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*Review*

# Wastewater System Inflow/Infiltration and Residential Pluvial Flood Damage Mitigation in Canada

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**Abstract:** Pluvial flooding in urban areas is one of the most significant drivers of disaster loss in Canada. Damages during pluvial flood events are associated with overwhelmed urban drainage (stormwater and wastewater) systems. During the period from 2013 to 2021, Canadian property and casualty insurers reported approximately CAD 2 billion in personal property (residential) pluvial sewer backup claims during flood catastrophes. There has been growing interest in managing pluvial urban flood risk, notably through newly funded national programs focused on climate change adaptation. These programs have included the development of new guidelines and standards focused on managing the underlying factors contributing to urban and basement flooding. Inflow and infiltration (I/I) has received limited attention in the pluvial flood literature, however. Informed by significant engagement with practitioners in Canada, this paper provides a review of the issue of I/I into wastewater systems and its relation to pluvial flooding. The paper will address concerns related to private property engagement in I/I and urban pluvial flood reduction programs. Both improved technical standards and administrative support are needed to ensure that wastewater infrastructure is less susceptible to I/I over its lifecycle.

**Keywords:** extreme rain; pluvial flood; basement flood; wastewater; inflow and infiltration; Canada



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## 1. Introduction

Pluvial flooding in urban areas associated with short-duration, high intensity (SDHI) rainfall events is a chronic cause of property damage and disruption in urban areas around the globe [1–8]. Pluvial flooding is a routine experience in many urban municipalities in Canada and results in hundreds of millions of dollars in insurance and uninsured disaster losses each year. During the period from 2013 to 2021, property and casualty insurers reported approximately CAD 2 billion in personal property sewer backup claims during flood catastrophes (i.e., catastrophe events where insured losses exceeded CAD 25 million) [9]. The flooding of residential properties, associated with SDHI events exceeding stormwater and wastewater systems' capacities, results in floodwater entering buildings via multiple flood mechanisms. These mechanisms include overland flow, infiltration/seepage, sewer surcharge/backup, and internal/building-specific plumbing and drainage system failures [10]. Sewer backup typically contributes more than half of the total insured losses during major urban pluvial flood events in Canada [9,11–13].

Aside from property damage, SDHI events may also drive sanitary and combined sewer overflow events with negative implications for surface water, and SDHI rain events result in significant damage and operation costs associated with municipal infrastructure [5,14]. Increasing urban development, aging public and private-side infrastructure, and sewer construction quality issues, among other factors, are expected to intensify the impacts of pluvial flood events in Canada [15–19]. While SDHI events drive major, damaging flood events, basement flooding associated with overtaxed or poorly maintained sewer infrastructure may occur during less intense rainfall events or even in dry conditions as a result of blockages in pipe systems.

Climate change impacts in many regions of Canada, which are anticipated to include the increased frequency and intensity of SDHI rainfall events, are expected to intensify pluvial flood risk [19,20]. Climate change impacts associated with urban pluvial flood are increasingly recognized in national climate change assessment reports and climate change adaptation-related guidance documents [15–21]. Maintaining and recapturing capacity in wastewater systems is also increasingly important, as urban municipalities across Canada emphasize the increased density of development, infill development, and affordable housing [22,23].

Vulnerable residents, including those occupying basement apartments in flood-prone urban areas [24], may suffer significant impacts during flood events. These residents, typically renters, are unlikely to have insurance coverage for any type of flood or property damage [25]. In the context of affordable housing, it is important to provide adequate basement flood and sewer backup protection for basement apartments [24].

Considerable international literature exists on the topic of urban pluvial flooding—for example, [1–8,26–36]. While it is recognized that extreme rainfall in urban areas causes excess flow of water in wastewater systems via rainfall-derived inflow and infiltration (RDII) [14,26,37], and that this excess flow results in the flooding of buildings via buried sanitary sewer conveyance systems [10,19,36], the specific role of wastewater systems and inflow and infiltration (I/I) in urban pluvial flood and options to mitigate I/I risk in the context of pluvial flooding have received limited attention in the literature.

This paper contributes to the literature on urban pluvial flooding by providing detail with respect to the role of wastewater (sanitary) systems in pluvial flood hazards, with a focus on Canada. The paper will specifically review practical approaches to improving I/I management in wastewater systems in Canadian communities. The discussion is informed by significant consultation with wastewater system practitioners associated with the development of new practical guidance documents [13,38–43], including the development of National Standards of Canada (NSCs). NSCs provide a basis for infrastructure system design, construction, maintenance, and operation and are developed by, and oriented toward, the application by the infrastructure management community in Canada.

