State of the knowledge: Long-term, cumulative impacts of urban wastewater and stormwater on freshwater systems

-- Final Report --

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by:

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Canadian Water Network

Canadian Water Network (CWN) is Canada's trusted broker of research insights for the water sector, shaping important conversations on policy and practice. When decision makers ask, 'What does the science say about this?' CWN frames what is known and unknown in a way that usefully informs the choices being made. That credible prioritization of knowledge to inform next steps is central to the CWN approach.

Purpose and Scope

The purpose of this whitepaper is to provide background information and a shared knowledge base for participants in an upcoming CWN workshop on the long-term impacts of urban wastewater and stormwater to receiving waters, and the associated relevance for planning, policy, and decision-making. The whitepaper contains an initial summary of some current scientific knowledge on contaminants and issues that may contribute to, or impact, the long-term, chronic effects of urban wastewater and stormwater on the environment. It should be noted that the information provided in this document is not exhaustive but is meant to provide an overview of major contaminants and issues as a starting point for further discussion among workshop participants. Participants are invited to review the information provided as a preface to the structured conversations planned for the workshop, and to consider the content of the paper in the context of the following questions:

- What contaminants and issues are of particular concern or might be particularly relevant to their context,
- What issues might be important to consider during planning, policy and decision-making, and why this is the case,
- Can you provide additional insights on potential long-term implications of contaminants or issues, and
- Would additional information or insights on a given issue be useful to inform current or future planning, policy, and decision-making at the municipal, provincial, or national level?

In developing this document, an attempt was made to capture the state-of-the-science on contaminant releases to water and physical processes affected by urbanization. To keep the scope manageable, the document excludes wastewater biosolids and biosolids disposal methods. Similarly other sector activities, including agricultural land uses, agricultural operations, and impacts from other sectors were excluded, recognizing that they are also important for a holistic understanding of the health of Canadian watersheds. Since this document focuses on understanding the significance of potential environmental impacts, specific wastewater and stormwater management or treatment options, and the relative effectiveness of those options, also were not included.

The discussion is intended to dovetail with work underway in response to fairly recent changes in the Canadian wastewater management landscape. The Canada-wide Strategy for the

Management of Municipal Wastewater Effluent (MWWE), developed through the Canadian Council of Ministers of the Environment and endorsed by a majority of members in 2009 [1], will influence wastewater infrastructure investments in Canada over the next three decades. The strategy, and subsequent wastewater systems effluent regulation under the *Fisheries Act*, prompts jurisdictions to implement effluent requirements equivalent to what can be achieved using conventional secondary wastewater treatment to reduce biochemical oxygen demand, total suspended solids and residual chlorine [2]. The approach also requires that there be no increase in the frequency of combined sewer or sanitary sewer overflows [2]. With the anticipated investments to address these requirements, and other potential government investments in green infrastructure, there are opportunities to examine our scientific understanding of the long-term impacts of urban inputs and to look for ways to proactively consider the implications for future decision-making.

Organization of this document

The whitepaper is organized around key issues and contaminants, grouped into five categories. First, a one-page list of the five categories (and subcategories) is provided for reference. This is followed by a one-page qualitative tabular summary that helps frame the relative contributions of wastewater treatment plants (WWTPs), stormwater infrastructure and overflows for each of the five categories. Within the main body of the document, each of the five categories is discussed in sequence, with a brief introduction containing descriptions and definitions of the contaminants and/ or issues and a synthesis of the science with respect to the implications of chronic, longer-term urban inputs to freshwater. Summary Tables of scientific findings from the literature are also provided, by issue category and contaminant, at the end of the document.

Abbreviations and Terminology

The use of acronyms and abbreviations has been minimized in this report for readability. Periodic table abbreviations are used for elements, in particular where numerous metals have been identified in the literature. Abbreviations are used for other contaminants that are commonly known by their acronyms (e.g. PCBs), with a definition on their first use.

The term WWTP is being replaced gradually by a more recent term, water resource recovery facilities (WRRF), in recognition of the need for holistic approaches to urban water management. The term WWTP is used in this report.

Overview of Issues and Contaminants

Issues and contaminants have been grouped into five categories, each of which is divided into sub-categories, as follows:

1. Conventional and legacy pollutants

a) Phosphorus and related issues
b) Other nutrients (especially nitrogen)
c) Legacy contaminants (PAHs; PCBs; VOCs)
d) Mercury
e) Other metals
f) Pathogens and related issues
    i. Pathogens, assessed via indicator pathogens
    ii. Chlorine and disinfection by-products (DBPs)
    iii. Parasites
g) Organic matter, BOD
h) Sediments, floatables
i) Chloride (including road salts)

2. Emerging contaminants

a) Surfactants
b) Endocrine disruptors, including pharmaceuticals and personal care products
c) Flame retardants
d) Nanoparticles/ materials
e) Micro and fibrous plastics
f) Anti-microbials and antibiotic resistant bacteria

3. Physical Alterations to watersheds from urban land use change with consequences for stormwater inputs to freshwater

a) Hydrologic change
b) Geomorphological changes
c) Thermal regime change
d) Anthropogenic responses to erosion and flooding

4. Global Environmental Trends potentially influencing urban inputs and natural system assimilation capacity

a) Climate change
    i. Hydrologic regime change (drought, extreme rain events)
    ii. Stormwater and sewage risks (overflows, contaminant loads)
    iii. Altered spring freshet patterns
    iv. Alteration of temperature regime and habitat quality
    v. Biological responses to chemicals
b) Biodiversity loss
    i. Urban stream syndrome
    ii. Loss of wetlands and habitat; role of stormwater facilities
    iii. Ecotoxicology and bioaccumulation/ biomagnification of toxic chemicals
    iv. Urban pressures reducing resilience or diversity
c) Invasive species linked with urbanization
d) Population growth in urban centers

5. Interactions and issues of local context

a) Receiving water characteristics
b) Synergistic/ antagonistic effects of multiple contaminants and issues
c) Total load management on a watershed/ sub-watershed basis

Key Sources of Issues and Contaminants by Category

By their nature, WWTPs receive substances used, by-products produced, and wastes disposed of by the communities they serve. Effluents contain contaminant remnants that remain in water after treatment (versus partitioning to solids or volatilizing), some of which are altered by treatment processes and others that are not. Similarly, rain washes urban surfaces and carries contaminants to receiving waterbodies, the quality of which reflects the urban environments they drain. Combined sewage and sanitary sewage overflows are intended to protect properties from flooding and infrastructure system surcharges but have consequences for receiving waters.

Following is a qualitative summary of the relative contributions of urban wastewater systems, stormwater systems and sewer overflows to contaminant releases or other issues that may be of concern over the long-term. This summary is only intended to provide a quick reference for the potential contributions for these infrastructure systems relative to each other. Check marks indicate the relative magnitude of contribution, with one check mark indicating lower contributions than two or three check marks. The summary pertains to the three urban infrastructure systems only. Note that contributions may be made even where no check mark is indicated but, relative to the other urban systems, the loading is estimated to be very low. For some contaminants, even low contributions can result in unacceptable dosages. Not all contaminants or issues will necessarily be of concern at a given location.

	Wastewater	Stormwater	Overflows[1]
1. Conventional and legacy pollutants			
a) Phosphorus	✓✓✓	✓✓	✓
b) Other nutrients (nitrogen)	✓✓✓	✓	✓✓
c) Legacy contaminants	✓	✓✓	✓
d) Mercury	✓✓		✓
e) Other metals	✓✓	✓✓✓	✓
f) i. Pathogens	✓✓	✓✓	✓✓✓
f) ii. Chlorine /disinfection products	✓		
f) iii. Parasites	✓		✓
g) Organic matter, BOD	✓✓	✓✓	✓✓✓
h) Sediments, floatables	✓	✓✓	✓✓✓
i) Chloride (including road salt)		✓✓✓	✓
2. Emerging contaminants			
a) Surfactants	✓✓	✓	✓
b) Endocrine disruptors, including pharmaceuticals, personal care products	✓✓		✓
c) Flame retardants	✓	✓	✓
d) Nanoparticles/ materials	✓		✓
e) Micro and fibrous plastics	✓	✓	✓
f) Anti-microbials and antibiotic resistant bacteria	✓		✓
3. Physical Alterations			
a) Hydrologic change	✓	✓✓	
b) Geomorphological changes		✓	
c) Thermal regime change	✓	✓✓✓	✓
d) Anthropogenic responses		✓	
4. Global Environmental Trends			
a) Climate change b) Biodiversity loss c) Invasive species d) Population growth	These global phenomena result in increased uncertainty with respect to impacts, possibly higher contaminant loads, potentially magnified effects and/or increased risk, and/or possibly increased vulnerability of biota		
5. Interactions and issues of local context			
a) Receiving water characteristics	✓	✓	✓
b) Synergistic/ antagonistic effects	✓	✓	✓
c) Total load management [2]	✓	✓	✓

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[1] Overflows include combined sewer overflows, sanitary sewer system surcharges and emergency bypasses

[2] The significance and applicability to urban sources depends on the pollutant(s) addressed.

Issues and Contaminants Analyses

1. Conventional and Legacy Pollutants

The pollutants and issues included in this group were:

a) *Phosphorus* (P). Phosphorus has been known as a limiting nutrient for eutrophication in freshwater systems since the 1970s [3] and it continues to require scientific study in at least two areas. Firstly, historic depositions of P in sediments can be re-released from sediments through re-suspension or re-dissolution from hydrolysis (Y. Comeau, pers. comm., 2016), with negative effects on lake water quality due to high biological availability [4], [5]. These internal P loadings can delay waterbody recovery even when external loads from watershed sources have been reduced [4]. Secondly, both non-toxic and toxic algae can increase in density to produce Harmful Algal Blooms (HABs) [6]. The occurrence of HABs may be associated with several variables, including elevated phosphorus levels, concentrations of other nutrients, increased water temperatures [6] and water column stability (P. Chambers, pers. comm., 2016). HABs are addressed within this category, although they are also potentially applicable under *Other Nutrients* or *Climate Change*.

b) *Other nutrients*. Other nutrients from point and non-point sources, in particular nitrogen in its aqueous forms (ammonia, etc.), contribute to aquatic toxicity and environmental degradation [6].

c) *Legacy contaminants*, including polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs) and volatile organic compounds (VOCs). PAHs comprise several hundred compounds from both natural and anthropogenic activities; they occur primarily in soil, sediment, oily substances and as particulate matter in air [7]. The production and use of PCBs has been banned in most industrialized countries since the late 1970s [7] due to their extreme persistence in the environment and in living tissue [8]. Although PCBs are banned in Canada, owners of equipment with PCBs can continue to use the equipment to the end of its lifespan [8]. VOCs are a large group of compounds that includes carcinogens known as the BTEX group (benzene, toluene, ethylbenzene, and xylenes)[7].

