STANDARDS RESEARCH

Future Innovation for Stormwater Management

March 2022

Author

Lisa Prime, MCIP RPP, LEEP AP, Founder, Prime Strategy & Planning Inc.

Steve Braun, P.Eng, Principal, Matrix Solutions, Inc.

Nadia Dowhaniuk, Head of Research, Prime Strategy & Planning Inc.

Project Advisory Panel

Adam Friedberg, BuroHappold

Bert van Duin, City of Calgary

Maciej Podoski, Cisco

Nick Gollan, City of Kitchener

Jennifer Teague, CSA Group

Lynn Barber, CSA Group (Project Lead)

Acknowledgements

The authors would like to thank Bob Bathurst, Century Engineering for his input on this research.

Table of Contents

Executive Summary

Smart stormwater technology (SST) is increasingly being implemented in Canadian municipalities to address multiple compounding factors, including stormwater management, climate change, aging municipal infrastructure, and as part of the smart cities agenda leveraging innovation and connected technology. Currently, the application of innovative technology in stormwater management is happening incrementally in individual systems and primarily through private applications. Incremental application of SST in municipalities (e.g., without overall contextual planning) has the potential to exacerbate pre-existing risks, especially considering potential impacts from climate change. The implementation of SST also introduces new risks to municipalities, water systems, and residents. Electronic and software controls, including those guided by artificial intelligence or machine-learning decision-making, can be vulnerable to issues that include physical or electronic failure of devices and software or communication issues between controller and device.

The current approach to stormwater management has not kept pace with the digitally-enabled environment and neither has the implementation of stormwater infrastructure. Smart stormwater systems have the potential to facilitate several benefits to integrated stormwater management. To support the effective and safe operation of future stormwater systems and retrofits, and to mitigate some of the challenges and risks associated with incremental applications of SST, greater clarity and consistency is needed in its implementation through standards.

The primary objective of this research is to better understand and define how SST can contribute to the overall stormwater management of runoff within a drainage catchment from a design and operation perspective. The focus considers what risks are associated with the use of SST and with the active controls that comprise it. This project examines communications between SST components and what is required to help ensure the fail-safe operation between various components of SST. The ability to connect single catchments into an integrated larger system is recognized as an inevitable future condition with a further set of challenges for SST.

A review of technologies and implementation experience with municipalities in Canada and the United States in addition to interviews with industry and municipal leaders across these regions informs the background report. Further research on examples of innovative stormwater management in Europe provide context for how SST may be integrated within Canada as well as best practices for integrated stormwater management that incorporates smart technology.

Overall, the research suggests that private sector innovators have developed smart solutions to problems associated with current stormwater management, including flooding and water pollution. While these solutions have largely remained underutilized by Canadian municipalities, industry continues to drive smart tech as a solution to assist municipalities build resilient and sustainable communities.

Consistency through standards can help ensure the safe operation of the overall communication system(s) controlling SST. Development of standard(s) at the micro scale is an important and necessary foundation to establish given the predicted scalability and significant benefits of SST for municipalities. Technological investments in essential infrastructure can lead to substantial community benefits. Bolstering the potential benefits while suitably addressing risks associated with SST will support uptake in municipalities for this innovative technology.

"Smart stormwater technology (SST) is increasingly being implemented in Canadian municipalities to address multiple compounding factors, including stormwater management, climate change, aging municipal infrastructure, and as part of the smart cities agenda, leveraging innovation and connected technology."

1 Introduction

1.1 What Is Smart Stormwater Technology (SST)?

Facing multiple challenges, local governments require improved solutions for managing urban stormwater that are more cost-effective, transparent, resilient, and sustainable [1]. Smart stormwater technology (SST) is increasingly being implemented in Canadian municipalities to address multiple compounding factors, including stormwater management, climate change, aging municipal infrastructure, and as part of the smart cities agenda, leveraging innovation and connected technology.

Within the context of this research report, SST includes but is not limited to automatic valving systems on stormwater pond outlets that optimize flow attenuation, improve water quality through increased residence time, and adjust pond levels in anticipation of future weather events being monitored. This research report recognizes the potential for linking many single catchments together to act in a coordinated fashion within a given watershed. The report focuses, however, on SST controls acting upon a single catchment, such as a single pond or other drainage element.

1.2 Purpose of the Research Report

The primary objective of this research is to better understand and define how SST can contribute to the overall stormwater management of runoff within a drainage catchment from a design and operational perspective. Focusing on the risks of using SST and its active controls, this project will look at communications between SST components and the requirements to help ensure the fail-safe operation between various components of SST. The ability to connect single catchments into an integrated larger system is recognized as an inevitable future condition with a further set of challenges for SST. This current research project does not address the additional complexities and additional risks that may be embedded within these larger systems of systems.

The background review consists of a review of technologies and implementation experience with municipalities in Canada and the United States, as well as interviews with industry and municipal leaders across these regions. Research on examples of innovative stormwater management in Europe provide context for how SST may be integrated within Canada, as well as best practices for integrated stormwater management that incorporates smart technology.

1.3 Background

Currently, innovative technology in stormwater management is used incrementally in individual systems, primarily through private applications. Incremental application of SST in municipalities (e.g., without overall contextual planning) could exacerbate pre-existing risks, especially considering potential impacts from climate change. Implementing SST also introduces new risks to municipalities, water systems, and residents. Electronic and software controls, including those guided by artificial intelligence or machine-learning decision-making, can be vulnerable to issues that include physical or electronic failure of devices and software or communication issues between controller and device.

The current approach to stormwater management has not kept pace with the digitally-enabled environment and neither has the implementation of stormwater infrastructure. Smart stormwater systems have the potential to facilitate several benefits to integrated stormwater management. To support the effective and safe operation of future stormwater systems and retrofits, and mitigate some challenges and risks associated with incremental applications of SST, greater clarity and consistency is needed in its implementation through standards.

This research supports the broader need to better understand how smart technology can help the evolution of a stormwater management system that responds to interrelated challenges and limitations.

