use, as well as temperatures, contaminant behaviour and rainfall properties (intensity, duration) lead to high variability in water quality parameters (Suits et al., 2023; Balderas et al., 2022).

Determining the information needed for proper management is key when designing a sampling schedule (e.g. peak vs average flow; temporal frequency; site selection).

Indicators of sanitary infiltration in stormwater and urban waterways

Capsule

Sanitary infiltration of stormwater systems erodes water quality and negatively impacts human uses of water and the health of fish habitat. Pathogens, nutrients, surfactants and other contaminants found in liquid waste may enter regional waterways as a result of overflows of combined sewer systems, septic tank failures, infrastructure that is in disrepair, cross-connections, illegal connections, and/or spills. With only three of the 23 MV members still with Combined Sewer Overflows (CSOs), and these being targeted for elimination, it is expected that sanitary infiltration will decline over time in MV. There exist numerous technological and analytical means to detect sanitary infiltration, offering MV and its members opportunities to investigate and/or monitor storm sewers, their outfalls and urban waterways. These include visual, chemical and biological indicators, and run from very simple constituents with limited strength such as nutrients, to complex constituents that provide sensitive and meaningful insight into sanitary contamination, such as chemical tracers and microbial source tracking (MST). Some of these options may be applied in the way of performance measures that may not only inform source identification but also the effectiveness of source controls and engineering investments, such as the separation of CSOs. Of note is that wet weather or storm events may result in sudden pulses of harmful substances in waterways, followed by dilution; this is worth bearing in mind when sampling and when interpreting monitoring data.

Introduction

A rapidly changing climate and the emergence of new CECs are increasingly challenging urban infrastructure planning and performance measures. The effectiveness of stormwater and wastewater management strategies can be evaluated in order to ensure the protection of urban watersheds, recreational, cultural and institutional uses, and aquatic life. Untreated wastewater may find its way into receiving waters through Combined Sewer Overflows, incorrect or illicit connections, cross-connections between sanitary and storm sewers, and leakages into the sewers through broken lines or poor pipe joints (Brown et al., 2004). A sanitary source tracking "toolbox" can provide an efficient approach to the detection and identification of sources of pollution via illicit discharges and wastewater infiltration and guide adaptive management practices to achieve the most cost effective and measurable changes in drainage systems.

There does not exist a single marker or tracer that can adequately identify the source of contamination in surface waters, especially in complex watersheds impacted by multiple nonpoint sources of pollution (Sidhu et al. 2013, Tran et al. 2015, Staley et al. 2016, Lim et al. 2017). A "toolbox" approach that combines Chemical and Microbial Source Tracking techniques specific to the region and land use that provide multiple lines of evidence to identify pollution sources is recommended (Sidhu et al. 2013, Tran et al. 2015, Staley et al. 2016, Lim et al. 2017, Hachad et al. 2022). Some of the common microbial source tracking (MST) and chemical source tracking (CST) markers are explored in this document.

Fecal indicator bacteria (FIB, fecal coliforms, E. coli, and enterococci) have been routinely used to assess fecal contamination and public health risk in surface waters (Health Canada, 2022). Although useful to determine whether water quality guidelines are being met, the use of FIB may not be sufficient to identify sources of pollution. Since FIB can be present in the feces of different animals, it can be difficult to distinguish between human and non-human animal sources (Tran et al. 2015). The use of alternative microbiological and chemical indicators to detect, identify and track sources of pollution has been on the rise due to their higher specificity to pollution sources (Tran et al. 2015, Staley et al. 2016, Hachad et al. 2022).

Microbial source tracking techniques use microbial DNA markers that are specific to a particular host species to trace fecal contamination to a particular species or source (e.g. human, dog, gull or livestock) (Edge and Schaefer 2006, Teaf et al. 2018). Chemical source tracking techniques employ routinely used compounds to identify the presence of wastewater in stormwater and receiving environments. CST techniques are generally limited to anthropogenic sources of pollution. These techniques can be applied when routine monitoring and assessment measures either signal a concern or fail to identify pollution sources.

Chemical source tracking

Primary chemical indicators

The basic water properties and parameters listed in Table 7 (included in Tier 1 and 2) can be used as the initial screen to identify the potential source of a discharge. These parameters are not sufficiently powerful to directly identify a source of pollution but can be used to determine the likely source and whether further investigation with more advanced methods is warranted (Clary et al. 2014). Clary et al. (2014) classified non-stormwater discharge flows that infiltrate stormwater into three different categories (in order of priority):

1. pathogenic or toxic pollutant sources (e.g. raw sanitary sewage),
2. nuisance and aquatic life threatening pollutant sources (e.g. laundry waste, landscaping irrigation runoff, automobile washing),
3. unpolluted water sources (e.g., natural springs, infiltrating groundwater) (Clary et al. 2014, Brown et al. 2004).

Table 7. Indicator parameters used to detect potential illicit discharges or cross-connections

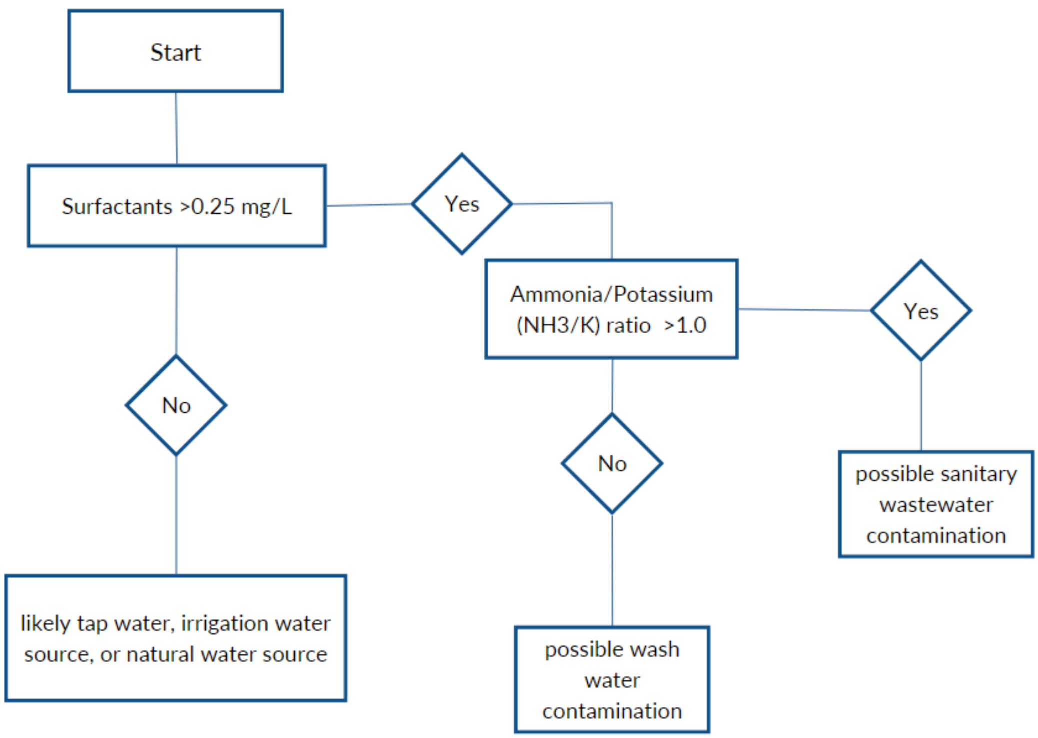
	Discharge type detected[1]				
Parameter	**Sewage**	**Wash water**	**Tap water**	**Industrial or commercial liquid wastes**	**Benchmark for further investigation**
ammonia	● (green)	● (yellow)	● (pink)	● (yellow)	>1.0 mg/L
colour	● (yellow)	● (yellow)	● (pink)	● (yellow)	any discoloration not attributed to natural phenomenon
conductivity	● (yellow)	● (yellow)	● (pink)	● (yellow)	
detergents-surfactants	● (green)	● (green)	● (pink)	● (yellow)	>0.25 mg/L
E. coli	● (green)	● (pink)	● (pink)	● (pink)	400 CFU/ 100mL
pH	● (pink)	● (yellow)	● (pink)	● (yellow)	< 5 or >9
potassium	● (yellow)	● (pink)	● (pink)	● (green)	NH_3/P >1.0 mg/L
turbidity	● (yellow)	● (yellow)	● (pink)	● (yellow)	
● (green) Almost always (>80% of samples) distinguish this discharge from clean flow types					
● (yellow) Sometimes (>50 % of samples) distinguish this discharge from clean flow types depending on regional characteristics or can be helpful in combination with another parameter					
● (pink) Poor indicator. Cannot reliably detect illicit discharges or tap water.					

1- Adapted from Brown et al. 2004.

Brown et al. (2004) developed a reliable method to identify the likely flow component infiltrating stormwater by fingerprinting the chemical characteristics of source samples. The Flow Chart Method (Figure 5) which applies ammonia, potassium, and surfactants as reliable tracers, is recommended because it is a relatively simple technique that can focus further source investigations (Clary et al. 2014). Although the ammonia/potassium ratio is a good way to distinguish sewage from wash water and should capture the majority of sewage discharges, the exact ratio may vary in different regions and water quality managers should evaluate the ratio in their own community (Brown et al. 2004).

The King County Illicit Connection and Illicit Discharge Field Screening and Source Tracing Guidance Manual provides detailed methods for field testing ammonia, potassium and surfactants as part of the preliminary screening process (Herrera and Aspect 2020). Surfactants can be measured in the field using test kits which commonly use a methylene blue active substances (MBAS) extraction method. As the surfactant field test kits typically contain Chloroform and sulfuric acid, staff must be trained in safe handling and disposal of hazardous substances (Herrera and Aspect 2020).

Figure 5. A basic screening tool used to detect cross-connections or illicit discharges in residential watersheds



Where select parameters indicated that further investigation was necessary, advanced chemical source tracking and microbial source tracking techniques may be applied to determine the specific sources of pollution. Adapted from Brown et al. (2004).

Chemical Tracers

Various chemical classes such as PPCPs, artificial sweeteners (ASs), and fecal sterols have been identified as potential tracers of anthropogenic pollution in aquatic ecosystems (Lim et al. 2017, Tran et al. 2019, Hachad et al. 2022). Chemical indicators assist with the identification of sources, the identification of recent or prior wastewater contamination, and the evaluation of the effectiveness of wastewater and stormwater management practices (Lim et al. 2017). Chemical indicators have relatively fast and sensitive detection methods, tend to be stable in the environment, and are source-specific (Panasiuk et al. 2015, Lim et al. 2017, Hajj-Mohamad et al. 2019). However, the presence of a chemical indicator does not guarantee contamination by wastewater, it can lack specificity, and may be impacted by environmental factors such as degradation and sorption (Lim et al. 2017).

The properties of a given substance and its transport and fate in the environment determine if a certain compound may be used as a suitable indicator (Sauvé et al. 2012). The solubility of a compound will determine its bioavailability in the environment. The octanol-water partition coefficient K_{ow} is commonly used to differentiate hydrophilic and hydrophobic compounds (Tran et al. 2015). Hydrophilic compounds, with a K_{ow} equal to or lower than 3.0, can be used to identify and quantify contamination in surface water and groundwater. Hydrophobic compounds tend to deposit in sediments during rainstorms, boating, dredging and other activities (Tran et al. 2015). It is also important to consider the persistence of chemical indicators in the environment, suggested by their half-lives, as this can provide clues to whether the contamination was due to a recent or past event (Sidhu et al. 2013, Tran et al. 2015, Lim et al. 2017).

PPCPs and ASs are consumed by people, excreted in urine and feces, and may be either removed by WWTPs or pass through the system unchanged (Sidhu et al. 2013, Panasiuk et al. 2015, Tran et al. 2015). The elimination rate of chemical markers in WWTP is referred to as removal efficiency, and represents an important characteristic to consider when selecting chemical indicators for source tracking (Tran et al. 2015). Compounds that are effectively removed in WWTP (often removed by more than 90%) can be used to identify raw wastewater discharges such as combined sewer overflows (CSOs) or leaky sewers (Oppenheimer et al. 2011, Luo et al. 2014). Conservative compounds that are not removed in WWTP can be helpful to trace the pathways of treated wastewater (Tran et al. 2015). Table 7 summarizes some of the common and established applications of chemical indicators.