d) *Mercury*. Mercury may be present in wastewater in trace amounts from sources that include dental practice wastes, paints, domestic waste and stormwater drainage contributions [9]. Mercury can also be naturally present in rocks and soils.

e) *Other metals*. Other metals that can be present in wastewater include inputs from domestic and industrial sources, including copper, zinc and antimony (used as a flame retardant in consumer electronics and paints) [9]. Stormwater can also contain metals from sources such as car brakes, tire wear, vehicle exhaust, commercial and industrial activities [10], building facades, structures and road pavements.

f) *Pathogens*. Pathogens are found in wastewater and stormwater effluents. These pathogens can be from both human and animal sources. Their presence is assessed through testing for reference pathogens that are considered to be representative of bacteria, parasites or viruses [11]. Chlorine and disinfection by-products are present in wastewater effluents where chlorine is used as a disinfectant and they are toxic in the aquatic environment [7]. Study of the effects of parasites on immune responses and vulnerabilities of organisms downstream of urban inputs (parasitology) can contribute to broader understanding of the ecological impacts of wastewater effluents or reaches exposed to chronic sewage overflows. This research is also informed by the incidence of pathological effects in biota downstream of urban effluents.

g) *Organic matter*, including biological oxygen demand (BOD) and the organic portion of total suspended solids (TSS). Organic matter is reduced through secondary treatment processes and/or improved primary processes; the oxygen sag phenomena downstream of waste discharges was first identified in the 1920s (e.g. [12]) and has driven improvements in wastewater treatment ever since.

h) *Sediments and floatables*. These contaminants are removed by conventional wastewater treatment processes but can be released to the environment during combined sewer overflow and sanitary sewer surcharge events. Floatables may include plastics, waste hygiene products, other refuse and raw sewage. Sediments can result from impervious surfaces, erosion, road sanding operations, among other sources.

i) *Chloride, including road salts.* Salts used on roads globally include sodium chloride, calcium chloride, potassium chloride and magnesium chloride [13]. Sodium chloride is the salt most commonly used on Canadian roads [13]. Chloride is a highly soluble and mobile ion, and its concentration in freshwater ecosystems is not affected by chemical or biological reactions [13]. As such, all chloride ions entering a watershed can ultimately be expected to reach surface waters [13][14]. The concentration of chloride in surface water is affected by the addition of chloride through inputs such as wastewater and stormwater discharges, dilution (e.g. through precipitation or inflow), and concentration by evaporation [13]. Conventional stormwater treatment technologies, such as stormwater retention ponds, do not remove dissolved salts from runoff [13][15].

State of the Science

A summary of key findings from the scientific literature is provided in Table 1 on page 20.

Synopsis 1: Science, uncertainty and potential for long-term impacts

Conventional and legacy pollutants have a history of scientific study, and much is known about these pollutants and their impacts and fate. However, there are a number of factors that continue to add uncertainty to a scientific understanding of their long-term impacts, for example:

- While there is an increasing understanding of receiving water assimilation capacity and cycling patterns of pollutants in the environment, more research is still needed to further understand the fate and effects of nutrients;
- Human population growth has the potential to add to the amount of conventional pollutants released in urban areas; and,
- Climate change is anticipated to affect management requirements for conventional pollutants (see Category 4, *Global Environmental Trends*).

Phosphorus (P) is the limiting nutrient in freshwater systems and therefore is linked to eutrophication of water bodies, with consequences for oxygen demand and habitat quality. Urban WWTPs and stormwater runoff are on-going sources of P to freshwaters. In addition, P that was deposited to sediments historically can become re-suspended in the water column under anaerobic and certain aerobic conditions, thus contributing to internal P loadings. There is some evidence that internal P loading can increase when external loading decreases [16]. Once external P loadings are reduced, the time required to reach a new nutrient equilibrium in lakes depends on the sediment P load and may take 10–15 years, or decades, to achieve. Similarly, estuaries are also affected by P and N loads, as well as organic material, but the processes and long-term effects are not well understood [17]. The long-term effects and processes affecting estuaries require consideration of nutrient loads from all relevant land-based activities, including agriculture, where estuaries drain large land areas (e.g. the St Lawrence Estuary). Predicting the internal P loading potential for a given waterbody requires data on various compartment concentrations, conditions and processes. One implication of the uncertainty related to internal P loadings pertains to setting allowable wastewater and stormwater input levels (concentration or total load) required to achieve waterbody rehabilitation goals: allowable input levels may change as better understanding of each watershed develops or as climatic or other conditions (e.g. direct industrial P inputs) change.

Toxic harmful algal blooms (HABs) are strongly correlated with elevated phosphorus concentrations and increased temperatures, which can exacerbate anoxic conditions, prompting higher sediment P release rates. However, the abundance of some HAB taxa is also correlated with the ratio of nitrogen (N) to phosphorus and, in presence of very high phosphorus concentrations, can be positively correlated with N concentrations [18]. Generalizations cannot be made about HABs with respect to the role of N enrichment. Prediction of HAB events is uncertain due to a number of confounding factors, such as the varied responses of taxa that potentially contribute to blooms (e.g. different responses at differing ratios of key nutrients) and the roles of N and temperature.

The N balance within a waterbody is impacted by contributions from the atmosphere as well as point and non-point sources. It is further complicated by the forms of nitrogen in aqueous environments, and chemical transformations. Ammonia is toxic to aquatic organisms and, along with P and sulfate, is associated with negative effects on the abundance and composition of macroinvertebrates and various fish species downstream of WWTPs. Conversely, long-term improvements in nutrient release and BOD reduction have been associated with improved water quality and fish assemblage composition as far as 200 km downstream of a WWTP (in Dallas Fort-Worth [19]).

Contaminant loads from legacy contaminants (PAHs, PCBs and VOCs) and mercury are decreasing in WWTP effluents due to restrictions on their use, but PAHs and PCBs continue to be present in monitored downstream sediments (e.g. in the St Lawrence River). Road surfaces, vehicles and contaminated sites are potential current sources of legacy contaminants in stormwater. Many metals that are toxic to aquatic biota continue to be released to waterbodies via WWTP effluents and stormwater. Chronic exposure toxicity of aquatic biota to metals is poorly understood and complicated by variable concentrations of contaminants in sediments and the water column, variable metal hazard indices, effluent- and receiving environment related factors that modify bioavailability, bioaccumulation and mobility of metals, as well as the intermittent nature of stormwater (CSO) inputs and wastewater effluent metals concentrations. Assessing the exposure of fish to contaminants can be further complicated by the migratory habits of some species.

Microbial contamination from stormwater inputs is highly variable, as are inputs from combined and sanitary sewer overflows. Pathogen presence is assessed by testing for indicator pathogens (typically fecal bacteria), so a complete picture of pathogen contamination is not scientifically available. The immune system response of aquatic species to pathogen exposure is a subject of on-going research; there is evidence that the severity of parasite infections in aquatic biota is increased downstream of WWTPs, although overall resistance of populations to parasites may not be affected (i.e. severity of disease is higher where disease occurs but prevalence of disease may not increase). Research on the toxicity of chlorine disinfection by-products is building an understanding of the variables and forms of by-products that have negative impacts on aquatic organisms. Dechlorination does not reduce toxicity of wastewater effluents to the levels found before chlorination, with potential implications for the adequacy of dechlorination as a treatment strategy to protect receiving waters[3].

Aquatic ecosystems exposed over the long-term to increased chloride concentrations are expected to be impaired in terms of aquatic community structure, diversity and productivity. Algal, invertebrate and fish communities experience toxicity with chronic exposure to salt. High concentrations of salts in lakes can change stratification profiles with increased meromictic[4] stability and subsequent changes to oxygen (annual turnover) and nutrient availability. Because chlorides do not degrade in the environment, surface waters are the ultimate reservoir for road salts, even those initially deposited to shallow groundwater. Depending on hydrogeological conditions and distance from the road network, road salts can be expected to flush to surface waters in 5 to 200 years.

Identification of the appropriate temporal and spatial scales for scientific assessment of conventional and legacy contaminants, and all contaminants, is challenging. Ecosystem responses include many slow, long-term changes to nutrient fluxes, and species successions that cannot be assessed by short, small-scale experiments. Scale issues contribute to poor understanding of mechanistic responses driving biotic community recovery. At least two spatial scales (reach and watershed) have been recommended in the literature to evaluate improvements to habitat as a result of changes to WWTP effluents. Other assessments are needed to understand the habitat quality of stormwater ponds, constructed wetlands, stormwater low impact development techniques and treatment lagoons. Inadequate

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[3] Chlorination of wastewater effluents is banned in the Province of Quebec. Ultra violet light, ozone and lagoons are used for disinfection (Y. Comeau, pers. comm.,2016).

[4] Meromictic lakes have stable, stratified layers that do not fully mix seasonally, creating differing habitats including an oxygenated top layer and an oxygen-depleted bottom layer.

assessments of ecosystem recovery poses management challenges for priority-setting and other rehabilitation decisions.[20] Current understanding of the effects of these pollutants may be further challenged by climate change; for instance increased water temperatures may affect the assimilative capacity of receiving waters (discussed in Category 4, *Global Environmental Trends*).