The discussion is organized as follows: Section 2 provides an overview of pluvial flood in Canada, including a discussion of common approaches to urban drainage, examples of recent pluvial flood events, and flood mechanisms in urban areas. Section 3 provides an overview of the issue of I/I, its impacts, and examples of I/I occurrence in pluvial flood events. Section 3 further reviews common sanitary sewer characteristics and discusses challenges associated with managing I/I that are attributed to sewer type and local governance characteristics. Section 4 provides detail on the factors that affect the occurrence of I/I in sewer infrastructure, with an emphasis on the administrative factors that lead to its occurrence. Section 5 provides a review of new NSCs that have been developed to respond to climate change impacts in Canada, including the potential increase in pluvial flood risk, focusing specifically on how I/I in wastewater systems can be addressed. Section 6 provides a discussion of the opportunities and next steps for I/I management, including the improved understanding of property owners' behavior and the methods to engage property owners in I/I reduction, recommendations for improved technical standards and administrative approaches to managing I/I, and improved consideration of the overall costs and benefits of I/I for the purpose of informing its management. Section 6 also addresses the study limitations and future research. A summary of the conclusions of the review is provided in Section 7.

## 2. Pluvial Urban Flood in Canada

Urban pluvial flood is defined as events where "[. . . ] rain-driven ponding or overland flow [. . . ] results from the exceedance of natural or engineered drainage capacity [. . . ]" in urban areas [8]. In Canada, urban pluvial flooding includes scenarios where SDHI rain events exceed the "[. . . ] combined hydraulic capacity of [an] area's storm sewers, ditches, and catch basins and water flows from the streets onto properties" [44]. This type of flooding can occur anywhere, including in areas that are not vulnerable to flooding associated with an overflowing water body [27,45].

Urban stormwater management systems may include minor drainage systems (storm sewers, catch basins, inlets, inlet control devices, gutters, ditches, and swales) and major drainage systems (streets, channels, ponds, natural streams, and valleys) which convey stormwater away from urban areas during and after storm events [44]. In Canada, the capacity of these systems may differ depending on the "era" of construction, corresponding to the approximate intervals of 1880–1970, 1970–1990, and 1990 to the current day (Table 1).

**Table 1.** Eras of stormwater management in Canada [1].

| Era | Summary |
| --- | --- |
| ~1880–1970 | • Sewer networks provided to quickly convey stormwater from upstream urban areas to downstream receiving waters<br>• Design capacity typically 1:2 to 1:10 year, occasionally 1:25 year |
| ~1970–1990 | • Stormwater detention facilities and overland systems incorporated to convey stormwater when minor system capacities are exceeded<br>• Minor system to manage 1:2 to 1:10 peak flows; major system to manage 1:50 to 1:100 flows |
| ~1990 to present | • Stormwater quality considered along with quantity; application of Best Management Practices to manage stormwater pollution in receiving waters. |

[1] [46–48].

Until the 1970s, urban stormwater management emphasized underground (minor) systems with design capacities ranging from 1:2 to 1:10 year return period flows, with limited consideration of overland (major) systems. From the 1970s to the 1990s, major systems were incorporated into urban drainage design. These systems conveyed stormwater when minor system capacity was exceeded and were typically designed to manage 1:50 to 1:100 year return period flows. Conventional approaches to urban stormwater management included "[collecting] and [conveying] water as quickly as possible while maximizing dry land area for urban development" [8]. By the 1990s, however, stormwater management practices also increasingly incorporated considerations concerning water quality for smaller storms [46–50]. Pluvial flood events may occur when rainfall intensity/runoff exceeds the design capacities of these systems, even when they are functioning correctly [8].

Recent pluvial flood events in Canada demonstrate the intensity of extreme rainfall events that exceed system capacity. Each of the events listed in Table 2 were classified as an insurance loss "catastrophe" with significant residential pluvial flood damage. Further, each of the total accumulations presented in Table 2 exceeded local 1:100 year return period short-duration rain events.