Some of the commonly used chemical indicators to track human fecal pollution and their characteristics, such as removal efficiency in WWTP and persistence in the environment, are described in Table 8. This list is not exhaustive; for a more comprehensive list, see Warner et al. (2019) or Tran et al. (2015). The utility of these tracers, individually or as part of a wider suite, is summarised in Table 9.

Table 8. Summary of typical characteristics of chemical indicators for tracking human fecal pollution

Indicator	Classification	Solubility (log K_{ow})	Range of reported removal efficiencies in WWTP (%)	Persistence in the environment[1]
acesulfame (ACE)	artificial sweetener	-1.33	21.5[2]-41[3]	half-life of 4.2–7.8 days under joint effect of microbial degradation and natural sunlight photolysis[4,5]
acetaminophen (ACT)	labile and hydrophilic PPCP	0.46	97[6]-99.9[7]	aerobic degradation half-life of 50 hr in river water samples photolysis half-lives of 35-56 h under sunlight exposure[8]
caffeine (CF)	labile and hydrophilic PPCP	-0.07	49.9-99.6[6,7]	half-life of 3.5 to 100 days in estuarine and coastal marine samples, lower values in eutrophic waters[9]
carbamazepine (CBZ)	persistent and hydrophilic PPCP	2.45	10[10]-23.1[6,7]	half-life of >100 days in estuarine and coastal marine samples[9]
Cholesterol	fecal sterol	8.74	85[6]	Half-life of less than 10 days under aerobic conditions[11]
coprostanol (COP)	fecal sterol	8.82	97[6]	Half-life of less than 10 days under aerobic conditions[11]
sucralose (SUC)	Artificial sweetener	-1	<20[2,3]	half-life of 8-124 days in soil incubation experiments[5]

[1] Adapted from Tran et al. 2015; [2]Tran et al. 2014; [3]Scheurer et al. 2009;; [4]Gan et al. 2014; [5]Buerge et al. 2011; [6]Oppenheimer et al. 2011; [7]Behera et al. 2011;; [8]Yamamoto et al. 2009; ; [9]Benotti and Brownawell 2009; [10] Lajeunesse et. al 2012; [11]Isobe et al. 2002 ;.

Fecal sterols/stanols

Fecal sterols are a group of cholestane-based sterols formed as metabolic products in the digestion of sterols in humans and animals (Isobe et al. 2002, Sargent et al. 2011). The feces of humans and animals contain a variety of sterols based on their diet, digestive processes, and gastrointestinal bacteria (Shah et al. 2007). Coprostanol (COP) is the most abundant in human feces and has been proposed as a marker for human fecal contamination due to its persistence during transportation in the environment (Isobe et al. 2002, Tran et al. 2015). Since coprostanol is hydrophobic (high log K_{ow}), it readily adsorbs to bottom sediments and has a reported half-life of less than 10 days in aerobic conditions (Isobe et al. 2002).

The differences in sterol profiles in human and animal feces can be used as "sterol fingerprints" to distinguish between human sources and those of other animals (Leeming et al. 1996). Several sterol ratio indices have been developed to successfully exclude and/or identify potential sources of fecal pollution (Shah et al. 2007, Lim et al. 2017). However, these methods cannot determine the percentage contribution of human or animal feces in mixed samples (Shah et al. 2007).

Caffeine

Being one of the most consumed psychoactive substances in the world, caffeine has been proposed as a distinct indicator of anthropogenic pollution in surface waters (Buerge et al. 2003, Daneshvar et al. 2012, Sauvé et al. 2012, Quadra et al. 2020). Caffeine removal in WWTP processes is generally greater than 90% making it a sensitive tracer of untreated sanitary wastewater, CSOs, and illicit discharges (Behera et al. 2011, Oppenheimer et al. 2011, Luo et al. 2014). With a half-life ranging from 3.5 days to 100 days (Benotti and Brownawell 2009), elevated levels of caffeine in surface waters strongly suggest a recent human fecal contamination event (Daneshvar et al. 2012).

The implementation of a caffeine sampling and testing program may provide a useful tool to identify sanitary contamination sources and help reduce surface water contamination (Sauvé et al. 2012). Caffeine concentrations in surface water are sufficiently high for reliable analytical quantification (Buerge et al. 2003) with low detection limits of less than 1.0 ng/L (Cantwell et al. 2016).

Carbamazepine

Carbamazepine (CBZ) is a commonly prescribed antiepileptic drug and mood stabilizer which enters the aquatic environment primarily through municipal wastewater effluent (CCME 2018). Although it is not as widely consumed by the public as caffeine or artificial sweeteners, it is one of the most persistent pharmaceuticals in the estuarine environment (Allen et al. 2012, Daneshvar et al. 2012, Sauvé et al. 2012). Studies have shown that concentrations of CBZ remain relatively unchanged after secondary wastewater treatment processes, such as activated sludge systems, with reported average removal efficiencies of only 10 - 23.1 % (Lajeunesse et al. 2012, Oppenheimer et al. 2011, Behera et al. 2011). Since CBZ is easily detected and highly persistent in the environment, it has been frequently used as an indicator of wastewater contamination in surface water and groundwater (Clara et al. 2004, Daneshvar et al. 2012, Panasiuk et al. 2015). With a half-life greater than 100 days in estuarine environments (Benotti and Brownawell 2009), CBZ is a promising tracer of cumulative persistent contamination (Daneshvar et al. 2012).

The application of CBZ as a wastewater indicator may require special analyses with sufficient analytical sensitivity (Benotti and Brownawell 2009, Panasiuk et al. 2015). The highest reported concentration in Canadian surface waters was approximately 1 ug/L in a river system downstream from 11 wastewater treatment plants in southern Ontario (CCME 2018).

Case study: Assessing caffeine as a tracer of wastewater contamination in Boston Harbor (USA)

In June 2015, the USEPA measured caffeine at 25 sites throughout Boston Harbor to identify temporal trends, evaluate the utility of caffeine as a tracer for untreated sanitary wastewater (CSOs and nonpoint discharges), and assess the efficacy of infrastructure improvements. Caffeine concentrations ranged from 15- 185 ng/L from the outer to the inner harbor. They compared their results to historic caffeine data from 1998 to 1999 and saw a significant reduction of caffeine concentrations (by a factor of 20) within the inner harbor. These results provided evidence of the improvement from the long-term upgrades to wastewater treatment infrastructure which has reduced CSOs. During the 2015 sampling, the spatial distributions of caffeine accurately mapped the CSO discharges that occurred within the inner harbor, identifying CSOs as the primary current source of sanitary contamination to the inner harbor. These results provide an example of the use of caffeine as an effective tracer of untreated sanitary wastewater in urban estuaries.[1]

1- Cantwell, M. G., Katz, D. R., Sullivan, J. C., Borci, T., & Chen, R. F. (2016). Caffeine in Boston Harbor past and present, assessing its utility as a tracer of wastewater contamination in an urban estuary. Marine Pollution Bulletin, 108, 321–324.

Acesulfame and sucralose

Acesulfame (ACE) and sucralose (SUC) are two popular artificial sweeteners in North America. ACE and SUC are not metabolized in the human body and therefore most of the ACE and SUC consumed ends in wastewater and septic systems (Marazuela et al. 2023). Being highly resistant to most WWTP processes, ACE and SUC enter the environment via municipal wastewater effluent and are readily distributed in surface water and groundwater (Oppenheimer et al. 2011, Spoelstra et al. 2013, Van Stempvoort et al. 2020, Marazuela et al. 2023).

ACE and SUC present some advantages over other chemical tracers. In comparison to CBZ, ACE and SUC are more widely used and are found at higher concentrations (Van Stempvoort et al. 2020). ACE and SUC are more persistent than caffeine (Warner 2019). These characteristics make ACE and SUC powerful tracers of the impact of municipal wastewater and septic plumes on receiving waters (Spoelstra et al. 2013, Van Stempvoort et al. 2020).

Reported detection limits in Canadian laboratories for ACE and SUC are 0.002 and 0.02 ug/L, respectively (Van Stempvoort et al. 2020). One of the disadvantages of SUC is that its detection limit is an order of magnitude higher than ACE, such that the latter may be detected when SUC is not (Buerge et al. 2009, Van Stempvoort et al. 2020). Van Stempvoort et al. (2020), suggest that both be used as co-tracers, given that one or the other may degrade under some conditions (2020).

Acetaminophen

Acetaminophen (ACT) is one of the most commonly used analgesics and has been studied as a potential tracer of untreated wastewater (Sidhu et al. 2013). With wastewater treatment plant removal efficiencies of 97 to 99.9%, ACT is a useful tracer for the contamination of surface waters from untreated wastewater, leaky sewers, or CSOs (Benotti and Brownawell 2007, Oppenheimer et al. 2011, Sidhu et al. 2013). Since ACT is likely to degrade quickly in the environment, its presence in surface waters may indicate a recent raw sewage contamination event (Tran et al. 2015, Staley et al. 2016).

Table 9. Summary of chemical indicators for source tracking applications

Application[1]	Indicator	Notes
Detection of domestic wastewater	carbamazepine	persistent compounds
	acesulfame	
	sucralose	
Detection of untreated wastewater	caffeine	compounds eliminated during WWTP process
	acetaminophen	
Intrusion of wastewater to groundwater	carbamazepine	
	sucralose	
Differentiation between treated and untreated wastewater (ratios)	caffeine/sucralose (C/S)	compound with high WWTP removal (>80%)/compound with low removal (<20%)
	caffeine/carbamazepine (C/CBZ)	
Quantification of the impact of a combined sewer overflow	caffeine	
Urban runoff	nicotine	
Agricultural runoff	current use pesticides	some can also be found in urban areas applied in facades or public gardens

1- Adapted from Warner et al. 2019.

Microbial source tracking

MST techniques are valuable tools for identifying and tracing the sources of microbial pollution in stormwater. MST uses microbial DNA markers that are specific to a particular host species to trace fecal contamination to a particular source species (e.g. human, dog, gull, cow) (Edge and Schaefer 2006, Teaf et al. 2018). Although there are numerous MST methods, each has limitations and there is no universally accepted best method (Edge and Schaefer 2006). MST experts therefore recommend the use of a comprehensive "toolbox approach" for identifying the sources of fecal contamination (Boehm et al. 2013, Layton et al. 2013, Demeter et al. 2023). This approach involves combining multiple MST markers, detection methods, and sampling strategies to acknowledge the limitations of individual markers and achieve more reliable and conclusive characterization of fecal pollution (Holcomb and Stewart 2020). The use of MST toolkits has become increasingly common in routine water quality monitoring in support of informed management decisions (Harwood et al. 2017).

MST detection methods

The first MST methods developed in the early 2000s were library-dependent methods (Demeter et al. 2023). These require a biochemical (phenotypic) or molecular (genotypic) fingerprint for bacterial strains isolated from fecal sources which are then compared to developed libraries to identify specific sources (US EPA. 2005, Demeter et al. 2023). The library had to contain a large number of isolates that are geographically specific for reliable source identification (USEPA, 2005). Over the past decade of MST research, there has been a shift from library-dependent methods to qualitative Polymerase Chain Reaction (PCR) and quantitative PCR (qPCR) or digital PCR (dPCR) techniques that target specific genes of host-associated bacteria (Layton et al. 2013, Teaf et al. 2018). These do not require the development of a library database and the techniques can be rapid (Sargent et al. 2011).

Molecular techniques including real-time qPCR are being increasingly adopted due to their speed of use, their high specificity, and their increased flexibility to detect and quantify a variety of specific targets (Layton et al. 2013, Harwood et al. 2014, Dorevitch et al. 2017, Shanks and Korajkic 2019, Demeter et al. 2023). Several qPCR assays have now been developed and revised by the US EPA (Shanks and Korajkic 2019, US EPA 2019). A limitation of qPCR is its vulnerability to polymerase function inhibition from common substances present in environmental waters (Griffith and Weisberg 2011, Sherchan et al. 2022). Furthermore, qPCR requires a calibration model for quantification (Demeter et al. 2023).