2. Emerging Contaminants

Emerging contaminants include:

a) *Surfactants*, which are used by industry and historically in a variety of products (such as stain resistant coatings), include nonylphenols (NP) and associated ethoxylates (NPEOx) and carboxylates (NPECx), perfluorooctansulfonate (PFOS) and perfluorooctanoate (PFOA). Some forms of the nonylphenol group of substances are endocrine disruptors [21]. PFOS and PFOA are persistent organic pollutants (also known as POPs) that bioaccumulate and are toxic [22]. Anionic surfactants are a class of chemicals used in household cleaning products including laundry detergents, the most commonly used of which are alcohol sulfates (AS), alcohol ethoxysulfates (AES), linear alkyl benzenesulfonates (LAS) and methyl ester sulfonates (MES) [23].

b) *Endocrine disruptors, pharmaceuticals and personal care products* (PPCPs) comprise a large group of substances with a variety of uses. The European Union has listed 564 endocrine disrupting chemicals, 147 compounds of which are likely to be persistent in the environment [24]. Drugs identified in scientific studies of wastewater effluents include antibiotics, anti-inflammatories, anti-depressants, anti-convulsive and cytotoxic drugs (used to treat cancers, rheumatoid arthritis, multiple sclerosis), lipid regulators, chemotherapy drugs, lipase inhibitors and hypertension drugs [21], [25]. In addition, caffeine, a nicotine metabolite [21], cocaine and other illicit drugs [26], birth control and natural estrogens have also been detected and studied in wastewater effluents. Personal care products are of potential concern for their endocrine disrupting properties, especially products containing phthalate esters, parabens, ultraviolet filters, synthetic polycyclic musks, antimicrobials [22] and silicone-based compounds (siloxanes). Commercial products that may contain these compounds include cosmetics, soaps, shampoos, hair sprays, nail polish, lotions [22] and perfumes, among others. Human and animal excretion is the main source of steroidal hormones in the aquatic environment [27].

c) *Flame retardants,* which comprise a group of substances including brominated flame retardants (polybrominated diphenyl ethers (PBDEs) and hexabromocyclodecane (HBCD)) and chlorinated flame retardants. (Polychlorinated biphenyls (PCBs) were also used as flame retardants but are addressed in Group 1). PBDEs have been used in many building materials, electronics, textiles, plastics and other applications; they comprise a family of 209 congeners which occur in various combinations within PBDE samples [28]. PBDEs are persistent organic pollutants that bioaccumulate and are toxic [22]. Chlorinated flame retardants include short-chain chlorinated paraffins (SCCPs) and medium-chain chlorinated paraffins (MCCPs), both of which are identified as toxic substances under Canada's Environmental Protection Act [22].

d) *Nanoparticles/ materials,* which are particles that are less than 100 nm (0.1 µm) in at least one dimension [22]. Nanoparticles are found in a growing list of commercial nanotechnology products including electronics, healthcare, chemicals, cosmetics and sunscreens, and elsewhere. These particles are used for a variety of purposes, including strengthening materials, cleaning environmental contamination and cancer treatments [22]. Nanosilver is growing in popularity for its anti-microbial and anti-odour properties and these particles are being incorporated into consumer products, such as socks, sports clothing, deodorants, washing machine additives, food packaging and wound dressings [29]. Nanoparticles also occur naturally in volcanic ash, sea salt aerosols and some metal oxides, and also can be produced during forest fires [22]. The size and composition of the particles affects their properties and environmental behaviour by influencing: "chemical (reactivity, solubility, etc.), mechanical (elasticity, hardness, etc.), electronic (conductivity, redox behavior, etc.), and nuclear (magnetic) properties" [[22], p.30].
e) *Micro and fibrous plastics.* Microplastics are particles less than 5 mm in diameter and can be characterized in terms of size and form (fibers/lines, pellets/beads, foams, films, and fragments) [30]. Sources of micro and fibrous plastics to water include photodegradation and/or mechanical breakdown of larger items (e.g. Styrofoam, plastic bags, bottles, wrappers, cigarette butts and tires), product spillage from industry or shipping (e.g. pellets and powders), abrasive microbeads (e.g. toilet cleaners, face scrubs, hand scrubs and toothpastes) and polyester fibers [30].
f) *Anti-microbial compounds and antibiotic resistant bacteria* are not targeted by conventional wastewater treatment processes, nor are antibiotic resistance genes [31]. Triclosan (5-chloro-2-(2,4- dichlorophenoly)-phenol) is an antimicrobial agent in widespread use in medical, household and personal care products, including shampoos, toothpaste, deodorants, skin creams and detergents [32]. Triclosan is not degraded during conventional wastewater treatment [32]. Estimation of antibiotic pollution is needed to manage threats posed by the spread of resistant bacteria [31] and other resistant microbes.

State of the Science

A summary of key findings from the scientific literature is provided in Table 2 on page 30.

Synopsis 2: Science, uncertainty and potential for long-term impacts

Emerging contaminants are a highly varied group, and understanding of their nature is evolving as new analytic technologies and knowledge arise. Scientific research for some substances is in the early stages, especially with respect to environmental impacts. Many of these contaminants have endocrine disrupting properties, including substances within the surfactants, pharmaceutical and personal care products and flame retardants groups. Some of the contaminants bioaccumulate and biomagnify in the food web (e.g. surfactants and flame retardants) and adsorption of harmful substances to the surface of micro/ fibrous plastic particles provides an additional pathway for bioaccumulation.

The ecological fate, transport and effects of emerging contaminants are poorly understood. Levels of surfactants, personal care products and flame retardants are higher downstream of wastewater treatment plants. Micro plastic particles have been detected in surface runoff and in higher concentrations in urban water environments, whereas micro fibre plastics are ubiquitous and not specifically associated with urban waters. Laboratory studies of the interactions of anti-microbials with the environment indicate a potential to increase microbial resistance and to have synergistic effects with other environmental conditions, but the scientific field is too new for definitive scientific conclusions. Similarly, results from in situ studies of nanosilver have not been concluded[5] and, more generally, the International Council on Nanotechnology has identified the detection, quantification, and characterization of nanomaterials in environmental matrices as a top research priority [29].

Trace quantities of pharmaceuticals have been measured in surface and potable water samples, confirming their presence in the environment as well as their incomplete removal by conventional wastewater and potable water treatment systems. Research results from the Experimental Lakes Area indicate that very low dosages of an endocrine disrupting substance, equivalent to typical concentrations in wastewater effluents (5 ppb of estrogenic compound), had substantial negative effects on minnow populations within a 2-year period. Minnows are short-lived species and therefore may be at greatest risk from exposure to endocrine disruptors. The effects on longer-lived species have not been determined but negative consequences are hypothesized. Some indirect effects on long-lived lake trout resulted from a loss of food supply (K. Kidd pers. comm. 2016).

Emerging contaminants are generally poorly understood in terms of their chronic effects on receiving water environments. (Similarly, chronic effects on human health are also poorly understood.) Chronic ecosystem effects of nanoparticles, micro plastics and antimicrobial substances will not be well understood until methodological and analytical approaches are developed. Further, data then need to be acquired for scientific analyses in accordance with the newly identified approaches. Further, synergistic or antagonistic cumulative effects among emerging substances, or between emerging and conventional pollutants, are not understood. Given limited scientific research to date on the effects of individual substances on aquatic ecosystems, the interactions of substances with aquatic ecosystem structure and function is also not understood.

Consumer and industry use of some emerging contaminants can (and have been) controlled at the source through management instruments applied to products or production (e.g. the pending micro-bead prohibitions in consumer products). However, effective source controls for other emerging substances, especially pharmaceuticals, are highly problematic because the substances are released into wastewater streams as a result of human consumption and excretion. Similarly, one source of micro-fibres is washing of synthetic fabrics, which are pervasive in homes and elsewhere in the market. In the absence of source controls, other

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[5] A study is underway in Ontario's Experimental Lakes Area on whole lake effects of nanosilver (http://yourontarioresearch.ca/2015/12/nano-silver-weighing-risks-and-benefits)

options within the treatment train would need to be considered. Future measures may be needed to control, mitigate, treat or divert emerging substances, including alteration of collection and/or treatment processes.

3. Physical Alterations

Land conversion to urban uses results in a number of issues and consequences that result in physical alterations to the form, function and habitat quality of freshwater ecosystems. Physical alterations include:

a) *Hydrologic change*, due to urban land use change (in particular, increased impervious surface area). Increased volumes of runoff during precipitation events change the energy and momentum of watercourses, as well as water velocity and the rate of change in water velocity (i.e. flow acceleration) [33]; these changes, in turn, affect the habitat quality, temperature and geomorphologic characteristics of fluvial systems. Between precipitation events, urban watercourses can have reduced base flows due to reduced groundwater recharge and interflow supply. Altered dry weather stream flow conditions (i.e. lower water levels) are further exacerbated by wider stream channels.

b) *Geomorphological changes,* due to alteration of the energy balance of urban waterbodies. These changes are inter-related with hydrologic changes and may lead to altered meander patterns, sediment loads, stream width, stream depth and erosion patterns.

c) *Thermal regime change*. Thermal regime changes in urban waterbodies means increased water temperatures due to reduced riparian vegetation, runoff from warm impervious surfaces and urban heat island effects. These changes lead to a loss of cold and cool water fisheries and may exacerbate other chemical processes such as eutrophication and algal blooms.

d) *Anthropogenic responses to erosion and flooding*. These physical alterations are the measures taken within urban areas to mitigate hydro-geomorphological changes, such as channel stabilization or stream restoration activities.

State of the Science

A summary of key findings from the scientific literature is provided in Table 3 on page 36.

Synopsis 3: Science, uncertainty and potential for long-term impacts

Geomorphologic, hydrologic and thermal changes to waterbodies have been well-studied individually. Gross changes and trends that occur with urbanization are clear. Hydrology is considered a master variable for physical changes in urban waterbodies. Changes in hydrology and geomorphology can be modelled with acceptable uncertainty and models indicate that changes begin to occur at very low levels of urbanization (well under 10% urbanization of a watershed). Watercourse function can become stressed to the point that morphologic change occurs outside the expected range of variance [34], in some cases resulting in destabilized stream channels that require on-going maintenance (such as gabion baskets).

The interactions of physical changes with biotic communities are uncertain due to a lack of understanding of mechanisms and processes that cause effects on biota (e.g. nutrient transport changes), variability among biotic end points, variability of natural watershed characteristics and climatic conditions, and variability of urban development patterns. Rivers, in particular, are dynamic systems with sediment loads, erosive forces, episodic hydrologic events and channel characteristics working together to support the ecosystem, including a natural streambed disturbance regime that is needed for biotic integrity. Environmental consequences of geomorphological change include alteration of food webs, nutrients, and wood and food source transfer from headwaters to downstream segments [35]. Climate change is expected to affect these dynamic interactions and processes (see Category 4, *Global Environmental Trends*).

The anthropogenic responses to physical changes arising from urbanization have evolved from installation of localized hard-engineered erosion-prevention infrastructure to catchment scale approaches that attempt to maintain and manage dynamic channels. However, channel enlargement and re-stabilization of stream channels are not predictable at the temporal or spatial scales required for management decisions. The spatial scale of river restoration projects is typically small relative to the larger spatial and temporal scales of the causes of degradation. Consistent metrics for study of the primary processes that drive stream degradation are needed so that comparisons among studies can be made and potential application of findings to other systems can be assessed.

4. Global Environmental Trends

Global environmental trends potentially influencing urban inputs and natural system assimilation capacity in aquatic systems pertain to large scale changes associated with numerous anthropogenic activities, many of which occur as a result of urbanization or activities within urban centers. Some consequences of these trends overlap with issues already identified under Categories 1 to 3. However, they are noted within this section primarily for the high degree of uncertainty associated with their consequences and the uncertainty in identifying the best approaches to mitigate the related risks.

Some new and unexpected effects or consequences may arise as a result of the following large scale global environmental changes:

a) *Climate change* is manifesting, in part, through changes to the hydrologic cycle with alterations to precipitation and evaporation patterns. Anticipated changes vary across Canada - and globally - but generally increased risk of drought, increased frequency of extreme rain events with resulting runoff, and earlier spring melt are predicted.
b) *Biodiversity loss* is occurring at an alarming rate, especially for freshwater aquatic species which are declining at five times the rate of terrestrial fauna in North America [36].
c) *Invasive species* are varied and have a range of potential implications for urban water systems. Zebra mussels provide one example of a species that changed water column chemistry and light penetration and fouled water intake structures.

d) *Population growth in urban centers* has the potential to affect contaminant loads and other urban-related impacts.