**Table 2.** Select SDHI/pluvial flood catastrophes in Canada with significant sewer backup loss components.

| Event | Rainfall Accumulation |
| --- | --- |
| Peterborough, ON, 15 July 2004 | ~80 mm in 1 h, ~260 mm in 24 h [51] |
| Toronto/GTA, ON, 19 August 2005 | 132 mm in 2 h, 149 mm in 12 h [52] |
| Hamilton, Ottawa, ON, July 2012 | 116 mm to 140 mm in 3 h in the Hamilton area [9] |
| Toronto, ON, 8 July 2013 | 102 mm in 2 h, 126 mm in 6 h [52] |
| Greater Toronto Area, ON, August 2014 | 150 to 200 mm total accumulation in Burlington [9] |
| Windsor/Tecumseh, ON, 28 September 2016 | 220 mm over 24 h, 110 mm in 2 h in Tecumseh, 115–230 mm in Windsor (24 h) [53,54] |
| Windsor/Tecumseh/Essex, ON, 28–29 August 2017 | 290 mm in LaSalle, +220 mm in Windsor, 190 mm in Essex [9] |

Buildings may be affected by a variety of mechanisms during pluvial flood events in urban areas, such as those outlined in Table 2. These mechanisms, reviewed in detail elsewhere [10,55], include:

- Seepage of ground and surface water (water seeps into the ground adjacent to the foundation walls, causing water to enter buildings through cracks, loose joints, etc. in basements and foundations, and/or groundwater enters homes through cracks the in foundations);
- Sewer backup (surcharging of sewers, resulting in the backup of storm, sanitary, combined, and partially separated systems into buildings, including backflow into foundation drainage systems);
- Overland flow of stormwater (stormwater surface flow enters buildings through aboveground openings).

Further to the above, a variety of property- and building-specific plumbing and drainage factors may exacerbate flood occurrence at the property and building scales, including poor lot grading and drainage, the poor installation and lack of maintenance of building sewer connections, and limited knowledge and maintenance of key interior and exterior sewer and drainage systems by property owners [55]. For example, sewer laterals that have become blocked due to a lack of maintenance or poor installation may drive isolated sewer backup events. With respect to public and private sewage conveyance systems, excessive water entering wastewater systems may drive regional-scale sewer backup events. Sewer backup events also result from site- and/or regional-scale factors affecting sanitary sewer systems. Public-side sewers are generally in a state of less-than-ideal repair, exacerbating flood risk during intense rainfall events [56].

## 3. Inflow/Infiltration (I/I)

An important mechanism driving the occurrence of sewer backup in wastewater systems during pluvial flood events is excessive water entering sanitary sewer conveyance systems, resulting in reduced system capacity and an increased vulnerability to the surcharge reversal of flow into buildings. This excess flow is referred to as "Inflow and Infiltration" or I/I [57,58]. In general, I/I is defined as any rain or groundwater in the sanitary sewer that should not be there. Infiltration includes "water other than sanitary wastewater that enters a sewer system from the ground through defective pipes, pipe joints, connections, or manholes." Inflow includes "water other than sanitary wastewater that enters a sewer system from sources such as roof leaders, cellar/foundation drains, yard drains, area drains, drains from springs and swampy areas, manhole covers, cross connections between storm sewers and sanitary sewers, and catch basins" [59].

I/I is a chronic issue in regions across North America and internationally [2–7,60], with the negative impacts of I/I exacerbated by increasing urban populations, increasing urban density/infill development, and aging infrastructure. It has been reported that roughly half of all wastewater volume may be attributed to I/I [7,59,61,62].

While this review focuses on the role of I/I in sewer backup flooding as a component of pluvial flood events in urban areas, it is important to note that I/I results in multiple negative impacts. From a public policy perspective, the role of I/I in driving pluvial flood damage via sewer backup should be considered in the context of its multitude of negative impacts [4–7,15,55].

I/I results in a lack of capacity at pumping stations and trunk sewer systems, limiting the potential for urban intensification and additional development in urban communities [42]. I/I also increases the lifecycle costs for wastewater systems and may reduce the years of service for new sewer infrastructure. For example, I/I causes the erosion of bedding and haunching, compromising pipe performance and resulting in early failure for sewer systems [63]. Wastewater treatment plants (WWTPs) may experience negative impacts associated with wet weather peaking, and overflow bypasses at pumping stations and secondary bypasses at WWTPs present significant risks to surface water systems associated with sanitary sewer overflows [3,42]. With respect to the direct financial implications of I/I, the US EPA reported [59]:

Wastewater collection and treatment cost can range from $2 to $5 per thousand gallons [$0.50 to $1.30/m$^3$]. An annual [I/I] volume of 150 million gallons [567, 800 m$^3$] would cost between $300,000 and $750,000 per year to transport and treat. For many older collection systems, infiltration can be quite substantial and has been calculated as high as fifty percent of the flow.