Digital PCR is a more recent PCR approach that has increased sensitivity and robustness to inhibitory substances and does not require standards for quantification (Cao et al. 2015, Holcomb and Stewart 2020). As such, it is likely to become an alternative to qPCR for water monitoring and source tracking, and some qPCR assays have already transitioned to dPCR (Cao et al. 2015, Zimmer-Faust et al. 2021). For example, dPCR has been adopted by San Diego County for routine beach water quality monitoring (Borchardt et al. 2021).

Technological advances in next generation DNA sequencing (NGS) technology methods have enabled the identification of entire microbial communities of environmental samples and pollution sources, characterizing thousands of sequences in one sample (Zimmer-Faust et al. 2021). One microbial community analysis (MCA) approach for fecal source identification involves a comparison of the sample to a local fecal reference sequence library to identify specific sources of fecal contamination. Another is to apply a library-independent method where profiles in the samples are compared to determine spatial and temporal gradients (Griffith et al. 2013, Demeter et al. 2023). Advanced bioinformatics tools such as SourceTracker, or fast expectation-maximization microbial source tracking (FEAST) are required to analyze and interpret the data (Demeter et al. 2023). Although MCA provides additional benefits to MST studies, it comes at a dramatically higher cost and requires extensive expertise and technology (Griffith et al. 2013).

Recent advances in the validation and standardization of MST methods have driven a shift towards the implementation of MST techniques for water quality management (Harwood et al. 2017, Demeter et al. 2023). MST methods and bioinformatics tools continue to be developed with improved sensitivity and accessibility, such that MST methods will likely become fully operational in the near future (Harwood et al. 2017).

Successful application of MST methods requires careful consideration of sample collection, handling, preservation, method selection, case analysis, result interpretation, validation, and quality assurance (Teaf et al. 2018). MST techniques include both traditional and molecular approaches (Table 10).

MST markers

A MST marker is a genetic marker that is strongly associated with a specific host species, generally a bacterial, viral or bacteriophage species (Paruch and Paruch 2022). The ideal MST marker should be widely present in the target population while being either absent or detected only at significantly lower concentrations in non-target pollution sources in the study area (Harwood et al. 2017). Many MST markers have been proposed and validated, and many more are in development (Layton et al. 2013, Demeter et al. 2023).

Human-source MST markers

Pinpointing human fecal sources in complex watersheds has been a high priority for water quality managers. As a result, many studies have aimed to identify a consistent and accurately measured genetic marker strongly associated with human feces (Boehm et al. 2013, Layton et al. 2013, Demeter et al. 2023). The most thoroughly studied genetic marker for human-specific pollution is HF183 found in *Bacteroides,* which live almost solely in the human gut (Converse et al. 2009, Boehm et al. 2013, Layton et al. 2013, Shanks and Korajkic 2019). It has consistently been identified as the most sensitive and specific of human markers in several evaluation studies (Boehm et al. 2013, Layton et al. 2013). For instance, Layton et al. (2013), tested 40 different fecal source identification technologies by a panel of 27 expert laboratories with double-blind samples and HF183 qPCR performed the best.

Due to its high performance, it has been recommended for assessing water quality in California (Holden et al. 2011, Griffith et al. 2013). In 2019, the US EPA developed a draft HF183 qPCR method (Method 1696) being one of the first established standardized procedures for qPCR MST human markers (US EPA 2019a). The limitation of HF183 is that it has been found to occasionally detect chicken or dog feces (Griffith et al. 2013). As such, it is recommended to pair the HF183 with HumM2, another human-specific marker that has an established procedure developed by the US EPA (Method 1697) (US EPA 2019b). Though less sensitive, HumM2 qPCR has also performed well (Griffith et al. 2013).

Case study: Monitoring water quality impacts following Hurricane Harvey

On August 25, 2017, extreme flooding caused by Hurricane Harvey damaged wastewater infrastructure in southeastern Texas, USA resulting in sewage overflows and contamination of floodwaters. Following Hurricane Harvey, Kapoor et al. 2018 measured levels of fecal indicator bacteria (*E. coli* and enterococci) and human MST markers (HF183 and BacHum) to identify and quantify the extent of fecal contamination into the Guadalupe River and Gulf of Mexico. The study results showed that the most heavily flooded areas had the highest FIB and MST concentrations, confirming that a large number of sewage overflows occurred during Harvey flooding. These findings provided the “baseline information” required to monitor long-term environmental impacts from Hurricane Harvey and were used to create a dynamic fecal source model for surface waters impacted by wastewater overflows during extreme flooding events.[1]

1- Kapoor, V., Gupta, I., Pasha, A.B.M.T., and Phan, D. 2018. Real-Time Quantitative PCR Measurements of Fecal Indicator Bacteria and Human-Associated Source Tracking Markers in a Texas River following Hurricane Harvey. Environmental Science and Technology Letters, 5: 322–328. doi:10.1021/acs.estlett.8b00237.

Viral human markers such as Human Adenovirus or Human Polyomavirus can be used to supplement human bacterial markers if needed (Griffith et al. 2013, Paruch and Paruch 2022). Human viral markers are typically highly specific but difficult to detect in most environmental samples as concentrations in the environment tend to be very low (low sensitivity) (Harwood et al. 2014). They are also more costly and require more specialized expertise than bacterial qPCR methods (Clary et al. 2014).

Non-human source MST markers

Non-human MST markers should also be included in the MST analysis if there is suspected animal contribution to the watershed (Hachad et al. 2022). Sometimes results may show high FIB concentrations with low human marker concentrations, indicating that the major sources of fecal pollution are animal sources (Clary et al. 2014). The US EPA has developed qPCR methods for cattle MST markers (CowM2, CowM3) and dog MST markers (DG3, DG37) (Table 11) (Shanks et al. 2020). Griffith et al. (2013) provided SOPs for additional non-human markers for pigs (pig2Bac qPCR), gulls (Gull2, Lee Seagull), and horses (Horse Conventional qPCR) (Clary et al. 2014).

Case study: Remediation of Bluffer's Park Beach in Toronto Area of Concern

Since the 1980s, Bluffer's Park Beach in the Toronto and Region Area of Concern had commonly exceeded beach water quality guidelines for more than 80% of the beach season. In 2005, microbial source tracking methods including library-dependent (antibiotic resistance and rep-PCR DNA fingerprinting of *E. coli* isolates) and library-independent (human HF183 bacterial DNA marker) methods identified animal fecal contamination as a more significant source of *E. coli* contamination at the beach than human sewage. They concluded that localized bird droppings were the primary source of *E.coli* into beach waters.

In response, the City of Toronto and the Toronto and Region Conservation Authority started a new bird management program and a marsh and dune restoration from 2006 to 2008 to prevent marsh and parking lot run-off from entering the beach. This significantly improved water quality at Bluffer's Park Beach, which received an internationally recognized Blue Flag designation in 2011.[1]

1- T.A. Edge, S. Hill, A. Crowe, J. Marsalek, P. Seto, B. Snodgrass, R. Toninger & M. Patel (2018): Remediation of a Beneficial Use Impairment at Bluffer's Park Beach in the Toronto Area of Concern, Aquatic Ecosystem Health & Management, DOI: 10.1080/14634988.2018.1497401

Table 10. Common MST methods to identify fecal contamination

	Indicator[1]	Application	Advantages	Disadvantages
traditional	Culture-based fecal indicator bacteria (E. coli, enterococci)	human health hazard identification, regulatory compliance	simple, inexpensive, reliable	not specific, no source identification, long turnaround time
molecular methods	Human MST markers (eg. HF183, HumM2, human adenovirus)	indicator of human fecal contamination in surface and stormwater	greater sensitivity and specificity, faster than culture-based methods	higher materials cost, shorter history of use
	Non-human MST markers (eg. CowM2, DG3, Gull2)	used as indicator of non-human fecal contamination (dogs, cattle, birds)	greater sensitivity and specificity for non-human fecal contamination	may not cover the full range of potential sources, especially in complex ecosystems with diverse wildlife
	DNA fingerprinting	determine source of contamination	distinguishes any source	relatively time consuming and expensive analysis

1- Adapted from Clary et al. 2014.

Table 11. qPCR Assays developed by US EPA

qPCR Assay[1]	Organism	Origin	Reference
HF183/BacR287	Bacteroides spp.	Human	(Green et al. 2014a)
HumM2			(Shanks et al. 2009)
CowM2		Cattle	
CowM3			
DG3		Dog	(Green et al. 2014b)
DG37			
CPQ_056	CrAssphage	Human	(Stachler et al 2017)
CPQ_064			
Entero1a	Enterococcus spp.	General	(Siefring et al. 2008)
EC23S857	E. coli		(Chern et al 2011)

1- Adapted from Kralj et al. 2021.

As the diversity of available sanitary tracers continue to expand, it becomes crucial to carefully assess and select the most suitable indicator for a specific application (Paruch et al., 2022). Expert knowledge on the advantages and limitations of different methods is necessary to identify effective and specific tracers for the region, geography, land use pattern and hydro-climatic influences (Lim et al. 2017). The absence of standardized approaches for field implementation and interpretation can create challenges during the process (Cao et al. 2018). Some of the more recent methodologies are costly and require expert support, and may have limited long-term datasets. The combination of multiple indicators and approaches increases confidence in the identification of pollution sources (Table 12).

Table 12. Comparative analysis of basic tools, chemical and microbial source tracking tools available for identifying sanitary sources of contamination

Tool[1]	Best Use	Caveats and challenges	Cost
Visual surveys	Homeless encampments, sites with frequent daytime use, under bridges, obvious contamination	Feces could be contained in newspaper or plastic bags	$
Geographic Information Systems GIS	Essential for planning and analyzing data in relation to infrastructure. Useful to target further investigations.	Requires accurate and detailed data for both storm drains and sanitary sewers	$
Dry weather outfall screening	Identification of flowing outfalls for water quality sampling, and physical observations (odor, color, floatables, deposits, stains)	Can come from contaminated or uncontaminated sources	$
Fecal Indicator Bacteria FIB (*E. coli* and enterococci)	Basic indicator of potential fecal contamination tied to regulatory receiving water limits	Recommended in conjunction with additional chemical or molecular tests. Extensive sampling is required to account for variable results.	$
Chemical indicators (basic flow fingerprinting/ non-human chemistry)	Essential for planning and analyzing data in relation to infrastructure. Useful to target further investigations	May not identify small wastewater leaks that are diluted by stormwater or other flows.	$
Advanced chemical indicators (markers of human waste)	Finding sewage leaks, characterizing stormwater and CSO discharges. Examples: sucralose, caffeine, carbamazepine	Plan repeated sampling to account for variable results. Sample more than one indicator to increase confidence.	$$
Closed circuit television CCTV of Storm Drains	To confirm where sampling data suggests sustained input of wastewater	Operators should look carefully at leaks and not clean the lines firs (in order to see solids on bottom of storm drain)	$$

Basic Dye test	To confirm where sampling data suggests sustained input of wastewater	Use bright green dye and UV light to look for dye in storm drains	$
Smoke test	Best for limited geographic areas with strong evidence for direct connections	Difficult in large pipes and densely populated areas	$$
Dye with rhodamine probe	Best for testing suspected sewage infiltration to storm drains when persistent human-waste markers are found	A fluorometer can be used to detect significantly lower concentrations. Applied after a cross connection or leak is suspected	$$
Automated continuous flow gauges, sensors and autosamplers	Best for drains and streams with evidence of higher flows, supports load estimation	Check specs carefully to find flow gauges suitable for dry weather flows	$$ (initial)
Human-specific MST markers	Best tool for quantifying inputs of human waste. Best for sampling in streams, storm drain outfalls	Plan repeated sampling to account for variable results. Requires more expertise and high cost.	$$$
Community approach, Next generation sequencing (NGS), eDNA	Best for sampling along a gradient of suspected inputs, may provide ability to discern human sources or identify animal sources for which markers have not been developed.	Requires more expertise and cost. It is recommended this work is conducted by qualified university researchers.	$$$$

1- Adapted from Clary et al. 2014.