State of the Science

A summary of key findings from the scientific literature is provided in Table 4 on page 40.

Synopsis 4: Science, uncertainty and potential for long-term impacts

Climate change trends are already being felt but future weather changes remain uncertain, particularly for precipitation regimes. Variations in modelled predictions of temperatures appear tractable (under scenarios for carbon emissions and policy responses) but variation in precipitation may be too overwhelming for reliable modelled predictions (e.g. [37]). Future changes may result in less predictable stormwater discharge, less predictable sewage overflow frequency and changes to contaminant loads. Warmer air temperatures, especially within urban centers, may alter or even eliminate spring freshet flows and affect water temperature regimes and habitat quality. In addition, altered precipitation patterns and increased temperatures will alter flow and water quantities in some watersheds which, in turn, can affect contaminant concentrations and temperature-mediated toxicity to aquatic biota.

Warmer environments present the potential for increased vulnerability of aquatic biota to conventional or emerging contaminants and increased stress on urban aquatic environments. Biological responses to chemicals in the environment, under warmer climatic conditions, are also expected to change. As a master variable, hydrologic changes arising from altered precipitation, snow melt and drought patterns can be expected to give rise to other physical, chemical and biological changes. Interactions among components of the water environment are poorly understood. Predictive models are available only for some water environment components and these models have parametric and structural uncertainties.

Advanced water security measures in developed countries, including infrastructure that provides reliable drinking water, prevents flooding and stores water for other purposes (such as power production), contribute to aquatic biodiversity decline [38]. Urban areas have long been recognized for negative effects on aquatic biodiversity due to temperature, chemistry, flow changes and loss of habitat, with the combined effects being labelled ‘urban stream syndrome’. Urban land use results in loss of wetland, riparian zones and other habitats. Urban pressures and systems further reduce the resilience and diversity of species by interrupting movement and migration (e.g. perched culverts, impassible storm drains, loss of watercourse connectivity) and introducing pollutants into water bodies (e.g. road salts, pesticides and sediments). Proliferation of aquatic invasive species can have direct effects (e.g. competition or predation) and indirect effects (e.g. habitat alteration, disease) that place additional stress on native aquatic species or infrastructure management (e.g. zebra mussel fouling).

With trends toward increased urban populations and aging populations, associated increased pollutant loads, including nutrients and pharmaceuticals, can be expected. Given other global trends and existing issues, demographic trends may challenge the assimilative capacity of receiving waters.

5. Issue Interactions and Local Context

Interactions and issues of local context include:

a) *Receiving water characteristics* of freshwater systems. Receiving water characteristics include the type of system (lotic, lentic, wetland) and the system's size/ volume/ depth, flow rates, circulation patterns, groundwater interfaces, stratification profiles, natural water quality, biota and seasonality of various characteristics. These characteristics vary widely among different systems.

b) *Synergistic/ antagonistic effects of multiple contaminants and issues.* These effects pertain to the uncertainties and science gaps associated with the multiple, simultaneous changes occurring in freshwater receiving bodies, including chemistry, climate and biodiversity.

c) Although the focus of this whitepaper was not on policy or technologies, a trend toward *total pollution load management* is worth noting as a potential option that could be applied to minimize long-term chronic impacts.

State of the Science

A summary of key findings from the scientific literature is provided in Table 5 on page 47.

Synopsis 5: Science, uncertainty and potential for long-term impacts

The range and variety of freshwater receiving waters make it difficult to know the extent to which scientific results identified for one waterbody can be extrapolated to others. Similarly, seasonal variation, annual precipitation variability and on-going watershed land use changes introduce variation. Risk assessments and decisions on management actions must attempt to take into consideration local characteristics and conditions as well as larger scale trends.

Toxicology typically examines individual contaminants. Research on the effects of multiple contaminants is difficult from the perspective of scientific study design. Some advances in modeling are occurring that facilitate the prediction of contaminant interactions in organisms (K. Kidd pers. comm., 2016). The presence of one stressor can modify the aquatic community's response or sensibility to another stressor. Combinations of two or more stressors can induce synergistic effects stronger than the sum of the individual effects. Wastewater effluents comprise complex matrices of contaminants, some of which are new to scientific study. Furthermore, ecological effects do not necessarily occur immediately. Coupled with anticipated climate-induced changes, attribution of long-term effects to specific causes may become increasingly difficult.

The United States (U.S.) and European Union (E.U.) have pollution management approaches which require dischargers to quantify total pollution loads, in the U.S. through the Total

Maximum Daily Load (TMDL) approach and in the E.U. through the Water Framework Directive requirement for good ecological and chemical status. These jurisdictions require that limits for discharges from point and non-point sources be established within the context of waterbody objectives and uses, environmental conditions, assimilative capacity and future waterbody uses. Examples of initiatives to mitigate or reverse chronic contaminant effects can be found in the Tri-State Western Lake Erie Basin Phosphorus Reduction Initiative and the Chesapeake Bay Program in the U.S., or the Helsinki Convention (known as HELCOM) agreement among nine countries and the European Union to reduce land-based pollution to inland and marine waters. Phosphorus has been of particular interest in these examples and elsewhere in European countries and U.S. States for management of eutrophication. Phosphorus recovery and reuse technologies are being implemented and alternative infrastructure designs researched, with concurrent potential to reduce the release of endocrine disrupting substances.

Conclusions and Uncertainties

There are a large number of contaminants and issues that may contribute to, or impact, the long-term, chronic effects of urban wastewater and stormwater on the environment. The scientific literature for all contaminants and issues, including those that have been the subject of research for many decades, has several recurring themes:

1. *Complexity*. Characteristics of receiving waters, individual contaminants present, interactions of contaminants with each other and with biota, synergistic effects, contaminant fate, contaminant transport and persistence, and changing baseline conditions all contribute to complexity in understanding the long-term effects of urban inputs to receiving waters. Also, the chemical composition of effluents is highly variable on short temporal scales, seasonally and over time as communities, processes and consumer goods change. Similarly, aquatic systems change over time on multiple scales, from the scale of rain events or shorter, to geologic time scales.

2. *Scale.* Spatial and temporal scales are an aspect of complexity but also apply to confidence levels in extrapolation of scientific results from laboratory to field conditions, or from a studied reach/ watershed to other waterbodies or larger basins. As spatial scale increases, other contributions (from industrial, agricultural, other urban discharges, air depositions) must also be considered. Feedback loops, such as nutrient resuspension, can only be understood on longer time scales. Similarly, potential aquatic ecosystem and human health effects of new contaminants are uncertain until their fate, transport and persistence are understood on appropriate temporal and spatial scales. As either space or time scales increase, new ecological variables and emergent interactions occur [39], [40]. Assessing the relative importance of WWTP and stormwater effluent contributions is difficult [21] given multiple dischargers, acute versus chronic effects, changing climatic conditions and other factors.

3. *Uncertainty*. Despite advances over the past decades in the understanding of various issues, uncertainty remains. Science is an on-going process of inquiry, requiring reductionist methodologies that naturally limit the scope of results. Scientific findings are continuously

challenged by the need for replicability, new questions and the evolution of new understanding. There is a particularly large degree of uncertainty around the ultimate impact of issues that are newly identified (e.g. nanoparticles) and that affect large scales (e.g. continental watersheds and global processes such as climate).

Discussion of the relevance of long-term chronic impacts to the environment and the associated implications for planning, policy, and decision-making, can provide a basis for identifying next steps for protection and improvements to watershed and aquatic ecosystem health.

Table 1: Conventional and Legacy Pollutants

Table 1. Conventional and legacy pollutants: state of the science research summary

1.	**Conventional and Legacy Pollutants**			
	Pollutant/ Issue	**Key scientific findings to date**	**On-going research questions and uncertainties**	**Potential significance for longer-term urban inputs to water resources**
a	*Phosphorus: two recent issues*			
	Re-suspension / re-dissolution from sediments	• Internal P loading in Lake Winnipeg occurred almost every year between 1999– 2012 and had probably also occurred in previous decades [4]. • In a study of basins in Estonia/ Russia, internal P loading increased during the period of decreased external P loading [16]; increased wave action was correlated with increased internal P loading[16] • P can be released from sediments under anaerobic conditions and also under aerobic conditions featuring high chlorophyll a, and certain temperature, mineralization of organic material and pH conditions [16] • Hysteresis: In most lakes, a new steady state was reached in 10–15 years after P inputs were decreased (measured in terms of total phosphorus, phytoplankton chlorophyll a and improved water clarity), although heavily loaded lakes may take decades to recover; internal P loading appeared to be the main reason for the delay [41]	• Ecosystem responses include many slow, long-term changes to nutrient fluxes, and species successions that cannot be assessed by short, small-scale experiments [41] • Studies of biotic responses to water-quality improvement are rare and mechanistic responses driving community recovery are poorly known [20] • Two biotic recovery targets (at the reach scale and at the watershed scale) are recommended to evaluate biotic responses to habitat improvements, such as WWTP improvements [20]	• Additional P from internal loading mechanisms may delay measurable improvements in aquatic health after reduced loading from urban inputs; alternatively internal loading may lead to more stringent management requirements for P releases
	Harmful Algal Blooms	• Toxic algal species, such as toxic cyanobacteria, produce toxins that can be fatal to aquatic organisms and contribute to health problems in humans; decomposition of non-toxic algal blooms depletes	• Nutrient enrichment contributes to increased prevalence of HABs, but the relationship of P versus N	• Interaction of HAB production with nutrients and warmer temperatures can be

1.	Conventional and Legacy Pollutants			
	Pollutant/ Issue	**Key scientific findings to date**	**On-going research questions and uncertainties**	**Potential significance for longer-term urban inputs to water resources**
		dissolved oxygen levels and contributes to the loss of submerged vegetation [6]. • Nitrogen inputs have not increased as rapidly as P inputs to Lake Winnipeg; a low N:P ratio favors nitrogen fixing species of Cyanobacteria [3]; the proportion of phytoplankton that is Cyanobacteria in Lake Winnipeg has increased from 56% in 1969 to over 80% [3] • Elevated P concentrations, along with increased temperatures, produced the fastest overall growth rate for toxic algal species [6] • The positive relationship between total cyanobacteria bio-volume and P concentration disappeared at high P concentrations; cyanobacteria bio-volume increased continually with N concentration, indicating potential N limitation in highly P enriched lakes [18] • Taxa had diverse responses to differential N versus P concentrations, and differences between taxa were not consistent with the hypothesis that N_2-fixing taxa would be favoured in low N relative to P conditions [18] • Cyanobacteria and N_2-fixing Nostocales should not each be treated as single groups with respect to effects of changes in nutrient loading on community structure. The two most abundant potentially toxin producing Nostocales in one study were found in lakes with high N relative to P enrichment [18]	enrichment and the effect of additional factors are unclear [6] • For Lake Winnipeg, climatic warming is expected to further increase sediment oxygen demand, P release rates, and occurrence of cyanobacteria [4]	expected to be subject of continued and growing interest