2 Canadian Municipal Context

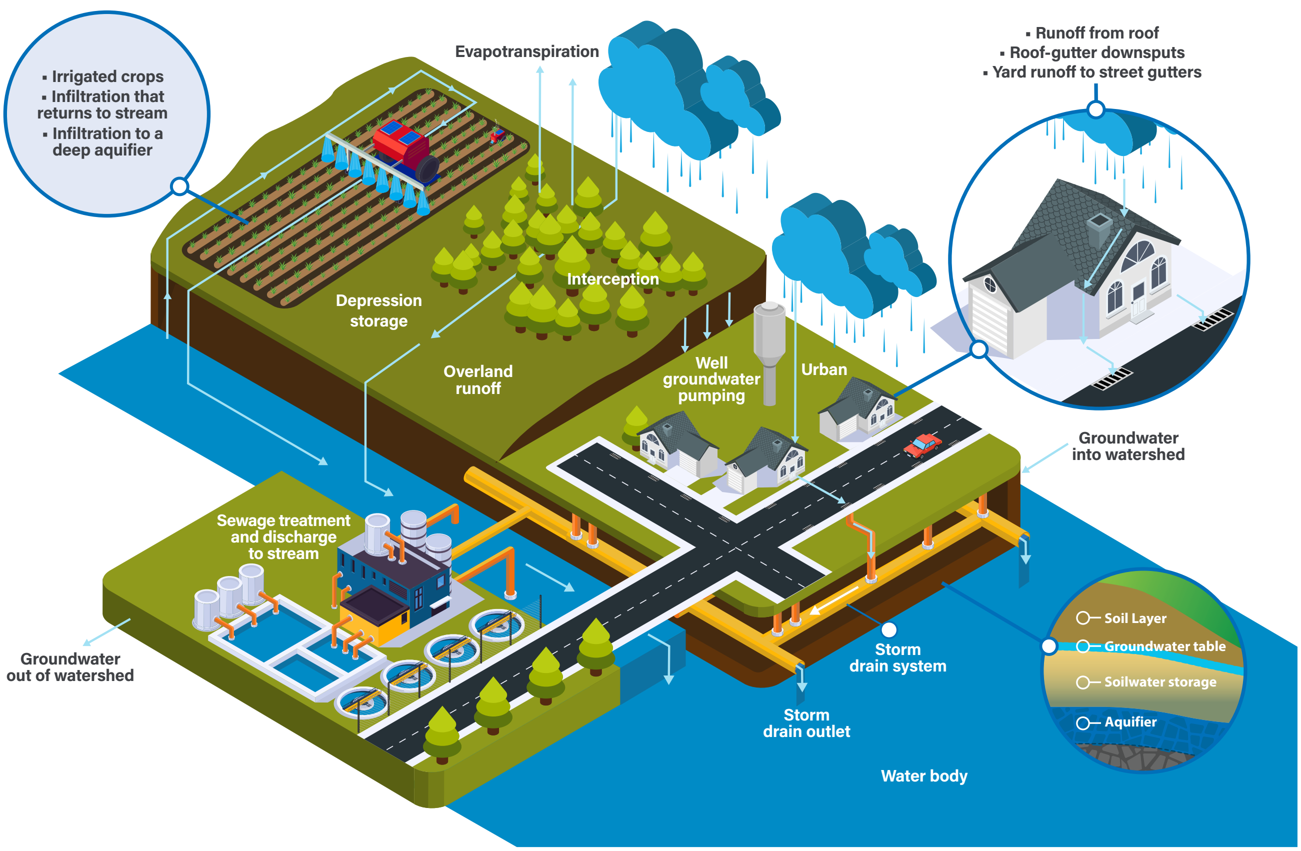
2.1 Stormwater Management

2.1.1 What Is Stormwater?

Among the many definitions of stormwater exist, most identify it as rainfall and snowmelt that runs off the land into storm sewers, streams, and lakes. On its journey overland to downstream receivers or into the ground via infiltration, it may be mixed with all manners of pollutants [2].

In natural conditions, most precipitation is intercepted by vegetation and/or otherwise absorbed into the ground and filtered, eventually replenishing aquifers, or flowing as runoff into streams and rivers. Later, part of it is returned to the atmosphere in the form of evapotranspiration (Figure 1).

Figure 1: Stormwater and the hydrologic cycle

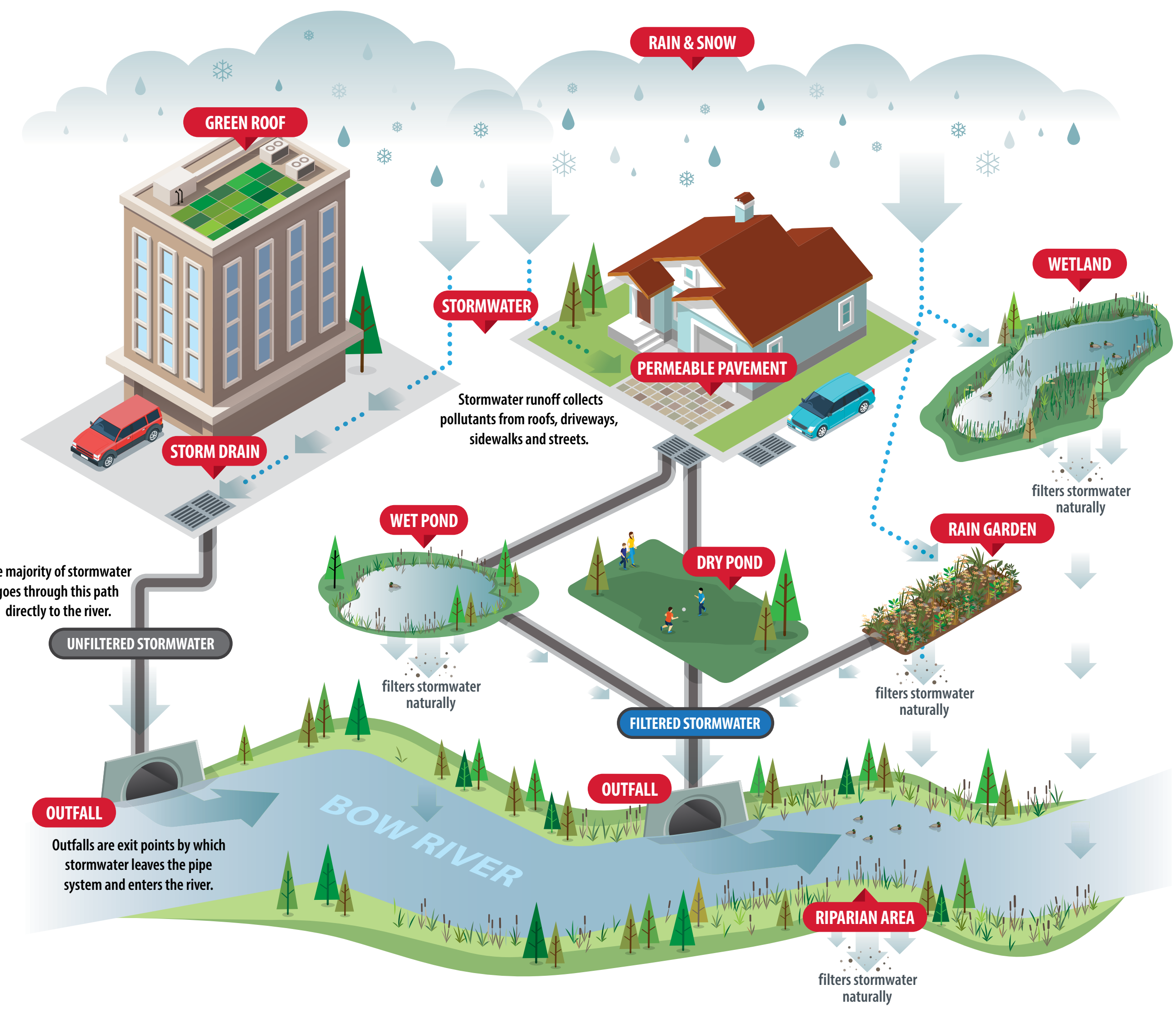


Before the urbanization of a watershed, the natural hydrologic cycle is a function of natural characteristics such as soil types, vegetation covers, and topography. Urbanization alters watershed characteristics in very significant ways. Impervious surfaces such as roads and roofs prevent precipitation from naturally soaking into the ground. Instead, water is mostly runoff that is channeled into streams, rivers, and lakes via storm drains, municipal sewers, and drainage ditches where it picks up pesticides, fertilizers, road salts, heavy metals, oils, bacteria, and other harmful pollutants common in urbanized environments (Figure 2).

There are several undesirable impacts of urbanization on watercourses and associated infrastructure, including [3]:

- Increased downstream flooding risks
- Decreased water quality
- Watercourse bank and bed erosion
- Increased turbidity (water cloudiness)
- Aquatic habitat destruction
- Changes in the stream flow regime
- Combined sewer overflows

Figure 2: Stormwater Runoff in Urbanized Environments. Reproduced with permission from the City of Calgary [4].



- Damage to infrastructure such as bridges
- Contaminated streams, rivers, and coastal water

As cities become more intensified and urbanized, the available space for managing stormwater becomes increasingly limited. Climate change is recognized to increase the frequency of intense storms, and generally make stormwater management more challenging [5].

2.1.2 Stormwater Management

Stormwater management is a component of local water management intended to control and mitigate the effects of urbanized storm runoff. The goal of stormwater management is to maintain the health of streams, lakes, and aquatic life, as well as provide opportunities for human uses of water by mitigating the effects of human development [2]. Traditional stormwater systems include conveyance elements like sewers, swales, and sometimes pumps that convey runoff to outlets. Often, storage elements such as ponds or tanks have been integrated into a system, thereby reducing flow rates and the chance for sediment to settle.

Stormwater management systems have historically focused on the goals of public health, efficient drainage away from private lands and public spaces to prevent flooding and protect properties, and sediment management. Other environmental and social considerations were not always integral to the system.