Chemical and microbial indicators serve as valuable additions to routine monitoring and assessment measures, facilitating the identification of pollution sources. These indicators therefore provide valuable guidance for the implementation of best management practices, infrastructure improvements, and remediation efforts. There is no universally-accepted indicator, with each indicator having its advantages and limitations. Chemical indicators can be effective at tracking and characterizing anthropogenic sources of pollution. The specific physicochemical characteristics of the indicators allow the discrimination of raw wastewater, treated wastewater, recent discharges, and prior discharges. Recent advances in MST methodologies have allowed for microbial indicator application to fecal pollution investigations. Employing the combination of CST and MST tracers strengthens water quality interpretations and overcomes limitations from specificity, sensitivity, or persistence in the environment.

Water quality topics and protocols from other jurisdictions

Capsule

Practices around liquid waste management, monitoring and evaluation vary widely around the world. This helps to address local concerns, priorities and aspirations, but constrains a fulsome comparison of performance metrics across comparable jurisdictions. These disparate approaches provide an opportunity for Metro Vancouver and its members to learn from the many experiences of others, and to craft a proactive approach to water quality monitoring over the next decade. The derivation of meaningful and understandable performance measures shape communication tools that speak to the effectiveness of investments in green infrastructure, source control efforts and regulatory developments.

Introduction

Urban development and population growth are putting significant pressures on aquatic ecosystems. Urban discharges may include runoff, stormwater discharges, or CSOs, and can carry waste and pollution to nearby aquatic environments. The value of healthy aquatic habitats and the perception of stormwater has changed considerably over the past decades such that many major municipalities in North America have been developing stormwater quality monitoring programs. These programs are an essential component of developing best management practices and ensuring healthy aquatic ecosystems. They are also important in terms of protecting public health. In this section, we present examples of water quality monitoring program components from a selection of major Canadian and US jurisdictions.

Water properties and sampling devices

Despite the growing interest in water quality monitoring in North American jurisdictions, sampling methodologies and frequencies vary, with different authorities employing different approaches. Examples can be viewed in Table 13. Differences in the frequency of sampling can largely be attributed to the devices employed by monitoring programs, with dataloggers offering semi-continuous sampling and hand-held spot samplers being used in less frequent sampling programs.

Table 13: Examples of in situ sampling techniques employed by various North American Municipalities

Municipality	Parameters measured in situ	Devices used	Frequency of sampling
Metro Vancouver Fraser River Environmental Monitoring Program	Basic water properties*	YSI ProDSS	Annually (Each location is sampled five times—once per week over a five-week period)
Metro Vancouver Burrard Inlet and Strait of Georgia Environmental Monitoring Program	Basic water properties *, Turbidity, ORP, Coloured Dissolved Organic Matter (CDOM), Chl A, Tryptophan	Seabird Electronics (sensors SB 3, 4, 43, 27), Seapoint (turbidity), Wet Labs (CDOM), Turner Cyclops 7F	Annually (Each location is sampled five times—once per week over a 30-day period)

		(Chl A and Tryptophan)	
Toronto[1]	Basic water properties*	Handheld multi-probe spot sampler	Monthly
Indianapolis[2] (Via IDEM)	Basic water properties*	YSI multiparameter Sonde data loggers	Continuous over one year – rotating through water bodies on a yearly schedule.
Edmonton[3]	Basic water properties*	YSI Multiparameter Sonde data loggers	Continuous – except in April when loggers are removed to prevent damage due to ice break-up.
New York[4] (NYSDEC)	Basic water properties*	multi-probe spot sampler	4x yearly, rotating through different basins each year
Chicago[5]	Tryptophan-like fluorescence (TLF) with temperature, and turbidity to capture CSO overflow activity and microbial water quality	Proteus probes: Real-time continuous data loggers	Continuous – real time measurements taken every 15 minutes
Halifax - LakeWatchers [6]	Basic water properties*	YSI multi-probe spot sampler	Twice yearly in the spring and summer.

*Basic water properties include temperature, pH, dissolved oxygen, turbidity, and conductivity.

Most municipalities (in conjunction with Provincial, State, and Environmental authorities and organizations) incorporate both in and ex situ sampling techniques to assess water quality. This table summarizes the in situ techniques, sampling frequency, and devices in use. ([1] Lambe, L. (2021). 2020 Annual Surface Water Quality Summary.[2] IDEM (n.d.) Surface Water Monitoring (Accessed August 2023) <https://www.in.gov/idem/cleanwater/surface-water-monitoring/> [3]Buendia-Fores, C., & Emmerton, C. A. (2021). The WaterSHED monitoring program: Technical progress report 2018-2019. Government of Alberta, Ministry of Environment and Parks.[4] NYSDEC (n.d.) Water Quality Monitoring (Accessed August 2023) <https://www.dec.ny.gov/chemical/23848.html>[5] H2Now Chicago Waterway Monitoring (n.d.) Data (Accessed August 2023) <https://www.h2nowchicago.org/data> [6] Halifax LakeWatchers (n.d.) LakeWatchers (Accessed August 2023) https://www.halifax.ca/about-halifax/energy-environment/lakes-rivers/lakewatchers)

Microbial and chemical source tracking

MST and CST to identify fecal sources in Toronto Harbour and Don River watershed

A study conducted within the Toronto Harbour and Don River watershed employed MST molecular markers (HF183, Gull4, human mitochondrial DNA, and Canada goose mitochondrial DNA) and human-associated CST markers (caffeine, acesulfame, carbamazepine) to investigate sources of fecal contamination and to identify hotspots of sewage contamination (Edge et al., 2021). The multiple lines of evidence approach consistently identified human sewage and bird fecal contamination in Toronto Harbour and Don River watershed during wet and dry weather. Elevated concentrations of HF183 and chemical markers in dry weather revealed widespread cross-connection contamination into stormwater. The use of MST and CST markers was important in detecting evidence of sewage cross-connection even when E. coli concentrations were low. The study results were used to identify priority areas for restoration and remediation.

The City of Toronto has since embarked on a significant stormwater management program with substantial infrastructure projects to improve water quality in the Toronto Harbour and Don River Watershed. The established benchmarks from this study will be useful to evaluate the success of water quality improvements in these areas.

Locating illicit discharges in storm sewers in Montreal using a multiparameter source tracking toolbox

In a study conducted in Montreal, researchers applied a multiparameter source tracking toolbox that combined chemical markers for wastewater (including caffeine, theophylline, and carbamazepine) along with human-associated molecular markers (HF183 and mitochondrial DNA) to identify and confirm illicit wastewater discharges into storm sewers during periods of dry weather. They developed a composite index which combined CST and MST markers to prioritize areas of high concern based on frequency and magnitude of human fecal contamination. Sites with moderate to high priority were subject to dye tracing to successfully verify household cross connections or indirect illicit discharges.

$$Composite\ Index = \Sigma \frac{Concentration\ of\ each\ sewage\ marker\ (MST\ and\ CST\ markers)}{Maximum\ concentrations\ at\ each\ sub-catchment}$$

Hachad, M., Lanoue, M., Vo Duy, S., Villlemur, R., Sauvé, S., Prévost, M., and Dorner, S. 2022. Locating illicit discharges in storm sewers in urban areas using multi-parameter source tracking: Field validation of a toolbox composite index to prioritize high risk areas. Science of the Total Environment, 811. doi:10.1016/j.scitotenv.2021.152060.

MST and caffeine used in local monitoring programs: Capital Regional District and BC MOE water quality assessment of Sooke watersheds

Both the Capital Regional District (CRD) of Victoria as part of its stormwater monitoring program, and the British Columbia Ministry of Environment and Parks (BC ENV) as part of its program to assess water quality in priority watersheds, have used a combination of MST and CST (caffeine) to evaluate contamination sources.

CRD conducts source investigations on stormwater discharges that have been identified as having a high public or environmental risk using MST and caffeine (CRD, 2023). In its study, BC ENV relied on the CRD MST data. Chemical markers such as caffeine have also been used in local water monitoring programs. Caffeine is stable in aquatic environments and is very source-specific making it an ideal candidate to track human-derived fecal pollution (Weigel et al., 2002). While there were limited correlations between caffeine and fecal coliforms in the Sooke watershed assessment, it was concluded that caffeine remains a valuable means to characterize sewage inputs and should be included in water quality monitoring programs (BC ENV, 2019).

The Canadian Council of Ministers of the Environment (CCME) Water Quality Index

The CCME adopted a general Water Quality Index (WQI) in 2001 which has been used extensively in Canada and internationally. The CCME WQI has been used in Metro Vancouver (Metro Vancouver, 2023), the Toronto Region (TRCA, 2017), a nation-wide evaluation of water quality in Canadian Rivers (CCME, 2023), as well as internationally (King County, USA, Orange County Stormwater Program, USA, San Diego watershed monitoring and assessment program, USA, Ventura Countywide stormwater quality management program, USA). The WQI is based on the combination of three factors (CCME, 2017):

- The number of parameters above the guidelines,
- The frequency with which the guidelines are exceeded, and
- The amount by which the guidelines are exceeded.

Once the WQI has been calculated, water quality can be classified into one of five categories (CCME, 2017):

- Excellent: WQI = 95 – 100: water quality is protected with a virtual absence of threat or impairment; conditions very close to natural or pristine levels;
- Good: WQI = 80 – 94: water quality is protected with only a minor degree of threat or impairment; conditions rarely depart from natural or desirable levels;
- Fair: WQI = 65 – 79: water quality is usually protected but occasionally threatened or impaired; conditions sometimes depart from natural or desirable levels;
- Marginal: WQI = 45 – 64: water quality is frequently threatened or impaired; conditions often depart from natural or desirable levels;
- Poor: WQI = 0 – 44: water quality is almost always threatened or impaired; conditions usually depart from natural or desirable levels.

In its technical guidance document for Water Quality Indicator practitioners reporting under the Canadian Environmental Sustainability Indicators Initiative 2008, the Government of Canada recommends choosing 8 to 15 parameters for the calculation of the WQI. When using fewer than eight parameters, the index tends to be more sensitive to the effects of individual parameters while, on the other hand, using too many can dilute the index (Government of Canada, 2008).

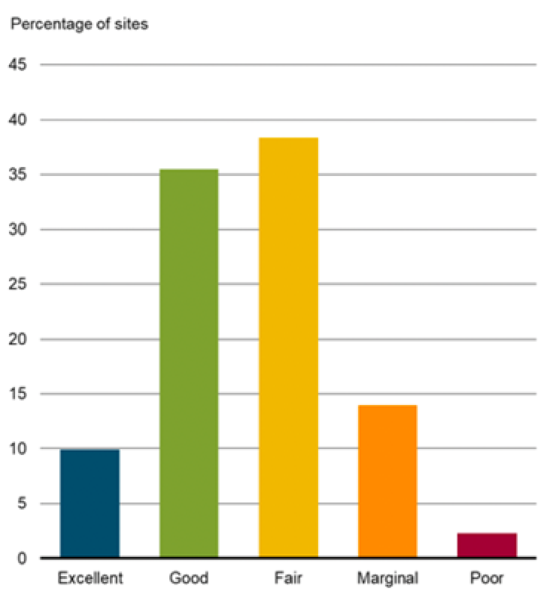
It should be noted that the application of the CCME WQI may be useful for tracking general water quality in select urban waterways, but it lacks the fine-scale data that would inform on source identification, risks to biota or the emergence of specific contaminants of concern.

Performance measures: Reporting and tracking changes

Reporting is a key component of any monitoring program. Results are typically displayed in a user-friendly manner in order to allow for a rapid visual assessment of overall water quality in the region. A more in-depth evaluation of data can then inform specific stormwater management actions. An efficient tracking of parameters and performance over time is also key to the evaluation of management measures put in place.