1.	**Conventional and Legacy Pollutants**			
	Pollutant/ Issue	**Key scientific findings to date**	**On-going research questions and uncertainties**	**Potential significance for longer-term urban inputs to water resources**
		• Nuisance periphyton biomass (>150 $\mathrm{mg{\bullet}m^{-2}}$) occurred (Bow River) at total dissolved phosphorus (TDP) > 6.4 $\mathrm{\mu g{\bullet}L^{-1}}$; macrophyte biomass was lower during high-discharge years [42]		
b	*Other nutrients (especially nitrogen)*	• Municipal and industrial WWTPs contribute significant nutrient loads to receiving waters [3] • “Point sources generally account for > 50% of nutrient inputs to rivers and streams draining urban areas in the U.S.” [3, p.210] • Atmospheric nitrogen contributes to N storage in sediments and in-lake N recycling [41] • Elevated runoff volumes from impervious surfaces increased pollutant loads compared with other land uses; automobile-related sources contribute nutrients to stormwater systems [43] • Ammonia (NH_3–N) can directly affect dissolved oxygen and accounted for 60% of variation in oxygen demand in the San Joaquin River, California [5] • Ammonia toxicity is exacerbated in receiving waters with alkaline pH [5] • Ammonia threatens viability of various fish species [5], [44] • Periphyton and aquatic macrophyte biomass (Bow River) declined following enhanced nutrient removal at Calgary’s WWTPs, with the greatest decrease following reduced nitrogen discharge [42] • A dose-effect response to increased nutrients (ammonium, sulfate, phosphate) and reduced		

1.	Conventional and Legacy Pollutants			
	Pollutant/ Issue	**Key scientific findings to date**	**On-going research questions and uncertainties**	**Potential significance for longer-term urban inputs to water resources**
		dissolved oxygen in WWTP effluent was measured in abundance and composition of macroinvertebrates after 1 week exposure to 30% effluent, and after 2 weeks in 15% and 30% effluents; exposure to wastewater effluent concentrations as low as 5% can have detectable ecological effects [45] • Attenuation of nutrients (P and N forms) and BOD over a 40 year period in the Dallas-Fort Worth urban area is associated with changes in water quality and fish assemblage composition in downstream reaches greater than 200 km away [19] • Macroinvertebrate total individuals, total species, and species richness were greatest near a WWTP outfall (Louisiana); municipal effluent (secondary treatment) resulted in high nutrient retention, enhanced forest productivity, and minimal impact on benthic community structure [46] • Concentrations of nutrients exceeded Canadian guideline thresholds during wastewater lagoon release (Manitoba), but returned to background levels once discharges ceased [47] • The highest peaks in total phosphorus (TP) and total nitrogen (TN) from seasonal release of sewage lagoon effluent (Manitoba) were associated with a watershed with the highest human population density [48] • An estimated 3% of rural TP and TN loads (S. Manitoba) are released from sewage lagoons [48]		

1.	**Conventional and Legacy Pollutants**			
	Pollutant/ Issue	**Key scientific findings to date**	**On-going research questions and uncertainties**	**Potential significance for longer-term urban inputs to water resources**
c	*Legacy contaminants (PAHs, PCBs, VOCs)*	• WW effluent is a principal contributor to the St Lawrence River at Montreal of PCBs and PAHs; in 1999, sediment concentrations were 170% and 300% higher, respectively, and detectible in the plume for 11 km [21] • PAHs were identified 10-fold higher in urban runoff suspended sediments (New Zealand) than in a rural catchment, possibly from a disused gasworks [49] • Levels of PCBs in the St Lawrence River have declined over the past 40 years [21] • Adult fish downstream of Montreal did not have higher levels of PCBs, Hg, trace metals or pesticides than upstream of the WWTP; fish migration and contaminant dilution were hypothesized explanations [21]		
d	*Mercury*	• Removal of Hg in WWTP has positive correlations with suspended solids removal and chemical oxygen demand, attributed to high-sorption characteristics of Hg [9] • Levels of Hg in the St Lawrence River have declined over the past 40 years [21]		
e	*Other Metals*	• WW effluent contributes relatively high levels of Cd, Cu, Zn, Ag to the St Lawrence River [21] • Dissolved metals bind with colloids; colloidal Fe (from WW process) and dissolved organic matter enhance the potential for effluent to act as a metal carrier and influence the fate and transport of metals studied in St Lawrence River (Al, Cd, Cu, Fe, Mn, Ag, Zn); colloids in the wastewater effluent plume decrease rapidly with	• Toxicity of chronic exposure to various forms of Cd, Cu, Zn, Ag is poorly understood [21] • Abundance of colloids in proximity of WW effluent outfall likely modifies bioavailability and bioaccumulation of metals [21] near the outfall	

1.	Conventional and Legacy Pollutants			
	Pollutant/ Issue	**Key scientific findings to date**	**On-going research questions and uncertainties**	**Potential significance for longer-term urban inputs to water resources**
		mixing, limiting long-range transport of colloid fraction of metals in effluents [21] • Suspended particulates in the wastewater effluent plume become metal enriched and have increased reactivity [21] • Metal partitioning (especially Cd, Cu, Zn) is impacted by organic carbon, Fe oxide, carbonate content [21] • Sediments with high aluminum content enhance phosphorus sorption [5] • Traffic more heavily influences risk of heavy metals in stormwater than land use characteristics [10] • Contaminant concentrations in runoff are seasonally dependent, and are typically high in early spring, coinciding with snowmelt [50] • Loadings of total suspended solids and trace metals in snow conditions increase with increasing snow age and traffic density [51] • Trace metals (Cd, Cr, Cu, Ni, Pb, Zn) bind to coarse street sediments (>250 μm) in dry weather but metal burdens are released by rainfall/runoff processes [43] • Metals in solids recovered from stormwater facilities were marginally-to-intermediately polluted by Cd, Cr, Cu, Fe, Pb, Mn, Ni, Zn, with some severe Cr, Cu, Mn, Zn at several facilities; sediment toxicity was confirmed at several sites [52] • Wild freshwater mussels (Grand River ON) exposed to effluents from 11 municipal wastewater treatment plants and stormwater from 4 cities had significant	• Metal mobility and exposure to aquatic organisms vary with WW effluent plume characteristics [21] and therefore effects may not be readily extrapolated from studies in other locations • Quantitative risk assessment is developing for human health implications of using stormwater as a drinking water source where heavy metals are present; heavy metal hazard index may be more important than concentration [10] • Street cleaning to remove coarse sediments (>250 μm) may also remove attached fine particles contaminated with metals [43]	

1.	Conventional and Legacy Pollutants			
	Pollutant/ Issue	**Key scientific findings to date**	**On-going research questions and uncertainties**	**Potential significance for longer-term urban inputs to water resources**
		cumulative increases in Cu, Pb, Zn, Al, Cr, and Ni in their gills; tissue concentrations increased with multiple urban inputs [53]		
f	*Pathogens and related issues*			
i	Pathogens	• Fecal bacteria concentrations from CSOs decreased by 66% after 13 to 14 hours in transit (Seine River); concentrations were initially 7 to 9 times higher than upstream; dilution, decay and sedimentation of initially suspended solids with attached bacteria explained the decline with time [54] • Microbial contamination in stormwater is influenced by the intensity of urbanization, streamflow and antecedent precipitation, but indications of higher concentrations in 'first flush' runoff were not indicated [55] • The average storm event delivered microbial contaminant loads equivalent to months of dry-weather loading [55] • In four urban catchments (Sweden), relative to dry weather baseflow concentrations, during rainfall and snowmelt, coliforms, *E. coli* and enterococci were 10 (snowmelt runoff) to 100 (rain runoff) times higher; mean *C. perfringens* concentrations were essentially constant; no reliable surrogate variable to predict bacteria concentrations was identified [56] • *E. coli* concentrations in stormwater runoff were ~2 orders of magnitude lower than in combined sewage overflows (Montreal / St Lawrence River) [57]	• Temporal loading of non-point source urban microbial contaminants is not well understood [55]	• Consideration of temporal loading patterns are important for implementation of appropriate best management stormwater practices [55]

1.	Conventional and Legacy Pollutants			
	Pollutant/ Issue	**Key scientific findings to date**	**On-going research questions and uncertainties**	**Potential significance for longer-term urban inputs to water resources**
ii	Chlorine and disinfection by-products (DBPs)	• DBPs can be toxic and may have a deleterious impact on aquatic organisms exposed to them [7] • General toxicity from DBPs is correlated with chlorine dose, total nitrogen, inorganic carbon, UV_{254} and pH [7] • Toxicity tends to increase in the order chlorinated < brominated < iodinated, for a given class of DBP [7] • Chlorinated wastewater effluents had the highest toxicity but dechlorination did not reduce toxicity to the levels found before chlorination [7] • Variable androgenic and estrogenic activity from DBPs at occurred at sampling sites [7]	• The effects of disinfection by-products in the environment are not well understood [7]	• Chlorination/ dechlorination may not be adequate treatment strategies for protection of receiving waters [7] • Although dechlorination can mitigate Cl toxicity, it does not remove DBPs [7]
iii	Parasites	• Certain parasites have increased pathological effects in polluted waters; exposure to municipal effluents decreases parasite tolerance, increasing disease severity at a given infection level; resistance appears to be unaffected so parasites are not more prevalent in waters polluted by municipal effluents [21]	• Immunosuppression of aquatic species is subject of on-going research [21]	
g	Organics (conventional), including BOD	• Incidents of dissolved oxygen depletion in Canada are usually associated with untreated or primary treated sewage or receiving environments with low flow or limited circulation [58]		
h	Sediments, floatables	• Construction activities contribute nutrients to urban stormwater runoff through transport of sediment-bound P; stormwater pollutant exports associated with construction sites may continue for several years until soils become stabilized post-development [6] • Potential threats from combined sewage overflows may be short-term, delayed, and long-term, and the		