Today, stormwater management is one part of the umbrella term 'integrated water management,' which can also include sewer and drinking water systems, and the services provided by natural areas, such as forested parks, tidal flats, vegetated buffers, and floodplain areas. Stormwater management continues to evolve as the science of watershed management evolves and climate change impacts present new challenges and opportunities. The effects of stormwater on water balance and downstream sensitive streams and other receivers are now often mitigated through applications that include green infrastructure in an effort to provide more low impact development (LID) types of approaches.

2.1.3 Regulatory Framework

Stormwater management regulations exist to use stormwater as a resource and work towards preventing its potentially harmful impacts. All levels of government hold key policy and regulatory levers that apply to water management. However, stormwater management can be complex due to the multi-functional purpose of the infrastructure system and the many agencies and authorities often involved.

In Canada, waters solely within a given province's boundaries fall mostly within the constitutional authority of that province. Exceptions include several areas of federal interest, such as fisheries, navigation, and international relations. Water governance areas with provincial legislative powers generally cover flow regulation, authorization of water uses, water supply, pollution control, and thermal and hydroelectric power development.

Beyond federal and provincial/territorial responsibilities, Canadian municipalities are generally responsible for municipal stormwater management, including its planning, design, establishment, operation and maintenance.

2.1.4 Financial Considerations

Responsible for stormwater management systems, municipalities typically construct engineered, or grey infrastructure, for stormwater management following historical climate trends. Yet, these design features underscore an important challenge for local governments—funding mechanisms available to build and maintain stormwater systems. These features and the challenges they pose to municipal funding are described below.

First, grey or "traditional" infrastructure is costly to maintain, upgrade, and replace. Such costs fall solely to local governments. In some older neighbourhoods, the infrastructure does not exist and must be built. According to the Canadian Infrastructure Report Card released in February 2016, of the estimated $134 billion in stormwater infrastructure assets across Canada, approximately 22%, or $31 billion in assets, are in fair to very poor condition, requiring replacement or upgrades in the near future [6].

There are significant potential consequences associated with neglecting stormwater management in water management programs. Further, lawsuits against municipalities are growing. Table 1 below highlights some examples of municipal losses due to risk-based infrastructure impacts [7].

Second, stormwater management systems are based on historical climate trends. Yet, climate data and projections suggest that historical data can no longer adequately guide stormwater, particularly as climate changes continue to alter trends in precipitation, evapotranspiration, and rates of discharge. Climate change impacts on stormwater management systems are further elaborated in the following section. However, it is important to recognize potentially significant financial consequences to poorly managed water programs that are not designed to respond to current and future climate realities.

The current funding mechanisms for supporting stormwater management systems are flawed, and the traditional infrastructure system is not cost-effective and creates a number of urban stormwater pollution problems [1]. The challenge of stormwater funding extends beyond the overall costs of stormwater infrastructure to include how the service is funded. In many Canadian municipalities, there is no dedicated revenue from stormwater services nor transparency in stormwater service costs.

The issue of stormwater management design, as well as the funding mechanisms available to support these systems is important to this research report because SST has a potentially significant role in addressing problems posed by aging infrastructure and stormwater design.

By integrating intelligent monitoring and resource management solutions, local governments can gain vital insights, such as water present in an overflow from a storm events and contaminants and pollutants that may be present in municipal pipes. Smart technology can also help detect anomalies in municipal systems. It can create visibility for typically unseen assets, allowing municipal water managers to understand the condition of infrastructure and treat issues before they become costly problems.

Traditional grey forms of infrastructure cannot support the quality of water infrastructure needed in today's communities. SST has the potential to achieve better management of critical water resources, offering real-time insights for protecting water quality and security.

2.2 Climate Change

Increasing global surface temperatures, melting glaciers, and rising sea levels are indications of global climate change impacts resulting from greenhouse gas emissions from human activities. Climate change is expected to result in significant impacts to the Canadian landscape, including but not limited to [8]:

- Shifts in the location and timing of rain and snow
- A projected increase in the intensity and frequency of floods
- An expected increase in drought in areas prone to receiving less snow and rain, such as the Prairies
- Higher temperatures causing glaciers to recede, which will also result in long-term changes to the amount of water flowing in some major rivers.

Table 1: Examples of Municipal Losses Due to Risk-Based Infrastructure Impacts

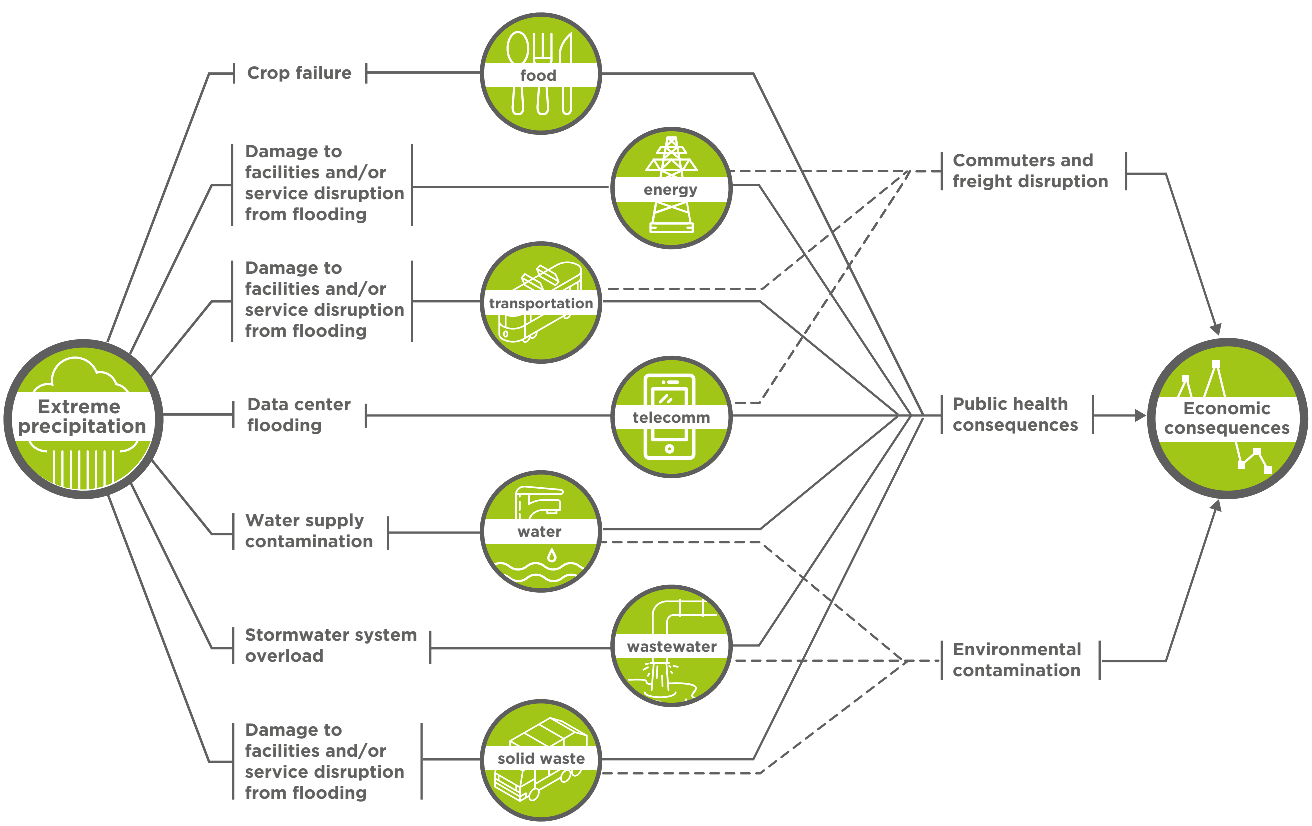
City or Region	Cases	Financial loss
City of Stratford	A settlement due to a class action against the city because of flooding in 2002.	$7.7 million
City of Thunder Bay	Complaint against the city for improper construction, maintenance, and operation of stormwater infrastructure.	$375 million
City of Mississauga and City of Brampton	Significant downfall in 2013 led to the costliest storm in Ontario's history, causing widespread property and infrastructure damage.	$932 million

Stormwater management systems are often designed to protect up to a statistical storm event (e.g., events with a one percent chance of occurring in any given year, also known as a 100-year event or 100-year recurrence interval). However, these traditional design approaches assume the natural systems driving precipitation and other processes are stationary and remain unchanged over time [9]. As climate change continues to alter trends in precipitation, evapotranspiration, and rates of discharge of rivers, climate variability challenges this assumption as it relates to water resources [10].