The use of a water quality Index allows for the water quality data to be summarized and visualized in a user-friendly way. Below are examples on how water quality data may be shared in a format that is appealing not only to managers but also to the general public (Figures 6 and 7). A combination of graphs and maps is beneficial in identifying areas of concern. Figures 6 and 7 reflect rudimentary measures that could be modified to reflect new and emerging approaches.

Figure 6. Environment and Climate Change Canada (ECCC) conducted a Canada-wide water quality assessment of Canadian rivers between 2002 and 2020

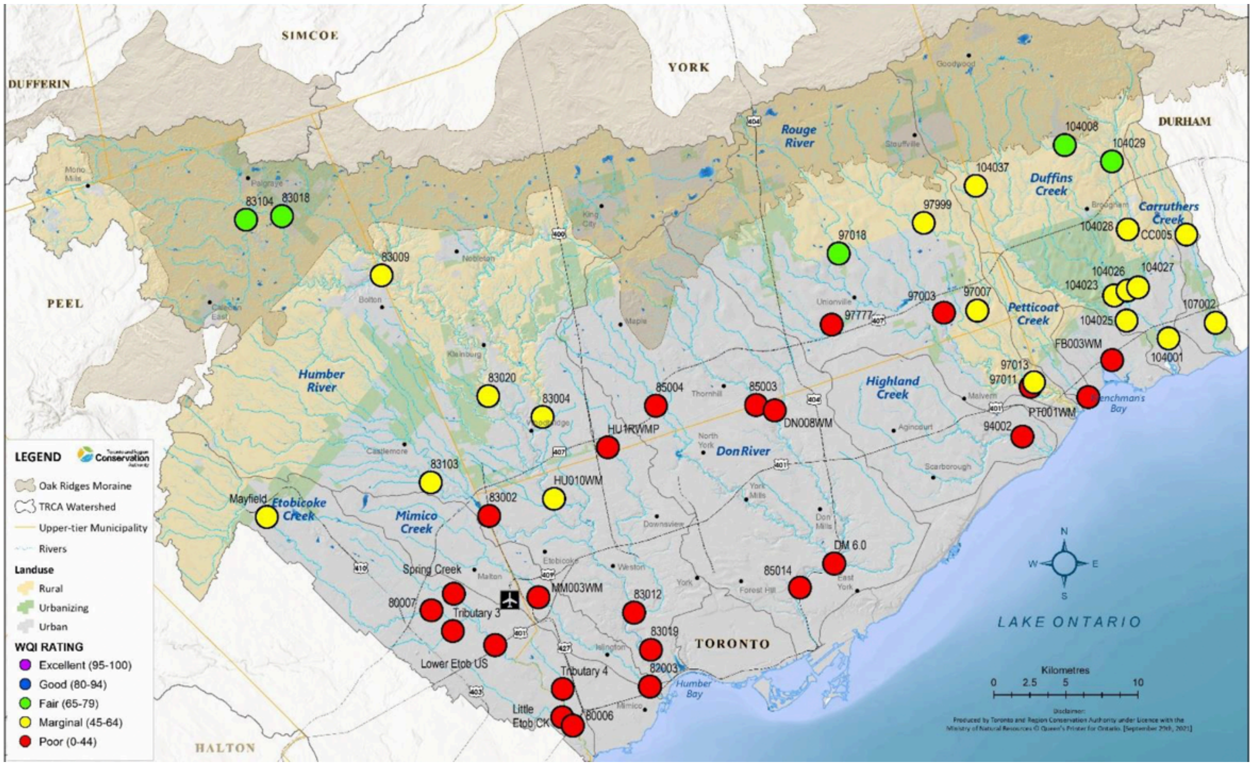


Water quality was evaluated at 172 sites across southern Canada using the Canadian Council of Ministers of the Environment's Water Quality Index. The histogram summarizes data between 2018 and 2020.

(From ECCC, 2023)

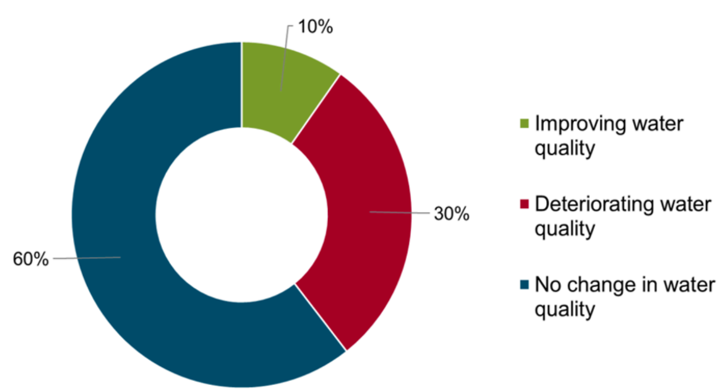
Figure 7. The Toronto and Region Conservation Authority (TRCA) is using simple visuals to display water quality across the region.

Water quality index scores for various sampling sites in the Toronto Region. From TRCA, 2021



Assuming members will be able to sample more than once during the next 10-year cycle, water quality index can be tracked over time by evaluating the change in water quality at each sampling site as shown in Figure 8 from the Water Quality in Canadian River report.

Figure 8. Environment and Climate Change Canada (ECCC) conducted a Canada-wide water quality assessment of Canadian rivers evaluate trends between 2002 and 2020



(From ECCC, 2023)

Water quality monitoring framework for stormwater systems and urban waterways in Metro Vancouver

Capsule

Numerous tools are available for application to identify and track pollution sources in stormwater systems and in urban waterways by Metro Vancouver and its members in support of healthy watersheds in the region. The recommendations in this section are based on a comprehensive literature review and an evaluation of protocols developed by other jurisdictions (Sections 2 and 3). Three scenarios can be envisaged as rationales for water quality monitoring, namely stormwater performance, fish habitat health, and incident response, within which a combination of toolboxes may be applied, including the proposed Basic, Intermediate and Advanced analytical suites. In addition, specialized toolboxes may be deployed for specific purposes, including sanitary tracking, responsive efforts and research. The selection and application of the toolbox is likely to be contingent upon local needs, opportunities and budgetary constraints. Ultimately, the ability to identify priority areas across Metro Vancouver will benefit from a team approach that combines common sampling protocols, draws from a common list of analytes and instrumental lab protocols, and generates data that are comparable across member jurisdictions.

Introduction

While water quality monitoring is a vital component of environmental stewardship, identifying pollution sources and implementing source prevention measures is essential for healthy watersheds. Many changes have shaped the field of water quality monitoring in recent years, from advances in analytical technologies to measure contaminants or track sanitary contamination, new legislation that places importance on the protection of aquatic environments, and the identification of new CECs. In addition, the impacts of a changing climate has had profound impacts on the health of aquatic habitats in urban and near-urban settings.

The recommendations and steps mentioned in this section are based on a critical review of the information presented in the previous sections. With no single or standardized procedure for evaluating water quality in complex watersheds, the value of a unique combination of techniques is apparent for different circumstances and goals. We propose here a novel framework to inform source identification and drainage system performance within the Metro Vancouver area.

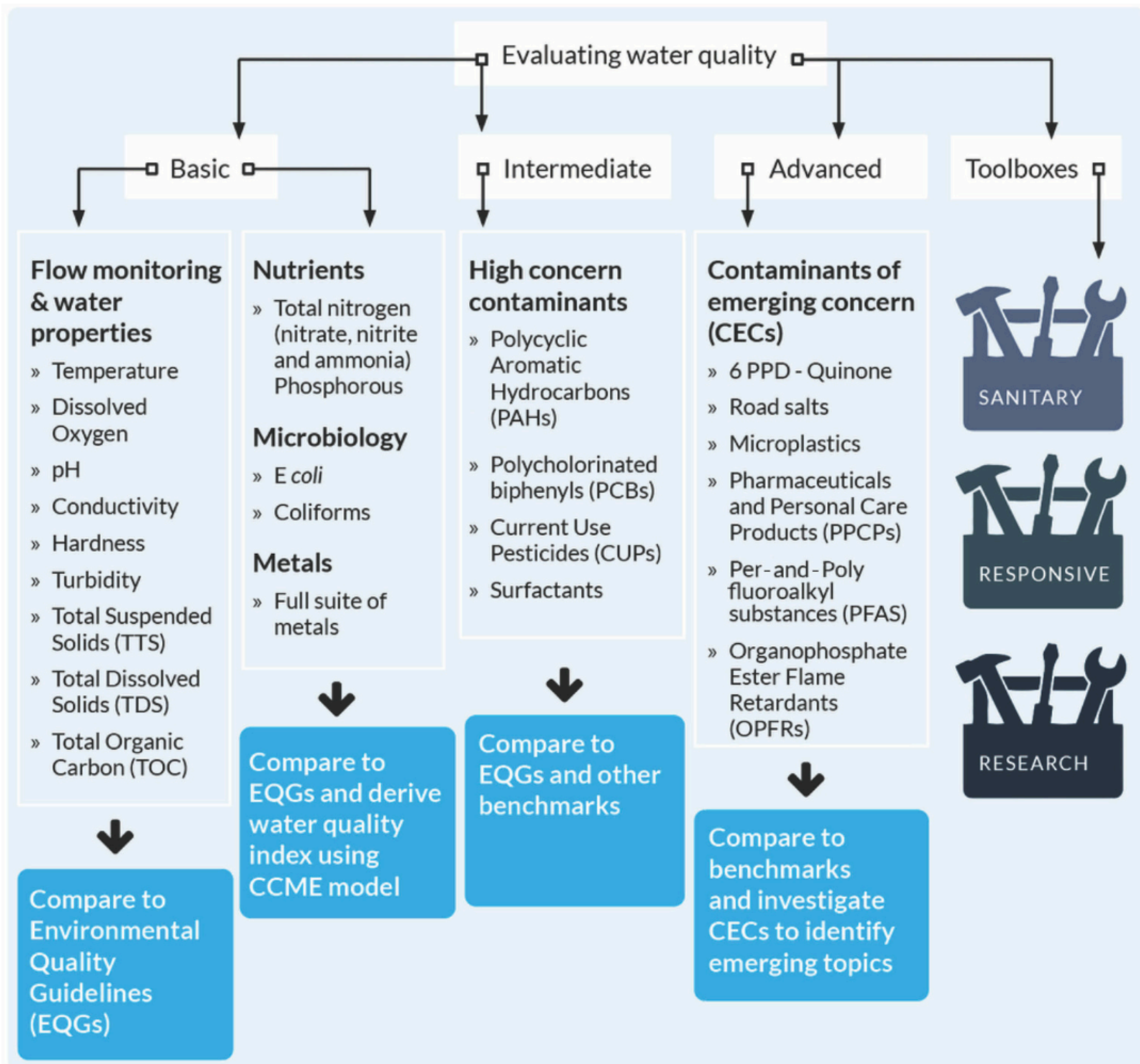
Water quality: Comparable data across Metro Vancouver is key

We recommend the use of a tiered approach to water quality evaluation (Figure 9) across Metro Vancouver, with a suitable mix of:

- Basic monitoring including flow monitoring, water properties, nutrients, microbiology and the full suite of metals, allowing a comparison to environmental quality guidelines and (partially) supporting a water quality index;
- Intermediate monitoring including high concern contaminants such as PAHs, PCBs, CUPs and surfactants, allowing a comparison to environmental quality guidelines and/or water quality objectives;
- Advanced monitoring including 6PPD-quinone, road salts, microplastics, PPCPs, PFAS and OPFRs, recognizing that this list would need to be kept up-to-date over the next 10 years as new contaminants emerge and threaten aquatic life;
- Specialized toolboxes for custom application as needed, including one focused on sanitary source tracking (see section 3), or on responsive monitoring in the event of a spill resulting in a fish kill, and one on research that allows for a constant review and update of emerging topics of interest (see next sections).

While the above will help in the derivation of tracking tools and performance evaluation, an in-depth evaluation of contaminant profiles, trends over space and temporal changes offer strong potential to document the source(s) of contamination.