1.	**Conventional and Legacy Pollutants**			
	Pollutant/ Issue	**Key scientific findings to date**	**On-going research questions and uncertainties**	**Potential significance for longer-term urban inputs to water resources**
		impact could be hydraulic, chemical, physical, pathological, biochemical, and aesthetic [59] • A wide range of pollutant concentrations can occur during a single activation of an overflow event [59] and from stormwater runoff [60]		
i	Chlorides, including road salts	• The Canadian Council of Ministers of the Environment limit for short-term exposure is 640 Cl^- per liter and for long-term exposure, 120 Cl^- per liter [14] • Of Canadian provinces, Ontario and Quebec apply the most chloride to roadways, but Nova Scotia has the highest loading per unit land area [14] • In 2008, chloride discharge from WWTPs was an order of magnitude lower than road salts in Ontario (175,000 tonnes versus 1,148,570 tonnes for roads) [14] • In 2011, a highly urbanized tributary to Lake Ontario (Mississauga) had chloride concentrations exceeding seawater (20,000 mg/L). [14] • Changes in algal communities occur as chloride increases from background levels (1.8–3.6 mg/L) to over 7 mg/L; shifts in lake algae populations were associated with concentrations of 12–235 mg/L [13] • More generally, increased chloride concentrations may affect aquatic community structure, diversity and productivity [13] • K chloride and Mg chloride salts are more toxic than Na chloride; Fish may be less sensitive to Ca chloride than to Na chloride but the reverse was observed for invertebrates [13][14]	• Steady state chloride concentrations in surface waters are not achieved until groundwater concentrations are flushed to surface waters; concentrations of chloride in surface waters can be expected to increase over the long-term; estimation of concentrations and trends depends on local hydrogeological conditions and other anthropogenic factors (e.g. road network density)	

1.	Conventional and Legacy Pollutants			
	Pollutant/ Issue	**Key scientific findings to date**	**On-going research questions and uncertainties**	**Potential significance for longer-term urban inputs to water resources**
		• Elevated chloride levels increase metal bioavailability [13] • Road salts in sufficient concentrations can affect density gradients in lakes, with ecosystem impacts on the depth-dependent availability of oxygen and nutrients [13][14] • Estimated average annual concentrations in runoff from Canadian highways can reach up to 31 000 mg/L, but are more typically between 1000 and 10 000 mg/L [13] which are acutely toxic levels under the CCME Guidelines [14]. • Chlorides are currently increasing in all five Great Lakes, following declines in concentrations in Lakes Huron, Erie and Ontario in the 1960s and 1970s. Where there were declines, reductions are likely attributable to industrial source control programs. Sources responsible for the increase may be attributable to diffuse sources, including road salts and private parking lot salting. Modelling indicates chloride concentrations in the lakes will continue to rise if loads are held at 2006 levels. A lack of monitoring and reporting hampers load estimations from point and diffuse sources. [61] • The time required for chlorides deposited to groundwater to discharge to surface waters depends on hydrogeological conditions; modelling suggests between 5 and 200 years for chlorides to be flushed from groundwater to surface waters [13]		

1.	**Conventional and Legacy Pollutants**			
	Pollutant/ Issue	**Key scientific findings to date**	**On-going research questions and uncertainties**	**Potential significance for longer-term urban inputs to water resources**
		• Decreased application of road salts does not result in associated decreases in chloride concentrations in surface waters because chlorides are persistent and are stored in subsurface waters (increasing baseflow chloride concentrations, resulting in a lagged timing for release to surface waters) [14]. • Increased baseflow concentrations of chlorides is associated with urbanization [15] • Stormwater management facilities that allow accumulation of chlorides can result in groundwater contamination, chemo-stratification and flushing of contaminated water during peak flow events [15].		

Table 2 Emerging Contaminants

Table 2. Emerging contaminants: state of the science research summary

2.	**Emerging Contaminants**			
	Pollutant/ Issue	**Key scientific findings to date**	**On-going research questions and status of inquiry**	**Potential significance for longer-term urban inputs to water resources**
a	Surfactants	• Nonylphenol is persistent in the aquatic environment, moderately bioaccumulative, and extremely toxic to aquatic organisms [22] • Discharges of alkylphenol ethoxylates and their metabolites from WWTPs and combined sewer overflows were important contributors to concentrations in Great Lakes, highest in proximity of outlets and low or non-detectable in open waters of the Great Lakes [22]. • Anionic surfactants are largely removed by biodegradation during wastewater treatment; concentrations in effluent of U.S. WWTPs is considered low but may increase with increasing populations [23] • Surfactant additives in detergents and personal care products contributed the highest ecological risk factors in a screening study of pharmaceuticals and additives [62]		• Although full scientific understanding of the long-term ecological effects of surfactants are not well understood, some management controls have been initiated through Environment Canada's Chemicals Management Plan
b	Endocrine disruptors (EDCs), including pharmaceuticals and personal care products	• Canada's Experimental Lakes Area ELA whole lake experiments over 7 years found exposure of fathead minnow to low concentrations (5-6 ng-L^{-1}) of 17a-ethynylestradiol resulted feminization of males, leading to near extinction of the species from the lake,	• Analytical detection of EDCs requires extraction due to trace levels (µg/L or ng/L); these methods have limitations, especially in complex matrices such as wastewater [24]	• Study of EDCs in the environment can be expected to be of continued and growing interest; source controls are inherently

2.	Emerging Contaminants			
	Pollutant/ Issue	**Key scientific findings to date**	**On-going research questions and status of inquiry**	**Potential significance for longer-term urban inputs to water resources**
		allowing the conclusion that exposures adversely impact the sustainability of wild fish populations [63] • Estrogenic hormone disrupting potency can be several thousand times higher than other chemicals such as nonylphenol [24] • Exposure of fish species to estrogenic compounds resulted in altered sexual development, presence of intersex species, changed mating behavior [27] • The proportion of female mussels downstream of Montreal's WWTP is consistently higher than upstream [21] • Samples up to 5 km downstream of Montreal's WWTP indicated presence of serotonin inhibitor drugs [21] • Short-lived fish species (e.g. fathead minnow) may be at greatest risk from exposure to estrogens and their mimics, but longer-lived species may eventually display similar results [63] • Zones of influence of organic contaminants downstream of WWTPs varied depending on a contaminant's removal; a contaminant's removal can vary from rapid in-stream removal, to partial attenuation, to persistence >100 km downstream. For example, ethylenediaminetetraacetic acid (EDTA) persisted for ~500 km (Texas); sulfamethoxazole concentrations were reduced 80% after 105 km (Saskatchewan) [64] • Even after wastewater treatment, fish and other aquatic organisms demonstrate developmental,	• Adverse health effects of estrogenic hormones on humans are subject of debate, in part due to variables such as lag time between exposure and manifestation of effects, age and duration of exposure [27] • An absence of population studies of fish inhibits understanding of endocrine disruptors effects [21] • Mechanisms of toxicity, bioaccumulation in aquatic organisms require study [21] • Fate and transport of pharmaceuticals and personal care products in natural aquatic environments is poorly understood [62]	problematic for many substances (e.g. pharmaceuticals), potentially placing the focus on removal technologies or infrastructure re-design

2.	**Emerging Contaminants**			
	Pollutant/ Issue	**Key scientific findings to date**	**On-going research questions and status of inquiry**	**Potential significance for longer-term urban inputs to water resources**
		reproductive, and behavioural changes from exposure to pharmaceuticals, personal-care products, or other pollutants [58] • Hazard quotients of micropollutants (pesticides, pharmaceuticals) after lagoon wastewater release (Manitoba) indicated minimal toxicological risk to aquatic biota, except erythromycin and diazinon presenting potential concern for algae and invertebrates [47]		
c	Flame retardants	• Compounds of a chlorinated flame retardant, Dechlorane Plus (DP), were found in trout at 2 magnitude levels higher than the concentration of the original product (DP); research into effects on the food chain is on-going [22] • Perflourinated compounds concentrations were 4 times higher than upstream samples in tissues of northern pike downstream of Montreal's WWTP [21] • Muskellunge, a non-migratory fish, downstream of Montreal's WWTP had significantly higher levels of PBDEs and antidepressants, as well as Fe (indicating exposure to coagulants from the WWTP process) [21] • Heron eggs downstream of Montreal's WWTP had PBDEs up to 10 times higher than upstream [21]	• Chlorinated flame retardant compounds have only recently been identified in fish; implications, if any, are unknown	• Although full scientific understanding of the long-term ecological effects of surfactants (including surfactants in flame retardants) are not well understood, some management controls have been initiated through Environment Canada's Chemicals Management Plan
d	Nanoparticles/ materials	• The dissolved fraction of silver and copper oxide nanoparticles largely contributes to their acute toxicity to *Daphnia magna* [65]. • Shape plays a role in toxicity; octahedral Cu_2O nanocrystals were more toxic to *D. magna* than cubic	• No in situ studies have been completed on the fate of nanosilver particles; there is a paucity of analytical methods to monitor the particles at	• Study of nano particles in the environment can be expected to be of continued and growing

2.	Emerging Contaminants			
	Pollutant/ Issue	**Key scientific findings to date**	**On-going research questions and status of inquiry**	**Potential significance for longer-term urban inputs to water resources**
		nanocrystals, probably because of higher surface activities with the higher number of facets; food ingestion was the main entry pathway of the micro/nanocrystals into organisms [66] • Lab studies of the fate of nanosilver particles in the aquatic environment indicate that they are influenced by temperature, ionic strength, pH, concentration of dissolved organic matter, and the rate of dissolution of the particles (which releases silver ion into solution) [29] • Nano plastics have a different impact on aquatic organisms than larger pieces of plastic due to their small size, high surface curvature, and large surface area [67] • Adsorption to algae interferes with photosynthesis and may affect their viability [67] • Effects of nano-plastics on top food web consumers were manifested after 2 - 3 months of repeated exposure [67]	environmentally relevant concentrations [29] • The International Council on Nanotechnology ranked the detection, quantification, and characterization of nanomaterials in environmental matrixes as a top research priority [29] • Few studies have studied effects of plastic nanoparticles on algae, with a focus on polystyrene; study is needed to evaluate negative effects of nano-sized plastics on algae [67] • Dose-response studies of nano-particles are difficult; a chemical effect can be manifested as a behavioural or morphological change, inducing a secondary effect on the next trophic level without a direct effect of the plastic [67]	interest; source controls (e.g. limiting nano particles in consumer products) may be required as part of the management approach
e	Micro and fibrous plastics	• Ingestion by biota can cause digestive system obstructions, clogging, oxidative stress, impaired reproduction, death, uptake and bioaccumulation of harmful chemicals, cancer and endocrine disruption [30][67]	• Micro plastics in freshwater have not been studied to the same extent as in marine systems. Data is lacking, particularly for small surface water systems. Sources and freshwater environmental	• Study of micro plastics in the environment and the role of urban inputs can be expected to be of continued and growing interest;