Precipitation within climate change scenarios can be more frequent, more intense, longer in duration, or some combination thereof, which can overwhelm the design capacity of municipal stormwater management systems [11]. Overwhelmed stormwater management systems can lead to backups that cause localized flooding or lead to greater runoff of contaminants.

Stormwater systems, and other forms of urban infrastructure, are also highly interdependent, formed of multiple connections, feedback systems, and intricate branching. This means that action in one area of infrastructure, such as a system failure, often results in synergies and trade-offs in another infrastructure sector [12]. Furthermore, infrastructure systems with critical interdependencies can be highly vulnerable to natural hazards. The increasing frequency and magnitude of extreme weather events many cities are facing cause ripple effects across these systems, with damaged facilities and reduced services in one sector impacting on others, as shown in Figure 3.

Figure 3: Example of Sectors Impacted by Extreme Precipitation. Reproduced with permission from C40 Cities Climate Leadership Group, Inc. [12].



2.3 Smart Cities

The rapid rise of urbanization has, in recent years, coincided with a massive growth in devices connected to the internet, otherwise known as the Internet of Things (IoT). Technological advances, such as computerization and automation, have increased the efficiency, reliability, and services provided by infrastructure systems. This has also contributed to tighter coupling of interdependent infrastructure systems as well as natural ecosystems.

To be competitive and prepared to respond to emerging urban challenges including climate change, there is an opportunity for municipalities to leverage rapid expansion of IoT infrastructure to support smarter, healthier, and more equitable and sustainable communities.

Defining 'smart city' is often unique for each community, tailored to the specific conditions and needs of each. Although early smart city initiatives were largely driven by technology, cities are beginning to shift the authority to decide on a city's technology needs to its citizens and capture this in the evolving definitions [13]. Done properly, technological investments in essential infrastructure can lead to substantial community benefits.

3 Opportunity for SST

Forecast-based real-time flow control of both connected and distributed stormwater infrastructure allows for adaptive management. This type of technology can integrate information from field-deployed sensors and combine it with real-time weather forecast data to directly monitor performance and actively control stormwater storage and flows [14]. There are several potential benefits to integrated stormwater management that leverages SST:

- Storage elements could be advantageously emptied well before predicted storm events, thereby providing needed storage when storm events arrive.
- Infiltration-type infrastructure could receive cleaner runoff by SST identifying sediment-laden flows and preventing intake during those times.
- Stormwater pond runoff could be monitored for temperature and released to receiving watercourses at advantageous times (e.g., mainly in the mornings), thereby minimizing thermal impacts from solar gain.
- Salinity monitoring could allow some winter/spring runoff to be held until there is sufficient flow (and therefore dilution available) in receiving watercourses.
- Actively controlled outlets could allow for outflows that better match natural conditions, ensuring better baseflows, erosivity effects, and capacity in receiving watercourses.
- Stormwater could be better tracked as a resource by logging and ensuring correct water supply and water quality to irrigated areas and technologies such as tree vaults located on streetscapes.

4 Smart Technology

4.1 Internet of Things (IoT)

Advances in environmental sensor and communication technology can allow users to monitor and control stormwater management systems at varying scales. Users can adapt formerly static designs with active controls that optimize performance and meet new objectives. The technology that enables smart stormwater management systems is considered as part of the Internet of Things (IoT).

IoT devices are used in a wide range of domains such as health, agriculture, and smart cities applications. There is no universal definition of IoT. It is broadly recognized from a technical perspective as physical objects connected to the Internet to perform certain objectives [15]. The heterogeneity of IoT's definition enables the depth and breadth of application. However, it also introduces complexity and a lack of standardization around software dependability and scalability [15].

To function effectively and responsibly, IoT devices that enable intelligent stormwater infrastructure must be designed to continually operate safely when subjected to unanticipated data amounts, or malformed or maliciously constructed data. This concept is known as hard anarchic scalability. For example, the default operation of an intelligent stormwater system should be limited to actions that do not need trusted data. This principle is called the zero-trust approach and is further described in the following section as it relates to data protection for SST [16].

In general, SST must be founded on the same conceptual approaches to IoT communication and control systems design been made resilient through experience and continual improvement. Good precedents exist to inform SST design implementations how to be secure, resilient, and effective in the ways an IoT approach is adapted to the specific requirements of stormwater control.

4.2 Data Protection and the Zero-trust Approach

With IoT infrastructure growth comes constant and concurrent risk evolution. Service disruptions, ransomware, phishing, malware, and other not-yet anticipated items place individuals and organizations at risk of privacy breaches that can cause significant damage [16].

Data protection is increasingly important to municipalities, not just in terms of stormwater but in terms of all data. Data that factors into knowledge of flooding, for example, becomes sensitive as it is considered the most significant natural hazard in several areas of Canada in terms of death, damage, and civil disruption and is the costliest type of natural disaster in Canada in terms of property damage [17]. This reinforces the evident need for robust data acquisition to prevent increasing risk. However, the increasing complexity of current and emerging cloud, multi-cloud, and hybrid network environments combined with the rapidly escalating nature of threats exposes the lack of effectiveness of traditional network cybersecurity defenses [18]. Effectively managing these risks calls for a new meaning and era of trust for systems, including for future SST system operations. More than just security, it calls for transparency, accountability, social responsibility, resiliency, and privacy, particularly as climate changes exacerbate flood risk.

Cloud applications and the mobile workforce have redefined the traditional security perimeter approach for achieving reasonable protection. Employees are bringing their own devices and working remotely. Data is accessed outside the corporate network and shared with external collaborators such as partners and vendors. Corporate applications and data are moving from on-premises to hybrid and cloud environments.

This newer perimeter is no longer defined or restricted to the physical location(s) of organizations. It now extends to every access point that hosts, stores, or connects to corporate resources and services. Interactions with corporate resources and services now often bypass on-premises perimeter-based security models using network firewalls and VPNs. Organizations relying solely upon on-premises firewalls and VPNs lack the visibility, solution integration, and agility to deliver timely, end-to-end security coverage [19].

The zero-trust approach acknowledges that security models must adapt to the complexity of the modern environment. The zero-trust model assumes a constant breach might have occurred and verifies each request as through it originates from an uncontrolled network [20]. This approach contrasts with one based upon the assumption that everything that has achieved identification and is behind a given corporate firewall is safe. Regardless of where the request originates or what resource it accesses, the approach consistently requires verification. An analogy to stormwater and flood planning is available here. Building a valuable structure behind a manmade dike is quite different from ensuring building only where flood susceptibility is naturally low.

4.3 Data Governance

Data governance in the smart city context is an emerging field and its definition and concepts are still evolving [21]. Canadian-based technology specialists, OpenNorth, describe data governance as the process of establishing who makes decisions, how decisions are made, and how individuals and/or groups are held accountable for their role in maintaining or controlling the data of an organizing group [21].

As the speed of technological change is rapid and its evolution not entirely predictable nor explainable, a widening gap is often produced between technological capabilities and institutional readiness [22]. Additionally, sectors such as energy, housing, and transportation are increasingly integrated through data in smart cities as cyber-physical systems. Institutional arrangements for data governance need to incorporate

"Private sector innovators have developed smart solutions to problems associated with current stormwater management, including flooding and water pollution."

the ability to learn from real-world use and experience and to improve performance through adaptation.

Discussions about data privacy and potential risks to data if misused (hacked, exploited, used improperly, etc.) have been central topics within Canadian municipalities' discussions about data governance [21]. Data governance is an important consideration for this research project on SST because institutional arrangements for data governance influence data collection, management, and usage in smart cities.