Figure 9: A proposed framework for water quality monitoring across Metro Vancouver can inform source identification and priority setting, and enable a community approach to watershed stewardship.



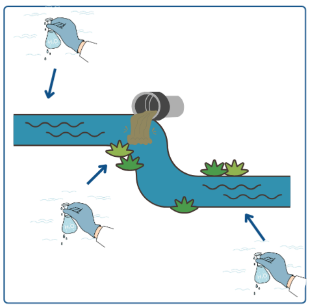
Analysis suites associated with Basic, Intermediate and Advanced tiers here offer on the one hand - incremental increases to documenting contaminants of concern and their sources in stormwater or in urban streams – and on the other – an ability to balance cost constraints. Three additional 'toolboxes' may be applied as needed in the case of suspected sanitary contamination, a spill of unknown origin or a custom research project. Monitoring of flow and basic water properties may be carried out using semi-continuous data collection, spot sampling in situ, or a combination of both. Results should first be compared to Environmental Quality Guidelines (EQGs) and/or Water Quality Objectives (WQOs), as appropriate. Results may also be compared to toxicity data from the scientific literature where no such Guidelines exist.

Sampling scenarios

Metro Vancouver members may apply the water quality monitoring protocols and specialized toolboxes to three different scenarios with various sampling frequencies recommended (Figure 10).

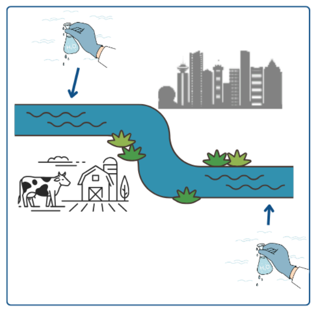
Figure 10. Sampling approaches to protect urban waterways

A. Stormwater characterization



- Conduct regular water property measurements using spot or semi-continuous (datalogger) approaches
- Sample water upstream, at end -of-pipe and downstream of outfall
- Conduct Basic analyses on a monthly basis
- Conduct Intermediate and/or Advanced analyses and/or Sanitary toolbox as warranted

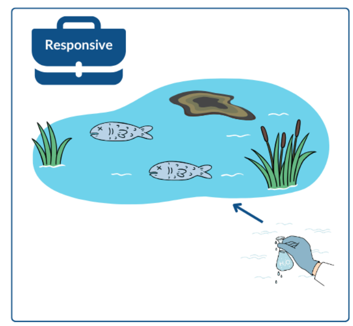
B. Fish habitat quality



- Sample water upstream and downstream of activity
- Conduct sampling in Dry and Wet seasons in year 0, 5 and 10
- Conduct Basic, Intermediate and/or Advanced analyses
- Apply Sanitary toolbox as warranted

C. Incident response

- Sample water, sediment and/or biota during incident and during recovery
- Apply selection of Basic, Intermediate, Advanced analyses and/or Sanitary toolbox



Protecting urban waterways will benefit from a blend of simplified approaches, including the A) monitoring of stormwater discharge and characterization, B) monitoring of a selected (valued) waterway within each MV jurisdiction, and C) the application of sanitary, responsive or research toolboxes as needed.

Stormwater characterization

Being able to identify sanitary contamination in stormwater from various sources (untreated sewage, pets, wildlife) is important to ensuring good water quality in urban environments, and offers a solution-oriented path forward. To evaluate stormwater quality, samples should be taken at three locations: upstream and downstream of the discharge as well as at the end of the pipe (Figure 10A).

Basic monitoring should be conducted at least 15 times per year to ensure acceptable coverage with (EPA, 2015):

- Five sampling events during the dry season ensuring that there is no measurable rainfall (<0.1 inch) in the 72h preceding sampling;

- Ten sampling events during the wet season, ensuring representation of storm events of various strengths i.e five sampling events should be conducted in wet weather in which CSO is expected to occur and five when CSO is not expected to occur.

For Intermediate and Advanced monitoring, samples should be collected during the dry season (July or August) wet season (November or December) upstream, downstream and end-of-pipe for a total of six samples.

Should a sanitary parameter be flagged, we recommend that the sanitary toolbox described below be applied to better understand the nature and source of contamination.

Routine water property measurements should be conducted using spot or semi-continuous (datalogger) approaches as an initial means of characterizing water quality.

Fish habitat quality

It is recommended that the 23 members of Metro Vancouver consider the application of standardized sampling and analysis protocols, and build a water quality monitoring program that incorporates analytes from the list provided here (i.e. from the Basic, Intermediate and Advanced suites). Budgetary constraints render it important for information sharing among MV members, with a major advantage stemming from the leveraging of data and lessons across 23 members.

An approach that will provide strong insight into priorities and emerging concerns across the region would entail each member identifying and monitoring a single urban waterway within their respective boundaries over the next 10 years, with analysis being conducted at the beginning of the next 10 year-cycle, 5 years in and at the end of the period. Samples should be taken upstream and downstream of key urban activities or developments of interest (Figure 10B). While the upstream site should be located further away from any activity to represent 'background' or 'baseline' conditions, the downstream site should be located sufficiently downstream of activities to reflect all of the human impacts in the area.

Basic monitoring should be conducted during the dry season (July or August) and wet season (November or December), and may incorporate spot and/or automated approaches for relevant analytes. Each of these seasonal sampling periods will benefit from the collection of five samples over a 30-day period, preferably on a weekly basis upstream and downstream, for a total of 20 samples per year. (Limited cost $)

For Intermediate and Advanced monitoring, samples should be collected during the dry season (July and August) and wet season (November or December) upstream and downstream for a total of four samples. (A range from moderate costs $ to high costs $$$ for analysis)

In the case of those MV members sampling from all three categories (i.e. Basic, Intermediate and Advanced), each sampling round would therefore consist of 24 samples for a total of 72 samples (60 for Basic, 12 for Intermediate and Advanced) over the 10-year period for three sampling rounds (0, 5 and 10 years).

Should a sanitary parameter in fish habitat be flagged, we recommend that the sanitary toolbox be applied to better understand the nature and source of contamination. This will help to identify cross connections, breakages and overflow events.

Incident response

In the event of spills or fish kills (Figure 10C), communities need to respond appropriately and protect public and aquatic health. The responsive toolbox was developed for this purpose. Briefly, samples should be taken during the incident wherever possible, as well as during recovery. In addition to water samples, consideration should be given to the analysis of sediment and/or biota samples. When selecting sample sites to assess the impacts of an incident, the Government of BC provides specific guidance for site selection in their document *Spill Sampling and Reporting Guidance* (2019).

Specialized toolboxes

Sanitary toolbox

The sanitary source tracking toolbox (Figure 11) describes the tools available should a sanitary parameter be flagged during regular monitoring of fish habitat or stormwater discharges. There are advantages and limitations to all techniques; communities will need to reconcile their budget with wider aspirations. The application of the sanitary toolbox provides a weight of evidence approach that increases confidence in the identification of pollution sources.

The sanitary toolbox is comprised of seven components and would be applied when a flag of a relevant parameter (such as fecal coliform, nutrients and acceptable tracers of human waste) is encountered during the Basic, Intermediate and/or Advanced analyses suites:

- Visual surveys: Conduct dry weather visual surveys to identify odors, colour, turbidity or any visual evidence of sources of sanitary pollution. These may include city encampments, sites with frequent daytime use, under bridges and/or any other obvious contamination.

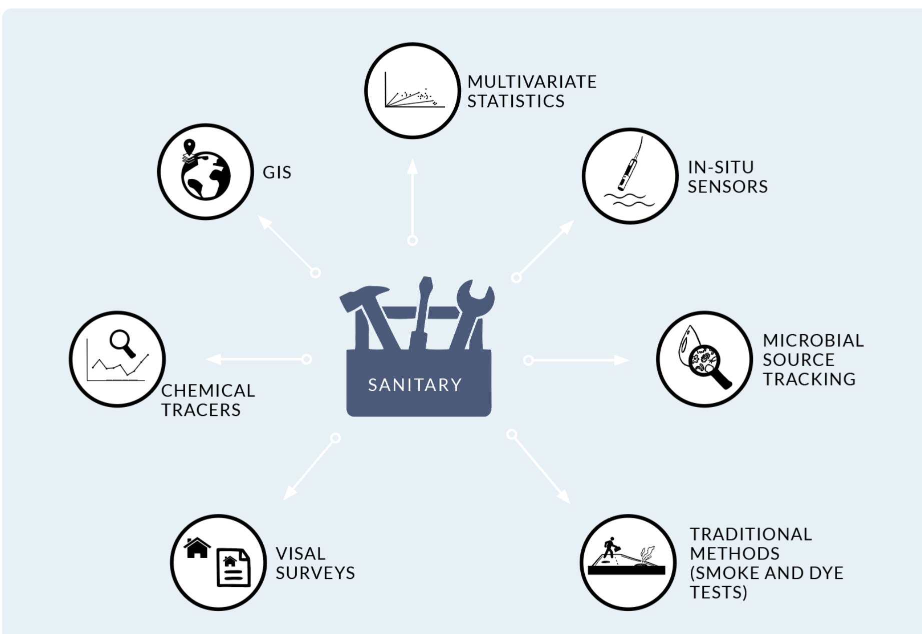
- In situ sensors: Turbidity, conductivity, and TLF sensors employed in semi-continuous data logging can be used to flag sanitary infiltration into surface waters.

- GIS: Use GIS to merge water quality data, MST, CST with spatial infrastructure into one GIS database to help identify sources.

- Traditional methods: These include smoke and dye tests and would be used as a means to quickly confirm the flag detected as part of the basic suite of analytes. (Note that smoke tests would be best for limited geographic areas with strong evidence for direct connections).

- Microbial Source Tracking: Apply human- specific MST markers as they are the best tool for quantifying inputs of human waste using standardized procedures when possible (see Table 10). These markers are most suitable for use in streams and storm drain outfalls.
- Chemical tracers: Use advanced chemical tracers such as sucralose, caffeine and carbamazepine to find sewage leaks, characterize stormwater and CSO discharges.
- Statistics: Summarise findings using tools such as applicable EQOs or EQGs, analyte ratios, multivariate statistical profiles using Principal Component Analysis, or other source identification tools, and compare where available to historical data for the site.

Figure 11: Proposed sanitary toolbox



Advances in analytical, technological and interpretative applications provide new opportunities to identify sanitary infiltration or discharge in storm sewers or urban waterways. The application of this sanitary toolbox as part of a regular monitoring program, or as a responsive approach, can serve to identify the problem, and assess the performance of the drainage system over time.

Responsive toolbox

A responsive toolbox was designed to allow MV to respond in the event of spills, illicit discharges, as communities are increasingly expected to protect public and aquatic health. No single "cookbook" or standard operating procedure exists for tracking pollution sources in complex watersheds in response to an incident. A unique combination of techniques is required for different incidents, communities and situations, with interagency collaboration and Indigenous Knowledge being important considerations.

The elements in this section are meant to guide communities in the development and implementation of investigating spills or incidents. The responsive tool box is comprised of eight components (Figure 12):

- Indigenous Knowledge and Science: In the event of an incident, Indigenous Knowledge and science may include specific, direct observations, experiences about the environment pre- and during the incident. It may also include long-term sets of observations that can add historical perspective and improve understanding of baseline conditions and variability pre-incident. Indigenous Knowledge will be key to understanding potential impacts of the incident to the wellbeing, rights and culture of local Nations.
- Interagency collaboration: Consultations with experts from different fields may be helpful, including public health officials, scientists, water quality managers, laboratory personnel and environmental engineers. Local knowledge can support expert support from different sources, and contribute to appropriate source tracking methods and risks to the aquatic environment. It is important to connect with the oversight agency, depending on the topic and the area of concern (e.g. freshwater, marine, terrestrial).
    - A useful summary of roles, responsibilities and contact information is available at Report an environmental concern - Province of British Columbia.
    - Spills and fish kills: The Government of BC provides a framework for spill sampling and reporting in BC in their document *Spill Sampling and Reporting Guidance* (2019).
    - Marine oil spill: Canadian Coast Guard has developed a response plan for marine pollution incidents in the greater Vancouver area (https://waves-vagues.dfo-mpo.gc.ca/library-bibliotheque/40880618.pdf).
- Visual observations: Conduct dry weather visual surveys to identify odors, colour, turbidity or any visual evidence of sources of pollution. These may include deposits and staining, fish kills, floatables, sewage bacteria, structural damage, surface scum or sheen, trash and debris.
- Water quality parameters:
    - Use a combination of the basic, intermediate and/or advanced suite of analytes with the collection of water, sediment and/or biota samples.
    - Collect samples during the incident and during the recovery period.