2.	**Emerging Contaminants**			
	Pollutant/ Issue	**Key scientific findings to date**	**On-going research questions and status of inquiry**	**Potential significance for longer-term urban inputs to water resources**
		• High sorption capacity of plastics enables accumulation of persistent organic pollutants, with concentrations 105 −106 times higher than in the surrounding water column [30] • Trace metals and pathogens also accumulate on microplastics [30] • Fragments, films, foams, and pellets/beads were positively correlated with urban watersheds and were found at greater concentrations during runoff-event conditions [30] • Fibers, the most frequently detected particle type, were not associated with urban-related watershed attributes, wastewater effluent contribution, or hydrologic condition [30] • Micro plastic particles can be ingested by many organisms, including detritivores, filter feeders, deposit feeders, zooplankton, mussels and seabirds; they were found in fish, and accumulated fragments in crabs' digestive track, stomach and gills [67]	fate are not studied. Data on biological effects in freshwater species is completely lacking as is data on ingestion and potential for increased chemical exposure for freshwater organisms [68].	source controls (e.g. micro bead restrictions in consumer products) may become increasingly important as a management approach
f	Anti-microbials and antibiotic resistant bacteria	• Incubation experiments on treated wastewater found chlorination and UV did not affect the overall bacterial abundance or the fitness of the bacterial community [31] • Disinfection based on chemically aggressive destruction of bacterial cell structures can promote a residual microbial community that is more resistant to antibiotics and more resistant to competitive stress in nature [31]	• Incubation of the effluent community in natural conditions is needed for the potential cell recovery to be assessed, meaning samples collected immediately following disinfection treatment are not well-suited to evaluate bacterial community resistance characteristics [31]	• Bacterial resistance issues could lead to further examination of the potential role of WWTP processes in altering bacterial strains/ proliferation

2.	Emerging Contaminants			
	Pollutant/ Issue	**Key scientific findings to date**	**On-going research questions and status of inquiry**	**Potential significance for longer-term urban inputs to water resources**
		• Triclosan affects the capacity of periphyton[6] to remove dissolved nutrients, to cope with toxicant loads in streams and to cope with grazing [32] • Grazing pressure magnifies toxicant negative effects on community structure and ecosystem functions (e.g. primary production, nutrient cycling) [32] • The antibiotic ciprofloxacin influenced algal community structure, with the potential to shift food web structure of streams [69] • Antibiotics and antibiotic resistance genes have been detected in finished drinking water [69]	• Bacterial resistance assessment is an emerging field of study • Interactions between emerging contaminants and other drivers of community structure and function are poorly understood [32] • Mechanistic studies of toxicant effects on species interactions are required to assess the risks of toxicant release into natural ecosystems [32]	

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[6] Periphyton is the aquatic community of algae, microbes, diatoms attached to submerged surfaces; associated with uptake of contaminants and nutrients; a food source for invertebrates, fish and other species [125]

Table 3 Physical Alterations

Table 3. Physical alterations to watersheds: state of the science research summary

3.	**Physical Alterations**			
	Pollutant/ Issue	**Key scientific findings to date**	**On-going research questions and status of inquiry**	**Potential significance for longer-term urban inputs to water resources**
a	Hydrologic change	• Urbanization increases the magnitude of peak flows and the frequency of large flows (due to decreased infiltration)[70] [71] • The rate of change in flow (flow acceleration) increases with urbanization [33] and is associated with decreased fish biodiversity [72] • Types and magnitudes of hydrologic changes in urban catchments are heterogeneous even for uniform urban patterns, depending on slopes and soil permeability [73][33] • Increased frequency of exceedance of the threshold discharge for streambed mobilization (Qcritical) is associated with decreased macroinvertebrate biotic integrity [74] • Mechanisms by which hydrologic alteration can affect stream ecosystem communities and processes include algal scour, export of nutrients and organic matter and physical washout of fauna. Indirect influences arise from changes in channel geomorphology and water quality [70]	• Hydrology is considered a master variable for degradation of urban waterways, but the extent to which flows can be reduced through stormwater management techniques requires further investigation [60], [75]–[77]	• Maintenance of natural streambed disturbance regimes is needed for biotic integrity [74] • Restoration of hydro-morphological characteristics (habitat structure, flow regime, watershed scale connectivity) is necessary for complete recovery of local invertebrate assemblages in multi-stressed reaches [20]
b	Geomorphological change	• Changes include higher channel bed mobility, reduced bank stability, channel simplification, increased fine sediment inputs, increased channel embeddedness, increased bed and bank erosion,	• Consistent metrics are needed for comparison and application of findings regarding primary processes that drive urban-	• An adaptive management approach is needed to develop low impact

3.	**Physical Alterations**			
	Pollutant/ Issue	**Key scientific findings to date**	**On-going research questions and status of inquiry**	**Potential significance for longer-term urban inputs to water resources**
		leading to increased channel widths and cross-sectional areas [70] and limited space for channel adjustment [78] • Altered urban sediment dynamics first increase sediment supply during road or subdivision construction and incision phases, but reduce supplies over the long-term in established urban catchments [78] • Channel enlargement can affect stream ecosystems by several mechanisms, including increased sediment, poor habitat quality in eroding channels, and water tables lowered below microbially active soil zones [70] • Large changes in several geomorphic variables were detected at very low levels of effective imperviousness (<2–3%) [76] • The greatest increase in erosion potential is associated with moderate flow events (recurrence interval <1:1.5 years), with implications for stormwater storage and the need to understand lower limits of scour resistance in given channel sections [79]	induced degradation of streams [80] • Biotic endpoints to asses change are fraught with uncertainty; biota can have differing thresholds for change along a disturbance gradient, different magnitude of change, different directions of response or no response [81] • The relationship between urbanization and indicators of channel enlargement is not predictable from scientific studies to date [70] • Urban channels may eventually stabilize but conditions for stabilization and occurrence are not understood [70]	development approaches to support diverse biological community and healthy ecosystem function [82]
c	Thermal regime change	• Water temperature increases with increasing urbanization [82]–[84] • Mechanisms that result in increased water temperatures include loss of riparian vegetation, decreased groundwater recharge, increased stormwater entering streams after it has been warmed by flowing over urban surfaces and/or		

3.	**Physical Alterations**			
	Pollutant/ Issue	**Key scientific findings to date**	**On-going research questions and status of inquiry**	**Potential significance for longer-term urban inputs to water resources**
		detention in stormwater facilities and [82] urban heat island effect [70]		
d	Anthropogenic responses to erosion and flooding	• Modification of stream channels by humans include concrete-lining to prevent migration or enlargement, channel straightening, lining with rip-rap, piping streams and filling streams [70] • Local reach stabilization with concrete causes dramatic habitat simplification and exacerbates hydrologic and geomorphic impacts downstream [70][85] • Concrete channels separate the stream from its natural connections to the floodplain and the hyporheic[7] zone, thus eliminating locations for biological activity [70] • More recent channel reconfiguration approaches (e.g. Natural Channel Design; targeted channel armoring) maintain channel stability as a primary objective but can be destroyed by erosion and have not consistently had measurable ecological improvements at catchment [78] or watershed scales [86] [87] • An 'anticipatory management' [85] approach (i.e. erosion is concentrated in specific areas based on geomorphic analysis) is part of a newer movement to dynamic channel management [78]		• The spatial scale of river restoration projects typically is small relative to that of the historical environmental degradation making it very difficult to achieve goals to support key species [40]

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[7] A zone beneath and along stream beds where shallow groundwater and surface water mix; an area where some fish spawn [126]

3.	**Physical Alterations**			
	Pollutant/ Issue	**Key scientific findings to date**	**On-going research questions and status of inquiry**	**Potential significance for longer-term urban inputs to water resources**
		• Some urban systems have been too extensively altered for full rehabilitation [88], requiring alternative ecological and social goals to be established		

Table 4 Global Environmental Trends

Table 4. Global Environmental Trends: state of the science research summary

4.	**Global Environmental Trends**			
	Pollutant/ Issue	**Key scientific findings to date**	**On-going research questions and status of inquiry**	**Potential significance for longer-term urban inputs to water resources**
a	Climate change	Several sub-issues related to climate change are discussed following, including: hydrologic regime change, stormwater and sewage risks, alteration of temperature regime and habitat quality, and biological response to chemicals with climate change.	• Local management (e.g. sub-watershed or reach scale) can have effects on discharge and water quality that exacerbate or ameliorate warming effects; interactions between climate change and other environmental factors are complex in large rivers [89]–[91] • Studies are needed on water and climate change at spatial and temporal scales appropriate for the decision scale [92]	• Predictability is reduced and uncertainty increased by climate change on multiple spatial scales
i	Hydrologic regime change (drought, extreme rain events)	• Climatic stationarity has been lost with climate change, with implications for water management [93] and predictability of the hydrologic regime • WWTP discharges may cause more pronounced effects during low-flow or drought periods when effluent constitutes the majority of base flow [5] • Just slight increases in precipitation have increased flooding frequency of the Red River, the main nutrient source to Lake Winnipeg, resulting in a near doubling of eutrophication in less than two decades [41]	• Rainfall pattern changes must be understood, or scenarios modelled, to assess impacts on stormwater management systems in terms of flooding, pathogen exposure and environmental protection [60]	• Risk assessment methodologies and contingency plans (e.g. for extended periods of drought in vulnerable watersheds) may need to be developed/ refined

4.	Global Environmental Trends			
	Pollutant/ Issue	**Key scientific findings to date**	**On-going research questions and status of inquiry**	**Potential significance for longer-term urban inputs to water resources**
		• Multi-seasonal drought modelling indicates a reduction of the dilution capacity of point source effluents could lead to water quality decline (Meuse River, N.Europe) [94], [95] • Climate change might further exacerbate hydrologic alteration, especially in regions where storms increase in frequency and severity [70] • Future urban growth, causing an increase in impervious area, may have disproportionately negative effects on stream biodiversity (macroinvertebrates) due to flows that become increasingly intermittent due to climate change [96] • Prolonged drought substantially altered macroinvertebrate assemblages (Australia); water quality and macroinvertebrate effects were mitigated by tree cover over 60% in upstream catchments [97] • Changes in sediment delivery from increased frequency of intense rainfall could be more important than changes in hydrological regime [98]		
ii	Stormwater and sewage risks (overflows, contaminant loads)	• Although modelling predicts increased CSOs, the effects on risk for human exposure are not predicted to increase due to a combination of changes in pathogen survival, dilution and recreational water use behaviour. Conversely, higher average infection risks downstream of WWTPs are predicted based on a decrease in dilution capacity of surface waters for relatively stable pathogens like Cryptosporidium and norovirus [94]		• Treatment adaptation measures at WWTPs may be more beneficial for human health than decreasing CSO events [94]