The research suggests that concerns over data management and data governance by Canadian municipalities is an important consideration when integrating smart technology into everyday operations and management of municipal infrastructure, including stormwater. Concerns hold true at the smaller scale of single runoff catchments, the scale central to this research project. Clearly, concerns will be magnified within integrated and connected systems of systems.

5 Current Application of SST in Canadian Municipalities

5.1 Methods

To provide critical insight to the current state of SST application in Canada, the following activities were undertaken: (a) survey and interviews with key experts in stormwater management and SST development, and (b) a review of the scientific and grey literature.

Overall, the research suggests that private sector innovators have developed smart solutions to problems associated with current stormwater management, including flooding and water pollution. While these solutions have largely remained underutilized by Canadian municipalities, industry continues to drive smart tech as a solution to assist municipalities build resilient and sustainable communities. Research findings are further described in Section 5.2.

5.1.1 Surveys and Interviews

Two separate questionnaires were prepared for public and private sector contacts to capture their experience and perspectives on opportunities and challenges with SST application. A short list of stormwater managers and core innovation experts were identified by the project team based on existing knowledge of stormwater experts in Canada as well as SST innovators and experts.

Once the short list of experts was identified, surveys and interview requests were distributed to provide key informants with background information on the project's objectives and the survey and interview questions.

A total of 21 surveys and interview requests were distributed. Twelve individuals responded and were available to participate in an interview. This includes municipal stormwater managers and experts from municipalities with at least 200,000 inhabitants in British Columbia, Alberta, Ontario, Quebec, and Nova Scotia.

Interviewees were asked to share success implementation experience and specific concerns regarding implementation of SST. The interviews supported direction for further research and relevant material to consider through the review of scientific and grey literature.

5.1.2 Review of Scientific and Grey Literature

Based on information received during interviews, additional research with scientific and grey literature was conducted. Where possible, interview contacts provided direct access to referenced literature.

5.1.3 SWOT Analysis

The research includes an analysis to evaluate the strengths, weaknesses, opportunities, and threats (SWOT) for the approach to different standards for smart technology for stormwater management. As smart technology becomes more commonly available and applied to stormwater management systems, new capabilities have the potential to introduce new vulnerabilities.

The SWOT analysis was conducted through the lens of common issues identified in the research. These issues are summarized below.

5.2 Results

5.2.1 Wastewater Systems and SCADA

The interviews revealed that several Canadian municipalities rely on supervisory control and data acquisition (SCADA) systems to manage water utilities. SCADA systems monitor and control the equipment and devices used in critical infrastructure, such as water and wastewater systems. This is particularly common in large urban centers where combined sewer systems collect stormwater runoff, domestic sewage, and industrial wastewater in the same pipeline.

Combined sewer systems often transport all wastewater to a sewage treatment plant where it is treated and then discharged to a water body. During periods of heavy rainfall or snowmelt, however, the wastewater volume in a combined sewer system can exceed the capacity of the sewer system or treatment plant. For this reason, combined sewer systems are designed to overflow occasionally and discharge excess wastewater directly to nearby streams, rivers, or other water bodies. These overflows, called combined sewer overflows (CSOs), contain not only storm water but also untreated human and industrial waste, toxic materials, and debris [23].

SCADA systems play a vital role in water utilities by giving municipal operations the ability to monitor and control their often stormwater-inundated wastewater collection systems consistently and reliably. SCADA systems are important for maintaining regulatory compliance by providing key monitoring, logging, controlling, and alarming capabilities. Ensuring a SCADA system is adequately protected from service interruptions and cybersecurity threats is vital.

As an automated control and remote human management system, the prevalence SCADA systems to water management systems in Canadian municipalities suggests that municipal staff, including operations and maintenance, would be familiar with the principles of automated control and remote management also applied in purely stormwater systems. The research also confirms that municipal water experts understand the risks to SCADA systems, including cyber-attacks, which could result in the failure of critical water infrastructure. Though SST is a different type of infrastructure than SCADA, the potential benefits and risks are similar, and municipalities are generally familiar with these as they apply to combined systems.

From a communications standpoint, the potential for SST to integrate into SCADA system operation is also made increasingly feasible through various Application Programming Interface (API) software intermediaries. API implementation would facilitate the communication between stormwater and wastewater. Remaining operational and organizational barriers that may still be preventing SST from being integrated into SCADA real-time control systems in combined sewers will need consideration. The security assurances required by SCADA systems will need to be adopted or translated within any SST systems potentially being integrated into that larger system in the future.

5.2.2 Monitoring Programs

The research suggests that several Canadian municipalities are relying on technologies like sensors and meters to optimize and monitor water systems, including stormwater systems, to prepare for and offset potential system risks. This occurs at a systems-level and also at smaller, single-catchment scales in some municipalities, but not always at both scales within the same jurisdiction.

Many utilities operating sanitary sewer and combined storm sewer systems face challenges with the control of significant inflows during wet weather (e.g., from stormwater) that affect the viability of treatment and water reuse operations. Additionally, the mitigation of pollutant loading into the environment from system overflows (i.e., combined sewer overflows or CSOs) have driven tens of billions of dollars in infrastructure spending [24]. If implemented effectively and with resilience and security, the emergence of stormwater related sensors (as part of SST) promises better real-time monitoring and operation of wastewater collection systems to more cost effectively address these challenges.

Monitoring programs in urban drainage systems have the potential to generate a significant amount of meaningful data from advantageously distributed sources. Cost effective sensors can work at relatively high sampling rates for extended periods of time. This data has the potential to allow communities to accurately record and report performance data and metrics, operate and maintain infrastructure, as well as achieve stormwater management and associated regulatory compliance targets. Potential machine-learning approaches to data interpretation and subsequent system control in the future may be on the horizon, even for single catchment SST controlled systems, especially if these systems are to be integrated in a coordinated fashion with other water systems.

Research suggests these full potential benefits are not being realized by municipalities. Municipalities struggle to understand the quality and quantity of the data to be collected. IoT and SST systems are beneficial to a stormwater/water system only if the data is meaningful to the municipality. A key challenge is knowing exactly what data is needed across relevant sectors and utilities, and how to manage and align these datasets.

5.2.3 Advanced Urban Systems

In Canada, urban stormwater systems are often less developed and supported relative to drinking and wastewater systems. Local governments responsible for stormwater management face key challenges, including lack of expertise and implementation funding, along with and maintenance requirements that must follow. These challenges are compounded by the fact that systems have been constructed piecemeal in the past, and often with conflicting goals, which have also evolved over time. For example, the quick and efficient removal of storm runoff from city streets through sewer conveyances has resulted in downstream watercourses being adversely affected by erosion.

Measures to protect against increases in peak flows going to the watercourses, through pond controls, have generally only worsened the erosion problem. The extreme variation of runoff amounts alone, made even more unpredictable by climate change, presents key challenges to local governments responsible for the management of stormwater assets. The water quality aspects of storm runoff, recognized as massive environmental pollutants, have a distinctly different but overlapping set of challenges.

Local governments struggle to address these stormwater challenges and require new solutions that are more financially sustainable, better at controlling runoff and capturing pollutants, better adapted to interactions with the natural world, and more resilient. The research suggests there are early adopters leading the way to achieve better urban stormwater management overall in Canada. Studies demonstrate that advanced urban stormwater systems often incorporate some version of smart technology. For instance, the research confirms that some municipalities permit and encourage rainwater harvesting from building rooftops. These systems rely on automatic controls to manage rainwater flow and within the context of this research report, it could be considered a form of SST because it involves the active control of stormwater.

Many municipalities continue to encourage various forms of green infrastructure. The latter most often refers to natural or human-made elements that mimic ecological and hydrological functions and processes [25]. It can include components such as bioswales, trees in soil vaults, and green roofs, just to name a few. The City of Vancouver, for example, has had a long-standing aspiration to develop blue-green systems, such as rainwater harvesting incorporated into green roofs, which improve livability and water quality in receiving water bodies [26]. Blue-green systems manage water and land in a way that is inspired by nature and designed to replicate natural functions and provide ecosystem services. Vancouver supports blue-green systems to advance objectives in the Rain City Strategy, including removing pollutants and reducing the volume of rainwater entering the pipe system. These objectives align well with potential benefits associated with SST management.