- Apply the sanitary toolbox should a sanitary parameter be flagged to better understand the nature and source of contamination.
- Archive samples for subsequent investigation.

- Statistics:
    - Explore analytical results using tools such as applicable Environmental Quality Objectives or Guidelines (EQOs or EQGs), analyte ratios, multivariate statistical profiles using Principal Component Analysis for example, or other source identification tools.
    - Assess availability of water quality data from before the incident to allow comparisons.

- GIS: Analyse data in relation to infrastructure which is essential for planning and useful to target further investigations, enforcement and mitigation.

- Non target analysis (NTA) of environmental pollutants: Such analyses allow for chemical measurements in samples of interest without the need for predefined chemical targets. Since there is no NTA method that can screen for all organic compounds, NTA water monitoring studies usually focus on a class of compounds (Manz et al., 2023).

- Public reporting:
    - Use detailed data and reporting to inform clean-ups.
    - Report and track water quality improvements during the recovery phase.

Figure 12: Proposed responsive toolbox

Accidents and unreported spills threaten the health of urban waterways, with forensic sleuthing being a key to source identification.

Research toolbox

The Basic, Intermediate and Advanced suite of analytes recommended here will generate high quality water quality data for waterways within the MV area. However, new topics, concerns and interests will inevitably emerge over coming years from the scientific literature, academia, non-governmental organizations (NGOs), government agencies and First Nations.

The Research Toolbox simply provides a conceptual space to allow for flexible and timely water quality research projects within the Metro Vancouver region that may complement ongoing programs and create added value for managers, stakeholders and partners (Figure 13). Examples of opportunities and topics for research projects include:

- Indigenous food security and food sovereignty: Indigenous foods can represent an important source of nutrients to local First Nations but are also a very important component of their cultural identity. With the environment being under increasing pressures, there has been a general decline in the use of Indigenous foods and increasing concerns over the quality and safety of traditionally harvested foods (Chan et al., 2011, Rao et al., 2022).

- Climate change: Droughts, flooding, wildfires are all consequences of climate change and can have significant impacts on water quality. In such events, in depth analysis of water quality with techniques such as NTA would be beneficial to better understand contaminants being released and their potential impacts on fish habitat quality. For example, a NTA approach was used to characterize contaminant profiles in San Francisco Bay stormwater samples after the northern California wildfires in 2017 (Wang et al., 2022).

- Partnership with academia, NGOs and government agencies: In order to conduct in-depth additional evaluation of water quality in the MV area, partnerships with various organizations will be key.

- Designing performance measures: Complex water quality datasets may impede a practical understanding of topics of concern and of emerging priorities, effectively constraining public appreciation and management actions. Simplified, high level and/or integrated performance measures are crucial to translating such a dataset into understandable messaging elements. The CCME WQI represents an elementary means to bring different parameters together into a more useful overview number. The CCME WQI does provide flexibility, allowing for additional analytes to be included. This offers the opportunity to use comparable data from across MV to support further use of this Index. We recommend considering the CCME WQI alongside other integrated / tracer / priority approaches, in an effort to come up with the most effective communications plan that has strong technical merit.

- Contaminants of Emerging Concern: As was aptly demonstrated with the tire chemical 6PPD-q in 2021, newly identified CECs may require prompt research to support engineering, source control or regulatory efforts.

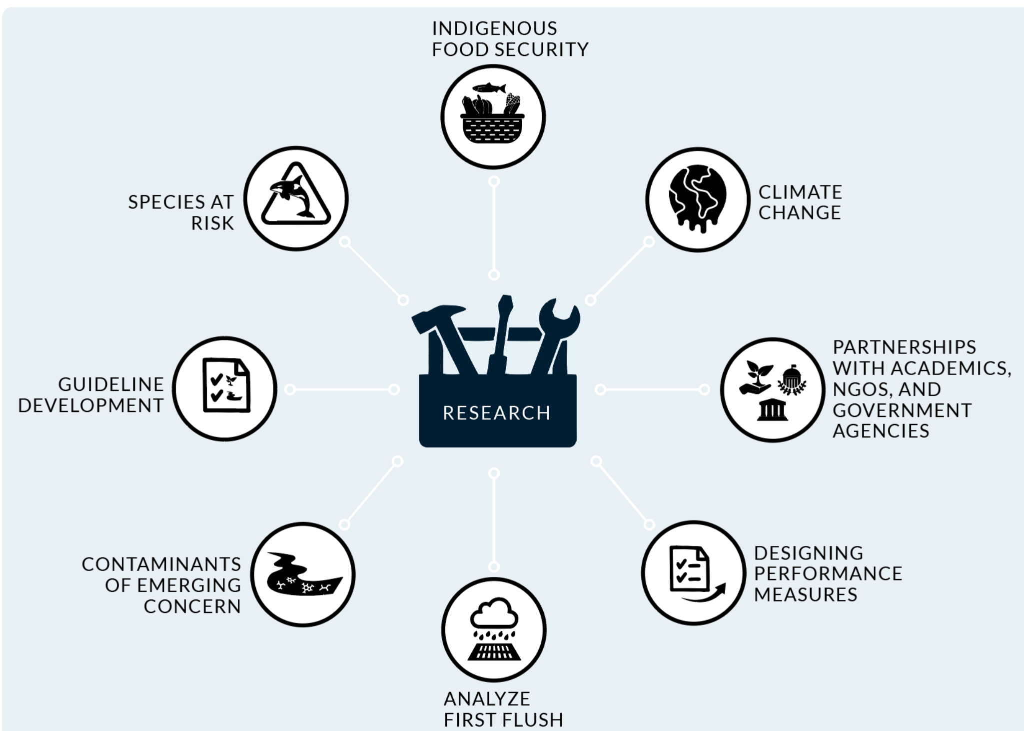
- Environmental Quality Objective / Environmental Quality Guideline development: Many contaminants lack EQO/Gs, and those agencies that produce EQO/Gs require a dataset from the lab and the field. In the case of urban pollutants, Metro Vancouver and its members are in a position to carry out or contribute to studies that support the derivation of new EQO/Gs that protect urban water quality. Metro Vancouver also has a compelling need to participate in the technical process of the development and review of EQO/G.

- Species at Risk: In BC, there are 65 species listed under the Species at Risk Act (SARA) that depend on aquatic habitats including amphibians, freshwater and marine fish, molluscs and marine mammals. Of those, the iconic endangered Southern Resident Killer Whale population, unable to recover due, in part, to contamination of their environment and decline in their main prey Chinook salmon.

- Analysis of first flush: As presented in section 2, the first flush can exhibit a unique contaminant signature and require special attention in order to effectively inform best management practices. A more in-depth analysis of first flush wherein basic, intermediate and advanced sampling is conducted at first flush would allow MV to identify contaminants with shorter aquatic half lives, such as 6PPD-Quinone, that might otherwise be missed by regular monitoring.

Figure 13: Proposed research toolbox

Emerging questions and opportunities underscore the importance of flexibility in water monitoring. New research initiatives may add value to the more routine water quality monitoring led by MV and its members.



Quality Assurance / Quality Control (QA/QC)

In order to generate high quality data that allow for a comparison of water quality data over space and time, and among MV members, it is important to minimize sources of error. This can be achieved by selecting appropriate sampling tools, ensuring proper equipment maintenance, standardizing sampling techniques, using the same analytical protocols, establishing data quality control routines, and being aware of the limitations of various analytical and statistical methods when interpreting water quality data (McMillan et al., 2018; Jakeman et al., 2018; Paakkunainen et al., 2007).

In the field

A field QA/QC program with the following components is advised (Metro Vancouver, 2014):

- Use of standardized field data sheets to ensure consistency with data collection: data sheets should include name and location of sampling point (GPS location), name of sampler, date and time of sampling and relevant description of site conditions.
- Daily equipment calibration and record keeping.
- Collection and analysis of a combination of replicate samples (extra sample collected at the same time and place as regular samples), field blanks (de-ionized water handled in the same manner as the regular samples in the field) and trip blanks (de-ionized water poured into the sample bottle prior to the trip and remaining unopened throughout): a minimum of 10% of the laboratory costs should be devoted to QA/QC.
- Transport and storage of samples as per specific requirements for the individual parameters.

Laboratory selection

Different in situ and laboratory methods are available to analyze contaminants in water samples. Variability among parties can introduce major constraints when tracking water quality trends over time and space and, more importantly, when comparing data across jurisdictions. Water quality samples should only be analyzed by laboratories with an ISO 17025 accreditation, care should be taken to have all MV members use the same laboratories - or at least the same instrumental protocols.

Data processing

When data is received from analytical laboratories, replicates, matrix spikes, reference samples, surrogate recoveries and/or lab and field blanks should be evaluated to make sure they meet the data quality objectives. In addition, all data should be processed in a similar manner to generate comparable datasets. Key steps include:

- Detection limit (DL) substitution: Due to limitations in chemical analysis procedures, low analyte concentrations cannot always be precisely measured, and datasets generated by laboratories will consist of both quantified (detectable) measurements as well as results below the DL. Substitution of non-detects ultimately depends on the goals of the study and an evaluation of DL substitution implications for each analyte for total concentrations and patterns is important. A conservative recommendation is that any non-detects be substituted with 0 for basic total concentration calculations and comparisons with EQGs. Alternative or additional options include substitutions with the

Detection Limit, half the Detection Limit, or a random number between 0 and the Detection Limit.

- Blank correction: Laboratory blanks are analyzed with each batch of samples and concentrations reported in the blanks should be deducted from analyte concentrations reported in samples from the same batch of analysis. Analyte concentrations should also be corrected for field and trip blanks, when available, and as appropriate.

Reporting

Results should be displayed and shared in an accessible, user-friendly manner in order to enable a rapid visualization of water quality in the region. Data can then be evaluated in a more in-depth manner to inform specific stormwater management planning. In addition, efficient tracking over time is also key to evaluate the performance of management measures put in place.

Several recommendations should be considered:

- Use a Water Quality Index (WQI) as one means to reduce the multivariate nature of water quality data: While reporting on a parameter basis is important in order to develop targeted measures for improvement, WQI can reflect the overall and ongoing condition of the water (CCME, 2017).

- Use reader-friendly maps and graphics to report and track changes over time: Several examples from other jurisdictions were presented in section 4 and should be used as guidance while preparing reports.

- Use guidelines to evaluate trends over time: When it comes to CECs for which guidelines are available, progress can also be tracked by evaluating the percentage difference from the guideline for each sampling event throughout the 10 year period.

- Use online interactive tools to support management decisions and allow members of the public to stay informed about the state of regional waterways. These tools have strong potential to promote public awareness, understanding and action to protect waterways in Metro Vancouver. The online tools developed by TRCA (Environmental Conditions of the Toronto Region) or Pollution Tracker are good examples (Pollution Tracker).

Ten steps to healthy waters: applying the water quality monitoring framework to urban waterways in Metro Vancouver

Our matrix comprising Basic, Intermediate and Advanced analytical suites provide a means to design a regular, performance-oriented program that can strengthen water quality monitoring, enable comparable tracking across the region, retain flexibility and consider cost effectiveness.

We present here a ten-step process to implement the water quality monitoring framework in local waterways. This generic framework can support priorities within each member jurisdiction, while contributing to a MV-wide understanding of water quality. Data comparability is the key to success as the MV community works to protect and restore healthy urban waterways.

The application of this process will provide a basis for community sharing, engagement and participation, and enable performance-oriented stewardship and restoration initiatives throughout the region.