4.	**Global Environmental Trends**			
	Pollutant/ Issue	**Key scientific findings to date**	**On-going research questions and status of inquiry**	**Potential significance for longer-term urban inputs to water resources**
iii	Alteration of temperature regime and habitat quality	• Internal phosphorus load is expected to increase with climatic warming due to increased sediment oxygen demand and associated P release [4], [98] . • Lower summer flows with longer residence times may increase eutrophication and algal blooms [98] • For the River Ouse (England): modelling of phytoplankton biomass predicts a shift due to climate change from oligotrophic/mesotrophic conditions to mesotrophic/eutrophic by 2080; reducing nutrient pollution was less effective at suppressing phytoplankton growth than establishing riparian shading; P loads in two modelled tributaries predict reduced loads from WWTPs will reduce peak phytoplankton by ~10%, whereas a reduction of ~45% is possible if riparian tree cover is also implemented [99] • Higher temperatures reduce dissolved oxygen; oxygen also depends on photosynthesis and respiration processes and, in lakes, depth and degree of mixing [98] • Species distributions and abundance may change due to alterations in metabolic rates, feeding, migration, physiological harm, exceeded thermal limits for spawning, migration and survival success [98] • Conversely, water quality improvements and increased temperatures had positive effects on macroinvertebrate diversity since 2000 (France) [91] and confounded effects in England [100]	• Interactive effects of multiple stressors in a warming climate [101] require more study	• See synergistic effects

4.	Global Environmental Trends			
	Pollutant/ Issue	**Key scientific findings to date**	**On-going research questions and status of inquiry**	**Potential significance for longer-term urban inputs to water resources**
		• Interactive effects on stream periphyton of fine sediment, nutrients and water temperature (eight levels, 0–6 °C above ambient) in running waters were manipulated had pervasive individual effects, but in combination frequently produced synergisms at the population level and antagonisms at the community level [101] • Increased water temperatures are predicted to increase litter processing by aquatic fungus at the expense of invertebrates [102]		
iv	Biological response to chemicals with climate change	• Sub-yearling Chinook salmon exposed to a pesticide (malathion) at elevated temperatures (19 and 20°C) had 11% higher mortality compared to exposure at optimal (11°C) temperatures; malathion concentrations for 50% mortality at 19°C were significantly lower than at 11°C [103]	• Risk assessments for individual chemicals may underestimate risk in the presence of other stressors [103]	• See synergistic effects
b	Biodiversity loss			
i	Urban stream syndrome	• Degradation of ecological health begins at very low urban cover (10% or even as low as 0.5%) [60], [75], [104] • Urban impacts on physical and chemical characteristics have very strong interactions, making attribution of issues to specific causes difficult [60], [75] • Algal assemblages respond inconsistently to urbanization, possibly because water chemistry varies spatially in response to historic and current land cover, and temporally in response to frequency of storms;		• See synergistic effects

4.	Global Environmental Trends			
	Pollutant/ Issue	**Key scientific findings to date**	**On-going research questions and status of inquiry**	**Potential significance for longer-term urban inputs to water resources**
		responses of fish assemblages to urbanization also are variable [105] • Wild freshwater mussels (Grand River ON) exposed to effluent from 11 municipal wastewater treatment plants and stormwater from 4 cities had a significantly lower condition factor and did not live as long (significantly reduced mean age) as the mussels collected upstream of the urban centres [53]		
ii	Loss of wetlands and habitat	• Burial of urban streams in pipes removes stream habitat (up to 70% of the stream network in studied catchments) [78] • Premium fish habitat is associated with complex, dynamically migrating channels [85], which are simplified by urbanization (see Table 3 above). • Large woody debris is an important ecological element, providing habitat [106], contributing to food webs, and providing riparian zone regeneration; it is often removed for flood control or road maintenance [107] • Species extinctions have lagged responses to habitat loss [108]. Lagged effects of species populations to increased road densities and urbanization have been identified in wetland and other aquatic ecosystems [109]–[111]		• See synergistic effects
iii	Ecotoxicology and bioaccumulation/ biomagnification of toxics	• The ecological risk from CSOs for organisms in benthic and hyporheic sediments was estimated to be much greater than for organisms in the water column [112]	• Population and community scale effects noted in aquatic life may be in response to ecological rather	• Strategies to manage toxics may be compromised if co-existing ecological

4.	Global Environmental Trends			
	Pollutant/ Issue	**Key scientific findings to date**	**On-going research questions and status of inquiry**	**Potential significance for longer-term urban inputs to water resources**
		• Biodiversity loss in dragonflies and damselflies were directly attributed to water pollutants; losses of specific species were attributable to particular contaminants [113] • Biodiversity indices were negatively correlated with metals and with urban catchment land use; organic chemicals (pesticides) and metals posed risk of acute effects at 42% and 44% of 77 sampling sites; risk of chronic effects occurred at all sites; emerging contaminants (e.g. an antidepressant and triclosan) contributed to chronic effects risk; [114]	than toxicological conditions, or a combination of both [21] • Research to develop biomarkers of vulnerability for the most vulnerable aquatic life stages and populations is needed to understand interactions among global changes, nutritional status, pathogens and toxic chemicals [115]	conditions drive changes to aquatic ecosystem populations/ community
	Urban pressures reducing resilience or diversity	• Road culverts are a significant obstacle to macroinvertebrate dispersal in urban streams [86] • Perched culverts impede freshwater fish movement [116], in particular for migrating fish, weak swimmers and early life stages [117] • Broad spatial understanding of stream network fragmentation is needed to assess ecological consequences; one barrier may have large impacts and multiple barriers may have cumulative impacts [118] • Water abstraction can have detrimental effects on water discharge trends [89] • Aquatic resource exploitation and harvesting is a stressor to aquatic biodiversity [119]	• The effects of local habitat / river restoration can be overwhelmed by continuing disturbances at larger scales [40] • Limited knowledge of aquatic invertebrate diversity and the need for improved connectivity within and across ecosystems are two conservation challenges [119]	• See synergistic effects
	Invasive species linked with urbanization	• Non-native species impact native species through competition, predation, herbivory, habitat alteration, disease and genetic effects (e.g. hybridisation) [98]		• See synergistic effects

4.	Global Environmental Trends			
	Pollutant/ Issue	**Key scientific findings to date**	**On-going research questions and status of inquiry**	**Potential significance for longer-term urban inputs to water resources**
		• Invasive alewife in the Great Lakes modified the diet of salmonids, resulting in thiamine deficiency in eggs causing early mortality; interaction of contaminants with thiamine deficiency may impair recruitment of salmonids [115]		
	Population growth in urban centers	• Ageing populations are expected to increase use of prescription drugs and over-the counter medicine, as well as the application of personal care products [62] • Increasing road densities with increased urban areas are negatively associated with numerous biotic indices [82], [120] • Urban sprawl results in increased pollutant discharge via wastewater and stormwater systems [112]		• See synergistic effects

Table 5 Interactions and issues of local context

Table 5. Interactions and issues of local context: state of the science research summary

5.	**Interactions and issues of local context**			
	Pollutant/ Issue	**Key scientific findings to date**	**On-going research questions and status of inquiry**	**Potential significance for longer-term urban inputs to water resources**
b	Synergistic/ antagonistic effects of multiple contaminants and conditions	• Montreal WWTP effluent bioassays reflected a range of acute, chronic sub-lethal and chronic lethal effects at various taxonomic levels [21] • Investments in long-term restoration aimed at protecting drinking water or sanitary services can result in benefits to biodiversity [121] • Investments in technologies for water security (e.g. impoundments, water withdrawals, wastewater effluents) have negative cumulative effects on the world's freshwater resources [38] • Hypoxic conditions in the deep waters of the St Lawrence Estuary, and water column acidification, have been increasing since the 1930s, attributed to eutrophication (associated high microbial respiration stimulated by an increased supply of organic material and nitrogen) and climate change (suspected of reducing input of water from the Labrador Current) [17] • Hypoxia has ecosystem-level effects, including direct loss of habitat or smaller habitat range, altered trophic relationships, changes in migration and biodiversity [17] • Downstream of the 2 Calgary WWTPs, fish biomass increased over 25-fold (rainbow trout) and over 5-fold	• Biological responses to urbanization range from broadly consistent to highly variable or understudied [105] • Diversity of biological effects from exposure to individual contaminants, different sensitivities during different life stages, the diversity of exposed organisms make it challenging to assess ecosystem impacts of PPCPs [64] • It is unknown whether organic matter from wastewater facilities discharging to the St Lawrence River contributes to hypoxic conditions in the Estuary (Y. Comeau, pers.comm.) • Nutrient and energy flows through the food web and food web dynamics are poorly understood and, in lotic systems, require study over broad spatial scales to understand how these	• Multiple synergistic / antagonistic effects create complexity that may not be scientifically fully understood • If wastewater facilities discharging to the St Lawrence River are found to contribute to hypoxia in the Estuary, more stringent controls on organic matter may be required • Seasonality of effects on receiving waters have implications for wastewater management and stream monitoring [123] to evaluate effects of episodic releases (lagoon, CSOs, stormwater)

5.	Interactions and issues of local context			
	Pollutant/ Issue	**Key scientific findings to date**	**On-going research questions and status of inquiry**	**Potential significance for longer-term urban inputs to water resources**
		(brown trout) at peak locations; conversely, whitefish biomass was very high upstream but declined rapidly below the WWTPs, leading to abrupt changes in relative species abundance [122] • Complete removal of the only known toxic contaminant (diethanolamine)in a study of industrial wastewater resulted in effluents with continued toxicity, possibly due to formation of unidentified metabolites during biological treatment [69] • Stream metabolism was significantly greater in reaches exposed to effluent from lagoons (Manitoba) but the degree of effect varied with timing of release (early versus late summer) [123]	processes interact in lotic systems [122]	
c	Total load management on a watershed/ sub-watershed basis	• WWTP effluent containing low nutrient concentrations can deliver large nutrient loads based on total volume released; WWTPs can influence water chemistry and nutrient dynamics, depending on relative proportions of effluent in downstream flow [5] • In 1987, the US Clean Water Act was amended to include Total Maximum Daily Loads (TMDLs) to manage pollutants from both point and nonpoint sources; TMDLs are the total of a specific pollutant that a river or stream can receive and still meet water quality standards and U.S. states must implement management plans to bring impaired streams into compliance [5], [124] • The European Commission's 2000 Water Framework Directive (WFD) requires achievement of a good		

5.	Interactions and issues of local context			
	Pollutant/ Issue	**Key scientific findings to date**	**On-going research questions and status of inquiry**	**Potential significance for longer-term urban inputs to water resources**
		ecological and chemical status for all surface water bodies in the European Union by 2027 [20], [124] and countries negotiate total load contributions to shared water basins • Total load restrictions for P release to receiving waters are starting to drive decision-making for P recovery technologies in U.S. and E.U. WWTPs		

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