Incorporating SST within green infrastructure systems on private and public developments suggests that the private sector can be an important partner for local governments to improve stormwater management. As innovative approaches to stormwater management gain momentum in the private sector, and federal, provincial, and local governments increasingly recognize the economic and environmental value of green infrastructure, there is growing opportunity for collaboration between private and public sector partners on SST implementation to benefit stormwater management.

Aging stormwater infrastructure presents municipalities with the opportunity to implement retrofit projects with SST. In municipalities with combined sewer systems, the potential for SST implementation is significant. Research suggests that SST is not being incorporated often now into these projects, primarily because the municipality is not equipped to manage a smart system and concerns exist regarding the security of smart systems connected to the internet. However, interviews suggest that some pilot projects are being implemented to control runoff, particularly to protect combined sewer systems.

Additionally, smart technology is used to monitor water performance. This occurs at the individual facility location and on full water system scales. For example, the City of Kitchener, located in the Waterloo Region, relies on groundwater for drinking water supplies. Groundwater is located in an aquifer (layers of sand, rock, and gravel) and is comprised of rainfall and snowmelt that soak into the ground, filling the void spaces between sand grains, rock, or gravel [27]. Communities dependent on groundwater for drinking water must consider potential contaminants that may infiltrate the source. There is potential to implement smart stormwater technology to monitor chloride/salt levels in urban storm runoff and to actively control its flow into aquifers from certain outlet points to better protect drinking water sources.

SST is also being used to control overflow in some municipalities. Local by-law provisions requiring that new development not increase overflows are being addressed by using smart technology to monitor overflow and control the operation of valves. Subject to local infiltration by-laws, smart technology is proving that it could be a cost-efficient solution to comply with municipal requirements or by-laws.

Additionally, the City of Calgary joined the Stormwater Management Cooperative (CSMI) in 2020, a regional partnership among municipalities in Alberta to protect the region against the impacts of severe weather in southern Alberta. Calgary has been an early adopter and promoter of smart technologies as part of water management in public and private spaces.

Halifax Water is the municipal water, wastewater, and stormwater utility serving the Halifax Regional Municipality in Nova Scotia, Canada. Halifax Water is currently using SCADA systems to actively control some combined systems. Also, stormwater control is being achieved through remotely controlled valves located on the outlet of a lake that contributes flows via a watercourse through the city.

6 Case Study Examples Across Jurisdictions

6.1 CEER Green Roof, Villanova University, Pennsylvania

Through the Villanova Urban Stormwater Partnership, Villanova University conducts research to understand and optimize best management practice performance and promotes innovative designs and technology to the industry [28]. The university partnered with OptiRTC to design and retrofit existing green infrastructure systems at the CEER Green Roof with real time control technology to evaluate system performance and investigate the role of automated, self-learning controls within traditional green infrastructure [9].

The green roof covers 750 square feet (70 square metres) and is used for research as well as reduction in stormwater runoff to the university's storm drain system. The cistern that collects runoff from a non-green roof is dynamically connected to the green roof to use the evapotranspirative capacity of the vegetated roof year-round. The 500-gallon (1,890 litre) cistern collects runoff from an additional 840 square feet (78 square metres) of non-green roof and has a water-level sensor, actuated valve, and a connection to the cloud-based decision device.

The software maximizes runoff capture from the non-green roof and optimizes irrigation to the green roof. Between storms, the intelligent irrigation logic releases water from the cistern to the green roof based on real-time soil moisture sensor readings. Before a storm, the software calculates the timing and expected runoff volume of the event. The software stops irrigation to the green roof and discharges water from the cistern to the storm drain as needed to make room for the incoming runoff.

These automated steps prepare both the green and non-green roofs for maximum runoff capture while reducing potable water demand for irrigation. During an event, the green roofs are designed to capture direct rainfall, and the cistern valve is closed to capture the non-green roof runoff.

6.2 Century Engineering Headquarters, Hunt Valley, Maryland

The Century Engineering Headquarters located in Maryland is outfitted with SmartSWM technology. The SmartSWM system monitors wet-weather forecasts to maximize pollutant removal and groundwater recharge. The SmartSWM releases excess runoff only when necessary and at the least discharge rate possible during the period immediately preceding the next wet-weather event. This approach allows the timing of discharges to be offset from that of other sources of stormwater runoff within the watershed. During extreme wet-weather events, the SmartSWM system leverages an algorithm that autonomously manages facility discharge to the least steady-state discharge rate possible to maximize the flood mitigation and stream channel protection potential of the stormwater management facility.

With SmartSWM innovative technology, sensors monitor water depth and other parameters, and a computer connected to the internet tracks local weather forecasts. The program autonomously controls a valve that releases water with precise timing, minimized discharge rates, and defined volumes for current and anticipated conditions.

Unlike traditional passive stormwater management facilities, the SmartSWM system's 'standard control' operational mode is designed to keep water in the pond longer, thereby allowing more pollutants to settle out and water to soak into the ground.

Figure 4: SmartSWM as Applied at Century Engineering Headquarters. Reproduced with permission from Century Engineering.

"Generally, smaller, rural municipalities are less equipped to understand, integrate, and effectively operate and maintain smart technologies compared to large urban centers."

Developed by civil/water resource engineers and technology professionals at Century Engineering, the SmartSWM system improves the water quality of receiving waterbodies, protecting wetlands and aquatic ecosystems while conserving water resources and enhancing baseflows.

6.3 City of Rotterdam, The Netherlands

During the past decade, thousands of building owners in the City of Rotterdam installed green roofs on their dwellings. While typical green roofs function as 'passive' sponges, the City of Rotterdam is working with public and private landlords to develop a green-blue grid. This term refers to equipping roofs with reservoirs or tanks to retain excess flow. The tanks are in turn equipped with electronically controlled drain valves that can be opened and closed remotely through smart technology [30].

The city envisions a coordinated system of linked valve control devices across the city that function, in effect, like a dispersed network of stormwater reservoirs that can be drained automatically in anticipation of a storm event.

At present, devices installed include highly sensitive weather radar stations capable of detecting rainfall up to 20 kilometers away from the device location. The project is still underway; however, it demonstrates how technology can be harnessed to address a pressing urban challenge.

7 SWOT Analysis

The SWOT analysis that informed this research was based on the following parameters.

Size, Age, and Geography of Municipality

The research suggests that qualities unique to each municipality influence a municipality's likelihood to adopt and integrate SST or smart technology into everyday operations and maintenance. Generally, smaller, rural municipalities are less equipped to understand, integrate, and effectively operate and maintain smart technologies compared to large urban centers such as Toronto, Halifax, Calgary, or Vancouver.

Geographic location of the municipality influences uptake of SST. Local geography will have a major impact on the hydrological cycle and thus how municipalities conduct stormwater management practices. Proximity to bodies of water, geology, and several other factors unique to geographic environment, including climate change impacts, influence stormwater management across Canadian municipalities. Application has shown to have potential in very urban settings as well as with ponds in lower density communities as we have seen through examples shared in the interviews.

Integration of Water Utilities (Stormwater, Drinking Water, Wastewater)

This research report previously described combined systems and CSOs as a major concern for municipalities with combined sewer systems. Though modern standards in North America do not permit the construction of new combined systems, many older cities rely heavily on this form of infrastructure. Several municipalities are beginning to replace combined sewer systems with separated ones based on provincial targets (or through EPA mandated consent decrees in the US). Other approaches to solving CSOs include construction of massive underground tanks or tunnels that are pumped to treatment following the end of rainfall events. Investments in these storage type approaches have been massive.

Smart technology has the potential to reduce and mitigate the impacts associated with CSOs by monitoring and managing the combined sewer system at various locations. The impact of climate change on precipitation may increase the frequency and magnitude of heavy precipitation events, with a corresponding increase in CSO discharges [31].