01. Identify candidate waterways to monitor

- Engage with First Nations to identify priorities for waterway selection and the application of Indigenous Knowledge to the initiative.
- Make a list of waterways in order to coordinate water quality monitoring efforts in shared watersheds in the region.
- Assess and collate existing datasets to determine what data are available from past efforts within the jurisdiction, from other government agencies, and from permitted point source discharges (e.g. industrial effluent monitoring).
- Summarise existing monitoring efforts for each waterway (e.g. Who? Where? When? What? How?).
- List and describe water quality concerns for each waterway.

02. Partner and share

- Engage with experts from different fields including water quality, freshwater science, toxicology, analytical chemistry and environmental engineering.
- Engage with community groups and members of the public to identify valued waterways and to share information on the initiative.
- Identify aspirational objectives for the waterway (e.g. Indigenous food security; recreational use; fish and wildlife habitat).

03. Choose a key waterway to monitor over the next 10 years

- ❖ Aim to select one focal waterway within each member jurisdiction that will be featured in monitoring and stewardship efforts, and contribute to a MV-wide evaluation of water quality. This is well suited for inclusion in a member's IRMP, and/or should be seen as complementary.
- ❖ Consider the ecological, Indigenous, and recreational values of a candidate waterway. Is it fish-bearing? Is it salmon-bearing and connected to the ocean? Is it culturally valued by First Nations? Is it heavily impacted? Is it a candidate for restoration?
- ❖ Review information gathered from the development of lists (step 1) and engagement initiatives (step 2).
- ❖ Establish a dialogue to consider and adopt metrics, analytical standards, and study designs that can be applied to the focal watersheds, and contribute to a means of identifying risks, tracking priorities, and measuring progress both within and among MV members.
- ❖ Define performance metrics that enable spatial and temporal tracking of water quality measures of concern, and inform managers on emerging problems. Consider their inclusion in the IRMP.
- ❖ Wherever possible, build on individual MV member efforts from the previous LWMPs.

04. Map selected waterway and its watershed

- ❖ Create a comprehensive list of putative sources of pollution in the watershed using existing data and information. Information sources may include:
    - ■ Land-use, hydrogeography and weather data.
    - ■ Location of sewage lines, combined sewers, stormwater discharge points, septic systems, contaminated sites and treatment facilities.
    - ■ Impermeable surface (roads, parking lots) density and distribution.
    - ■ Point source discharges from industry.

05. Characterize basic water quality in the selected waterway

- ❖ Apply the Basic suite of analytes at appropriate sites and frequencies. Consider partnering with Indigenous communities, streamkeeper groups, and/or other organizations that regularly sample water quality or are able to do so. The Basic suite of analytes provides a low-cost but important means of characterizing water quality in a given waterway. The Basic suite, however, will not provide detailed insight into sanitation infiltration, pesticide use, industrial discharges or petrochemical inputs.

06. Characterize priority and emerging contaminants in the selected waterway

- Apply Intermediate and Advanced suites of analytes at selected sampling sites and at suitable frequencies.The Intermediate suite of analytes will provide information on classes of contaminants that are established as ongoing concerns in urban waterways in Canada, including PAHs, pesticides, and surfactants. The Advanced suite of analytes includes notable contaminant classes of contemporary of emerging concern, including pharmaceuticals, tire-related chemicals, road salts, PFAS and organophosphate ester flame retardants. Some of these analyte classes are costly to determine, but reflect recent concerns, new chemicals or policy priorities in Canada.

07. Share data through interpretation and visualisation

- Assemble data using performance metrics and illustrative visuals.
- Produce reports to inform Integrated Rainwater Management Plans.
- Display results in an accessible and user-friendly approach that appeals to water managers and the general public.

08. Protect the selected waterway through engagement, innovation and action

- Implement corrective actions through engineering measures, source controls and/or enforcement actions upon documenting the release of high levels of contaminants of concern.
- Conduct public engagement sessions to advance short-, medium- and long-term solution-oriented practices and stewardship initiatives that address concerns and sources identified through monitoring.

09. Respond to spills, illicit discharges and fish kills

- Select from Basic, Intermediate and Advanced suites of analytes to best document and characterise the nature and origin of the spill.
- Consider the Responsive and Sanitary toolboxes, as appropriate under the circumstances of spill incidents.
- Notify and collaborate with appropriate provincial and federal authorities as well as impacted First Nations.

10. Evaluate the effectiveness of remedial actions, source control, and/or best management practices

- Work with MV and other MV members to design trackable performance metrics that illustrate trends over time for Basic, Intermediate and Advanced suites of analytes. Track water quality over time using suitable indicators, such as analyte concentrations, contaminant profiles (signatures), and water quality indices.
- Compare findings with Environmental Quality Objectives, Environmental Quality Guidelines, Water Quality Objectives and other benchmarks that help to characterise changes in the health of fish habitat.
- Share information with relevant MV working groups so as to leverage results and contribute to region-wide reporting.

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Appendix A: Select environmental quality guidelines available (August 2023) for the protection of freshwater aquatic life

	Short-term acute WQG	Long-term chronic WQG	Reference
Chloride	600 mg/L	150 mg/L *(Human activities should not cause the Cl- of marine and estuarine waters to fluctuate by more than 10% of the natural Cl-)*	Summarized in BC MOE, 2021
Metals			
Aluminum	0.1 mg/L (for pH > 6.5)	0.05 mg/L (for pH > 6.5)	Summarized in BC MOE, 2021
	WQG = $e^{[1.209-2.426(pH)+0.286(pH)2]}$ (for pH < 6.5)	WQG = $e^{[1.6-3.327(\text{median pH})+0.402(\text{median pH})2]}$ (for pH <6.5)	
Arsenic	Max: 5 µg/L *(12.5 µg/L)*		Summarized in BC MOE, 2021
Barium		1 mg/L	Working guideline* - Haywood and Drinnan, 1983.
Boron		1.2 mg/L *(same for marine waters)*	Summarized in BC MOE, 2021
Cobalt	4 µg/L	110 µg/L	Summarized in BC MOE, 2021
Manganese	≤ 0.01102*hardness + 0.54 (for water hardness between 25 and 259 mg/L $CaCO_3$)	0.0044*hardness + 0.605 (for water hardness between 37 and 450 mg/L $CaCO_3$)	Summarized in BC MOE, 2021
Mercury		0.0001 / (MeHg/total Hg), where MeHg is mass (or concentration) of methyl mercury and THg is total mass (or	Summarized in BC MOE, 2021

		concentration) of mercury in a given water volume; When MeHg ≤ 0.5% of total Hg, WQG = 0.02 (same for marine waters)	
Molybdenum	46 mg/L	7.6 mg/L	Summarized in BC MOE, 2021
Nickel		25 µg/L (for water hardness between 0 and 60 mg/L CaCO3 or when hardness is unknown)	CCME, 1987
		CWQG (µg/L) = $e^{\{0.76[\ln(hardness)]+1.06\}}$ (for water hardness > 180 mg/L)	
Selenium		2 µg/L; Alert concentration = 1 µg/L *(same for marine waters)*	Summarized in BC MOE, 2021
Thallium		0.8 µg/L	CCME, 1999
Pesticides			
Aldicarb (Carbamate)		1 µg/L	CCME, 1993
Atrazine (Triazine)		1.8 µg/L	CCME, 1989
Bromacil		5 µg/L	CCME, 1997
Bromoxynil		5 µg/L	CCME, 1993
Carbaryl (Carbamate)	3.3 µg/L *(5.7 µg/L)*	0.2 µg/L *(0.29 µg/L)*	CCME, 2009
Chlorothalonil		0.18 µg/L *(0.36 µg/L)*	CCME, 1994
Chlorpyrifos	0.02 µg/L	0.002 µg/L *(same for marine waters)*	CCME, 2008
Cyanazine		2 µg/L	CCME, 1990
Deltamethrin		0.0004 µg/L	CCME, 1997
Dicamba (Aromatic carboxylic acid)		10 µg/L	CCME, 1993
Diclofop-methyl		6.1 µg/L	CCME, 1993

Didecyl dimethyl ammonium chloride		1.5 µg/L	CCME, 1999
Dimethoate (organophosphorus)		6.2 µg/L	CCME, 1993
Dinoseb		0.05 µg/L	CCME, 1992
Endosulfan (Organochlorine)	0.06 µg/L *(0.09 µg/L)*	0.003 µg/L *(0.002 µg/L)*	CCME, 2010
Glyphosate (Organophosphorus)	27,000 µg/L	800 µg/L	CCME, 2012
Hexachlorocyclohexane (Organochlorine)		0.01 µg/L	CCME, 1987
3-Iodo-2-propynyl butyl carbamate (Carbamate)		1.9 µg/L	CCME, 1999
Linuron		7 µg/L	CCME, 1995
Methylchlorophenoxyacetic acid (4-Chloro-2-methyl phenoxy acetic acid; 2-Methyl-4-chloro phenoxy acetic acid)		2.6 µg/L *(4.2 µg/L)*	CCME, 1995
Metolachlor (Organochlorine)		7.8 µg/L	CCME, 1991
Metribuzin (Triazine)		1 µg/L	CCME, 1990

Permethrin (Organochlorine)		0.004 µg/L *(0.001 µg/L)*	CCME, 2006
Phenoxy herbicides		4 µg/L	CCME, 1987
Picloram		29 µg/L	CCME, 1990
Simazine		10 µg/L	CCME, 1991
Tebuthiuron		1.6 µg/L	CCME, 1995
Triallate		0.24 µg/L	CCME, 1992
Trifluralin (Dinitroaniline)		0.2 µg/L	CCME, 1993
PAHs			
Acenaphtene		6 µg/L *(same for marine waters)*	Summarized in BC MOE, 2021
Acridine	0.05 µg/L	3 µg/L	Summarized in BC MOE, 2021
Anthracene	0.1 µg/L	4 µg/L	Summarized in BC MOE, 2021
Benzene		40 µg/L *(110 µg/L)*	Revised interim BC WQG based on review of Canadian Council of Ministers of the Environment (1999) WQG.
Benz[a]anthracene	0.1 µg/L	4 µg/L	Summarized in BC MOE, 2021
Benzo[a]pyrene		0.01 µg/L *(same for marine waters)*	Summarized in BC MOE, 2021
Fluoranthene	0.2 µg/L	4 µg/L	Summarized in BC MOE, 2021
Naphatalene		1 µg/L *(same for marine waters)*	Summarized in BC MOE, 2021
Phenantrene		0.3 µg/L	Summarized in BC MOE, 2021

Pyrene	0.02 µg/L		Summarized in BC MOE, 2021
Quinoline		3.4 µg/L	CCME, 1999
Toluene		0.5 µg/L	Summarized in BC MOE, 2021
Xylene		0.03 mg/L	Summarized in BC MOE, 2021
Nonylphenols and its ethoxylates			
Nonylphenol and its ethoxylates		1 µg/L (*0.7 µg/L*)	CCME, 2002
Microplastics	no guidelines - see text		
6PPD-Quinone	10 ng/L		British Columbia Ministry of Water, Land and Natural Resource Stewardship, 2025
PFAS			
PFOS	6.8 µg/L		ECCC, 2018
PPCPs			
17αethinylestradiol	0.75 ng/L	0.5 ng/L	Summarized in BC MOE, 2021
Carbamazepine	10 µg/L		CCME, 2018
Triclosan	0.38 µg/L		ECCC, 2017

Water quality guidelines available for the protection of freshwater aquatic life and, when available, guidelines for marine waters are presented in brackets. When no BC provincial guidelines were available, federal guidelines are presented. (*listed as a working guideline under BC MOE; CCME guidelines retrieved at https://ccme.ca/en/current-activities/canadian-environmental-quality-guidelines; the year indicates when the guideline was developed).

Peter S. Ross, Marie Noel, Melany Sanchez and Samantha Scott. 2025. **Water quality monitoring strategies for Metro Vancouver:** A framework that informs source identification and drainage system performance. Raincoast Conservation Foundation.

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