I/I is expected to be affected by climate change. In general, rainfall-derived I/I (RDII) is expected to increase with higher rainfall intensity/accumulation [8,27,64–69], and SDHI rainfall events are expected to increase in terms of frequency and severity under changing climate conditions in many regions of Canada [15,16]. Further, reduced periods of frozen ground in northern climates due to higher temperatures may result in increased infiltration during the winter [70]. Coastal regions also face an increasing risk of I/I, as sea level rises increase groundwater levels and saltwater intrusion, leading to compromises in system integrity and contributing directly to extraneous flows in wastewater systems [3,71]. Changing climate conditions may also affect antecedent conditions (i.e., rainfall and moisture conditions before/between SDHI events), with further implications for RDII [37].

### *3.1. I/I and Pluvial Flood Events*

Engineering studies commissioned by local governments following pluvial flood events provide insight into the role of I/I in the flooding of buildings. This section provides examples of recent major pluvial flood events in urban municipalities. An emphasis is placed here on the role of wastewater systems, how I/I contributed to these flood events, and proposed solutions that focus on mitigating I/I.

The Binbrook community of Hamilton, Ontario experienced an SDHI rainfall event on 22 July 2012. The total rainfall accumulation over a four-hour period was estimated at 90–140 mm (depending on the rain station location), exceeding local 1:100 year events for the region. Roughly 100 residents reported flooding to the City of Hamilton after the event. Flow monitoring indicated that the sanitary sewer system responded rapidly to the SDHI event, and the flows exceeded the capacity of the local pumping station. Flow monitoring further indicated the reversal of flow within the sanitary sewer pipe. Surveys of the affected residential subdivisions indicated the backing up of water via basement floor drains and basement shower drains, indicative of sanitary sewer surcharging [72].

The City of Peterborough, Ontario experienced a severe SDHI event on 14–15 July 2004. The total accumulations exceeded 225 mm in 24 h and 75 mm in 1 h, exceeding local 1:100 year return period events. The following factors were identified as contributors to significant regional residential flooding during the storm in the City's flood reduction masterplan [51]:

- Extreme rainfall;
- Impervious surfaces in areas where intense rainfall was centered;
- Insufficient storm system capacity;
- Poorly design overland flow routes;
- Excess I/I in the sanitary sewer system.

With respect to the separated sanitary sewer systems, accidental interconnections between storm and sanitary systems, inflow through maintenance hole covers, foundation drain connections to sanitary sewers (permitted until 1991), roof downspout connections to sanitary systems, and groundwater infiltration into the sanitary system (attributed to damaged or misaligned sanitary sewer pipes) contributed to flood damage. Previous monitoring at the City's wastewater treatment plant indicated chronic I/I in the City's sanitary sewer system before the flood event. In dry weather, the plant received twice as much water relative to the domestic water supplied by the City's domestic water treatment plant. In wet weather, the flows were six times higher than expected. The post-flood assessment further indicated higher rates of I/I in high groundwater areas and lower rates of I/I in high elevation areas [51].

On 19 August 2005, in Toronto, Ontario, rainfall accumulation of 132 mm in two hours and 149 mm of accumulation over 12 h [52] resulted in significant regional basement flooding (4200 basement flood complaints were recorded by the City) [73]. Thirty-four basement flood protection areas were created to assist in identifying the causes and solutions for recurring basement flood occurrences [73]. While separated storm sewers were commonly constructed in the areas affected by the flood (designed to accommodate 1:2–5 year return period events), affected areas were constructed before major drainage systems were common practice [74]. Multiple factors drove basement flooding in the affected areas, including both the capacity limitations in storm systems and I/I in sanitary systems.