Interdependencies

Smart stormwater technology is inherently interdependent. It integrates information from field-deployed systems with cloud-based control systems and real-time forecasting. This presents an opportunity for municipalities to leverage potential benefits of SST, including the ability to control the timing of release and maximize the capacity of existing infrastructure. However, the risk of SST failure due to any number of identified risks (e.g., vandalism to physical device, software or sensor failure, etc.) and the organizational coordination required to ensure SST is seamlessly integrated into existing municipal operations, and presents a significant threat to municipalities.

Monitoring

Research suggests smart technology is used to monitor and evaluate water assets in some urban municipalities. Some municipalities have adopted modern sensors and data acquisition systems to monitor green and grey forms of infrastructure to provide real-time performance metrics (e.g., SCADA). In some cases, monitoring technology is integrated with the ability to control water flow directly and proactively in pipes, ponds, and other forms of water infrastructure.

The connection between a monitoring system and the active control of water is not fully realized in most Canadian municipalities. Yet, research suggests there is general awareness by Canadian water professionals that the ability to control these systems presents the biggest impact to water quality.

Uptake

Smart technology uptake refers to the factors that impact, positively or negatively, the uptake of smart technology for stormwater at the municipal level. Uptake to support stormwater management was a common issue raised during the research.

A significant barrier to uptake is that traditional stormwater infrastructure is costly to maintain and upgrade and few funding mechanisms are available to municipalities to fund improvements.

Technology Interface

The issue of technology interface refers to the integration of different technologies across an organization or platforms. For example, a municipality may consider how integrating an IoT device may relate to an existing SCADA system. This could also refer to software and hardware from different manufacturers. Communication between technologies, within a device or at the scale of a system, requires a willingness to understand how these systems operate and how they may function as part of a larger system.

8 Role of Standards

8.1 Purpose of Standards

Standards play an important role in supporting the efficient and safe use of technology. Along with the necessary regulations, standards can provide confidence to users that products and services are safe and fit for use in appropriate contexts. With the new generation of “smart” products and services, enabled by cost-effective and powerful information and communications technology, it has become increasingly difficult for users and policymakers to be confident that these new products and services continue to be safe and fit for use, and that they are not being misused.

The level of confidence needed depends upon the consequences of failure to meet product or service expectations, and performance requirements are often left to end users to confirm.

8.2 Potential Integration with Existing Standards

This research report supports the potential development of standard(s) for SST communications. An important component of this research is understanding the links to other standards that may support and/or inform a standard for communication.

Given the complexity of stormwater management, including who has authority and jurisdiction over the construction and operation of stormwater facilities, it is important to consider potential competing and/or influencing standard(s) that a new standard for SST communications must consider. Generally, municipalities responsible for stormwater management will develop their own standards for water, wastewater, and stormwater.

Existing standards identified in table 2 may inform and support the development of a new standard(s) for SST communications. These standards are categorized based on the organization/group issuing the publication.

Continued work in this space is critical to the effective management of stormwater by municipalities highly affected by climate change impacts and facing major fiscal budget impacts in uncertain times. In addition to existing standards that may co-exist with new standard(s) for SST in Canada, standards in other countries may support knowledge for implementation of SST standards. This may include Standards Australia or European Standards.

Standardization provides an important international recognition to support municipal solutions. This work will further support standardizing bodies and/or organizations, including CSA, with progress in this area and increased recognition and uptake.

Table 2: Existing Standards Relevant to Standardization for SST Communications.

Group	Standard
International Organization for Standards (ISO)	▪ ISO 24536:2019 – *Service Activities Relating to Drinking Water Supply, Wastewater, and Stormwater Systems* ▪ ISO 37106:2021 – *Sustainable Cities and Communities – Guidance on Establishing Smart City Operating Models for Sustainable Communities* ▪ ISO 37122 – *Sustainable Cities and Communities – Indicators for Smart Cities* ▪ ISO 37123 – *Sustainable Cities and Communities – Indicators for Resilient Cities* ▪ ISO/ICE 27400 – *Cybersecurity – IoT Security and Privacy*
Canadian Standards Association (CSA)	▪ CSA EXP200 – *Evaluation of Software Development and Cybersecurity Programs* ▪ CSA W204-19 – *Flood Resilient Design for New Residential Communities* ▪ CSA Z800-18 – *Guideline on Basement Flood Protection and Risk Reduction* ▪ CSA W200-18 – *Design of Bioretention Systems* ▪ CSA W201-18 – *Construction of Bioretention Systems* ▪ CSA PLUS 4013-19 – *Technical Guide: Development, Interpretation and Use of Rainfall Intensity-Duration-Frequency (IDF) Information: Guideline for Canadian Water Resources Practitioners* ▪ CSA W205-19 – *Erosion and Sedimentation Management for Northern Community Infrastructure* ▪ CSA W202-18 – *Erosion and Sediment Control Inspection and Monitoring* ▪ CSA W211:21 – *Management Standard for Stormwater Systems* ▪ CSA W210:21 – *Prioritization of Flood Risk in Existing Communities*

8.3 Considerations for SST Communications Standard(s)

This research report helps inform the risks and potential mitigation options that may be addressed through a standard. Informed by the research, the following recommendations are provided for future standard(s) to address SST communication resiliency:

Power Source

SST and IoT devices are typically battery or line powered. Factors that must be considered when determining power source include connection opportunities, length of battery time, back-up power sources, and overall resiliency of the power source.

Mobility

SST devices are typically static and located in the same position to continuously monitor water levels and maximize the stormwater facility's performance. Whether a device is mobile or static will influence and/or be influenced by the power source (e.g., a mobile device will likely be operated by a battery) and the frequency of data reporting. The higher the frequency of data transmission, the more power required. It is important to understand what the ideal frequency of transmission is and how often data can be extracted from these systems.

Data Collection (Quantity)

Municipalities and/or users of SST devices will need to consider the quantity of data being collected. Collecting, collating, and reporting data is often not feasible due to limited resources and technology at the municipal level. The experts interviewed identified this as a significant barrier to the adoption of SST and data-centered approaches to municipal operations in general.

Data Collection (Quality)

Findings indicate the water sector has not embraced big data analytics and IoT as rapidly as other industries. While some utilities are collecting significant amounts of data, data quality is an issue that hampers data utilization. Ensuring collected data is used and translated into actionable measures is essential if SST benefits are to be realized. A municipality and/or user of SST may consider how often sensors report and the type of data reported.

Range

The range that data will need to be transmitted to/from the SST device and receiving end must be considered. Wireless IoT systems use antennas to transmit or receive information and typically operate in association with wireless routers to improve the signal to and from the device they are connected to. Range refers to the relationship between the physical device and the wireless connection. The type of network, for instance, will enable or impact data transmission.

Density

Users of SST must consider how many SST devices will be deployed and within what proximity to other SST devices. This consideration may be more relevant to the development of future standards for SST at a larger scale than the single catchment focus of this report. However, SST has been employed at a wide range of scales, including city-wide sewer sheds; thus, the eventual integration of these devices into one cohesive system will be essential to the health and safety of communities.

9 Future Opportunities

Smart technology and IoT devices will continue to experience significant growth through public and private sector development projects and this growth will include stormwater management systems. While this project focuses on the implementation of SST to single-catchment projects in Canadian municipalities, it is important to consider the future of implementation at the municipal and/or watershed scale.

Consistency through standards can help ensure the safe operation of the overall communication system(s) controlling SST. Standard(s) development at the micro scale is an important and necessary foundation to establish given the predicted scalability and significant benefits of SST for municipalities. Technological investments in essential infrastructure can lead to substantial community benefits. Bolstering the potential benefits while suitably addressing risks associated with SST will support uptake in municipalities for this innovative technology.

References

[1] S.J. O'Neil and S. Cairns, "New solutions for sustainable stormwater management in Canada," Smart Prosperity Institute, Ottawa, Ontario, Canada, 2016. [Online]. Available: https://institute.smartprosperity.ca/sites/default/files/stormwaterreport.pdf

[2] Government of Ontario, "Understanding stormwater management: An introduction to stormwater management planning and design." Environment and Energy. [Online]. Available: https://www.ontario.ca/page/understanding-stormwater-management-introduction-stormwater-management-planning-and-design

[3] Toronto and Region Conservation Authority, "TRCA flood risk management: stormwater management," Toronto and Region Conservation Authority. [Online]. Available: https://trca.ca/conservation/stormwater-management/

[4] City of Calgary, "Homeowner water guide. Stormwater management system," [Online]. https://www.calgary.ca/uep/water/water-and-wastewater-systems/homeowner-water-guide.html

[5] Intergovernmental Panel on Climate Change, "Managing the risks of extreme events and disasters to advance climate change adaptation. A special report of working groups i and ii of the intergovernmental panel on climate change," Intergovernmental Panel on Climate Change. [Online]. Available: www.ipcc.ch/pdf/special-reports/srex/SREX_Full_Report.pdf

[6] Canadian Construction Association (CCA), the Canadian Public Works Association (CPWA), the Canadian Society for Civil Engineering (CSCE) and the Federation of Canadian Municipalities (FCM), "Canadian infrastructure report card: Informing the future," 2016. [Online]. Available: http://canadianinfrastructure.ca/downloads/Canadian_Infrastructure_Report_2016.pdf

[7] H. Mashayekhi, "Integrated stormwater management, rules & regulations," The W Booth School of Engineering Practice, McMaster University, Ontario, 2015. [Online]. Accessed: https://cvc.ca/wp-content/uploads/2016/09/Appendix-I-Integrated-SWMRules-and-Regulations.pdf

[8] Government of Canada, "Changes to water quantity: Drivers and impacts," Environmental indicators. [Online]. Available: https://www.canada.ca/en/environment-climate-change/services/environmental-indicators/changes-water-quantity-drivers-impacts.html

[9] J.R. Lefkowitz, A.K. Saramanian, and M. Quigley, "Continuous monitoring and adaptive control – the internet of things transforms stormwater management," *Journal of the New England Water Environment Association*, vol. 50, no. 1, pp. 44-50. Apr. 2016. [Online]. Available: https://www.newea.org/wp-content/uploads/2014/03/NEWEA-Journal_Spr16.pdf

[10] P.C.D. Milly, M. Falkenmark, J. Betancourt, and R.M. Hirsh, "Stationarity is dead: Whither water management?" *Science*, vol. 319, pp.573-574. Jan. 2008. [Online]. Available: https://www.researchgate.net/publication/200043757_Stationarity_Is_Dead_Whither_Water_Management

[11] United States Environmental Protection Agency, "Climate adaptation and stormwater runoff." Available: https://www.epa.gov/arc-x/climate-adaptation-and-stormwater-runoff (accessed Dec. 2021).

[12] N. Farhad, S. Garg, R. Huxley, and K. Pillay, "Understanding infrastructure interdependencies in cities," C40 Cities, 2019. [Online]. Available: https://www.c40knowledgehub.org/s/article/Understanding-infrastructure-interdependencies-in-cities?language=en_US

[13] Canadian Urban Institute, "Smart city master planning guide," 2018. [Online]. Available: https://canurb.org//wp-content/uploads/CUIPublication.SmartPlanningOurSmartCities.June2018.pdf

[14] SNC-Lavalin Group, "The 'smart' stormwater management solution," 2021. [Online]. Available: https://www.snclavalin.com/en/beyond-engineering/cmac-the-smart-stormwater-management-solution

[15] T. Lynn, P.T. Endo, A.M. Ribeiro, G. Barbosa, and P. Rosati. "The Internet of Things: Definitions, key concepts, and reference architectures," *The Cloud-to-Thing Continuum,* pp. 1-22. Jul. 2020. [Online]. Available: https://link.springer.com/chapter/10.1007/978-3-030-41110-7_1

[16] A. Grieco, "The new trust standard," CISCO Blog, Sept. 2021. [Online]. Available: https://blogs.cisco.com/security/the-new-trust-standard

[17] Association of Municipalities Ontario, "Come hell or high water: Flooding, climate change and municipal responses," Oct. 2020. [Online]. Available: https://www.amo.on.ca/sites/default/files/assets/DOCUMENTS/Reports/2020/ComeHellorHighWaterFloodingClimateChangeandMunicipalResponses20201019.pdf

[18] National Security Agency, "Embracing a Zero Trust security model," Feb. 2021. [Online]. Available: https://media.defense.gov/2021/Feb/25/2002588479/-1/-1/0/CSI_EMBRACING_ZT_SECURITY_MODEL_UOO115131-21.PDF

[19] Microsoft, "Zero Trust Maturity Model," Microsoft, 2021. [Online]. Available: https://query.prod.cms.rt.microsoft.com/cms/api/am/binary/RWJJdT

[20] Microsoft, "Embrace proactive security with Zero Trust," 2021. [Online]. Available: https://www.microsoft.com/en-ca/security/business/zero-trust

[21] S. Coutts, and S. Gagnon-Turcotte, "Data Governance and digital infrastructure: Analysis and key considerations for the City of Toronto," Open North, 2020. [Online]. Available: https://www.toronto.ca/wp-content/uploads/2020/08/95fb-2020-07-10-Open-North-Data-Governance-Report-Main-report-WEB.pdf

[22] Frontiers in Sustainable Cities, "Research topic: Data governance for innovation in sustainable smart cities," 2021. [Online]. Available: https://www.frontiersin.org/research-topics/16285/data-governance-for-innovation-in-sustainable-smart-cities#overview

[23] United States Environmental Protection Agency, "What are Combined Sewer Overflows (CSOs)?" 2017. [Online]. Available: https://www3.epa.gov/region1/eco/uep/cso.html

[24] The Water Research Foundation, "Intelligent water systems," 2019. [Online]. Available: https://www.waterrf.org/sites/default/files/file/2019-07/TO_IntelligentWaterSystems.pdf

[25] Government of Ontario, "Provincial Policy Statement," 2020. [Online]. Available: https://files.ontario.ca/mmah-provincial-policy-statement-2020-accessible-final-en-2020-02-14.pdf

[26] J. Zammer, "Integrating blue-green systems planning. Administrative report to Vancouver City Council." City of Vancouver, Oct. 2019. [Online]. Available: https://council.vancouver.ca/20191105/documents/rr1b.pdf

[27] Region of Waterloo, "Groundwater", 2021. [Online]. Available: https://www.regionofwaterloo.ca/en/living-here/groundwater.aspx

[28] C. Lewelly, and B. Wadzuk, "Evaluating green infrastructure performance using real-time control from a risk perspective," 2017. [Online]. Available: https://optirtc.com/assets/images/resources/articles-and-papers/papers/Evaluating_Green_Infrastructure_Performance_Using_Real-Time_Control_from_a_Risk_Perspective-Villanova_University.pdf?_cchid=d4526f64849b6bda2a07e946676505be

[29] SmartSWM, "SmartSWM: How it works," 2021. [Online]. Available https://smartswm.com/

[30] J. Lorinc. " Rotterdam is using smart city tech to solve pressing urban problems. Here's what Canadian cities can learn from the Dutch model," Toronto Star, Jan. 2021. [Online]. Available: https://www.thestar.com/news/atkinsonseries/2021/01/07/rotterdam-is-using-smart-city-tech-to-solve-pressing-urban-problems-heres-what-canadian-cities-can-learn-from-the-dutch-model.html

[31] A. Roseboro, M.N. Torres, Z. Zhu, and A.J. Rabideau, "The impacts of climate change and porous pavements on combined sewer overflows: A case study of the City of Buffalo, New York, USA," *Frontiers in Water,* vol 3, Sept. 2021. [Online]. Available: https://www.frontiersin.org/articles/10.3389/frwa.2021.725174/full

CSA Group Research

In order to encourage the use of consensus-based standards solutions to promote safety and encourage innovation, CSA Group supports and conducts research in areas that address new or emerging industries, as well as topics and issues that impact a broad base of current and potential stakeholders. The output of our research programs will support the development of future standards solutions, provide interim guidance to industries on the development and adoption of new technologies, and help to demonstrate our on-going commitment to building a better, safer, more sustainable world.

CSA GROUP™