System modelling in study area 30 indicated that sanitary systems were vulnerable to surcharging under historical storm events and design storm events. Rainfall-derived I/I (RDII) rates were estimated to be 1–3 times the accepted design value for the area (0.26 L/s/ha). It was further observed that overloaded sanitary sewers, along with overloaded minor and poorly defined major storm sewer systems, contributed to flooding [75]. Post-flood flow monitoring (conducted in 2006) in study area 29 indicated sewer flow rates indicative of leaky sanitary systems or sanitary systems with significant inflow from residential foundation drain connections. The recommendations for flood remediation included continued operations and maintenance programs to reduce I/I in the sanitary sewer system. These programs included the sealing of maintenance hole covers, maintenance hole rehabilitation, sanitary sewer relining, and cross connection elimination [76]. Managing I/I to control flood risk was recommended throughout study area 28. The factors contributing to flood occurrence in study area 28 included:

- I/I in the sanitary systems;
- High groundwater tables;
- Surface runoff accumulation in low-lying areas;
- The existence of reverse-slope driveways in residential buildings (directing surface flows into buildings and into sanitary sewers via basement plumbing fixtures);
- Overflow depths above street right-of-way elevations;
- Undersized storm systems;
- Blocked or broken sanitary sewers, manholes, and catch basins.

Many of the study areas affected by the 2005 pluvial flood event in Toronto were affected again by an SDHI rainfall event on 8 July 2013. The July 2013 event included 102 mm of rainfall accumulation over two hours and 126 mm over six hours, again exceeding the local 1:100 year return period events [52]. Following the event, 4759 flood complaints were received by the City. Similar to the 2005 event, the factors that drove flooding during the SDHI event included an overloaded sanitary sewer system attributed to excessive I/I, as well as overloaded storm sewer systems and surface flooding [73].

In May 2009, the Sherwood Forest area of the city of London, Ontario experienced an SDHI rain event, with maximum intensities exceeding 100 mm/hr. High rates of I/I in the separated sanitary sewer system were observed (flow rates reaching 50 L/s—twice the capacity of the sewer system) and contributed to regional basement flooding. In this region of the city, it was common to connect foundation drainage to separated sanitary sewers until the year 1985, and significant inflow into the sanitary sewer was directly attributed to residential foundation drain connections. Specifically, the analysis by Jiang et al. [77] indicated that 85% of RDII was attributed to foundation drain connections in the sanitary sewer and that disconnection could result in a 78% reduction in RDII. The municipality established a source-control approach, focusing on the subsidization of foundation drain disconnection by private residential building owners. Observations following the implementation of a pilot foundation drain disconnection program with partial uptake indicated that flows in the sanitary sewer were halved during wet weather events [77–80].

### 3.2. Sewer Types and Implications for I/I

In Canada, municipalities are serviced by variety of sewer system types (Table 1). New construction in Canada is serviced by separated sewer systems, while older areas may also be served by legacy "combined" systems. In many regions of Canada, subdivisions constructed during the mid-20th century are served by systems that are separate within the municipal right-of-way but include building downspout and foundation drain connections to sanitary laterals. These older systems may experience significant I/I problems, as exemplified in the cases discussed in Section 3.1. Due to the differing eras of development in any given urban region, communities may be served by a combination (or hybrid) of the systems listed in Table 3.

**Table 3.** Common types of wastewater conveyance systems in Canada: Sanitary, combined, and semi-combined/partially separated systems [1].

| Type | Description |
| --- | --- |
| Separated | Sewer systems comprised of fully separated storm systems (which convey stormwater to surface water features and stormwater-management infrastructures such as stormwater ponds) and sanitary sewer systems (sewers that collect domestic wastewater and direct it to a central location for treatment and discharge to the environment). |
| Combined | Legacy systems that convey both stormwater and sanitary sewage. |
| Semi-combined/ partially separated | Legacy systems: Separated systems are present on the municipal side of the property line, but household/private-side foundation drainage systems, eavestrough downspouts, area drains, etc. are connected to sanitary sewers on the private-side of the property line. |
| 3rd pipe | Separated storm conveyance systems designed for the dedicated management of building and private property discharges, including foundation drainage and/or downspout drainage. |

[1] [10,13,16,55].

Where urban areas are serviced by separated storm and sanitary sewer systems, stormwater and groundwater should be discharged to underground storm sewer conveyance systems and overland flow routes. Very limited amounts of "clean" storm or groundwater should enter the separated sewer systems [5], and, indeed, there exist clear allowable I/I values (e.g., leakage) at acceptance in all construction specifications on the municipal side and in building construction codes in Canada [81]. It is expected, however, that sanitary sewer systems will deteriorate with age, and I/I rates will increase over time [7,13]. The factors influencing deterioration include physical defects, design flaws, illicit connections, root penetration, poorly adjusted manholes, corrosion, soil conditions, and the location of systems below groundwater levels.

Sanitary sewers are typically assumed to have a design life of 75 years, at which time the system is presumably taken out of service and replaced. At the end of the 75 year period, the sewer should still be capable of conveying peak domestic flow and the peak long-term I/I allowance. For this reason, when designing sanitary sewers, an allowance for peak, long-term I/I is included in the calculations for pipe sizing. This value is essentially a safety factor. While local standards vary [81], a value of 0.28 L/s/ha (also expressed in other units) is commonly used across Canada (note that sewer managers in the Province of British Columbia, Canada use half this value) [13]. Sewers demonstrating leakage at or below amounts permitted at construction are deemed "leak acceptable" [42]. Field experience and extensive consultation with sewer managers in Canada, however, has indicated that the occurrence of excessive I/I in "brand new" separated sewer systems is prevalent, indicating issues with the design, construction, and acceptance that have implications for the long-term operation and I/I rates in sewer systems. Specifically, flow monitoring data collected between 2015 and 2017 by Norton Engineering Inc. revealed that 34 of 35 new subdivisions in Ontario, Canada were experiencing I/I rates far exceeding the expected values [38]. Extensive consultation with municipalities across Canada has indicated that excessive I/I in new sewer construction is an issue experienced nationally [39,40,42].

While new combined sewers are no longer constructed in Canada under normal conditions [16], and semi-combined/partially separated systems are no longer permitted in most new construction, sewer systems in service within municipalities in Canada frequently include combinations of the types outlined in Table 3 [13,82]. Third pipe systems, which may include buried gravity pipe systems dedicated to managing building foundation drainage and/or roof drainage, are less common due to their additional expense, but they serve as an effective means of managing these flows by gravity without discharging directly to sanitary systems.

### *3.3. Distinguishing between Public- and Private-Side I/I*

Further complicating the management of I/I in Canada are jurisdictional boundaries with respect to the design, construction, operation, and maintenance of sewer infrastructure. In most regions of Canada, an important distinction can be made between the "public" and "private" sides of the property line (Table 4) [10,42].

**Table 4.** Jurisdictional challenges associated with managing Inflow/Infiltration in Canada [1].

| Jurisdiction | Management Implications |
|---|---|
| Private property ("private side" of the property line) | • The factors driving flood risk and I/I in *existing* buildings are under the control of households/property owners<br>• Addressing private-side flood and I/I risk requires complex, iterative private-side remediation activities in buildings and on private properties<br>• The factors driving building and site-level flood risk and I/I for *new* construction are largely under the jurisdiction of provincial, territorial, and/or municipal authorities responsible for building and plumbing construction codes and building bylaws<br>• With some exceptions (including sewer use by-laws), municipalities/local authorities have limited jurisdiction and control over private-side actions to reduce I/I |
| Public property ("public side" of the property line) | • Local governments have significant control over the design standards, guides, and local practices governing the design of sanitary sewer conveyance systems, as well as the operation, maintenance, and repair of existing infrastructure<br>• Managing I/I risk in new construction requires engagement and coordination with sectors typically not involved in the design, maintenance, or operation of wastewater systems, including construction code authorities and building and plumbing code inspections staff |

[1] [10,13,42,83,84].

In addition to the issues outlined in Table 4, the two-tier local government systems in Canada can be problematic when working to resolve I/I. Where two-tier local governments exist, in general, the upper tier municipality is responsible to the regulator (i.e., provincial government authority) for meeting the I/I and overflow targets, while the lower tier municipality owns and operates the pipes where the I/I occurs, including on the private-side. To some extent, this situation introduces a degree of conflict when the upper and lower tier local governments work to mitigate I/I [13].

## 4. Factors Affecting the Occurrence of Public and Private-Side I/I

As part of recent efforts to develop practical guidance documents concerning the management of urban pluvial flood and I/I, extensive consultation with local government staff, sewer pipe and appurtenance manufacturers, and building and infrastructure regulators across Canada occurred in 2015–2021, documented in [13,38–43]. The consultation focused on multiple issues driving urban pluvial flood risk, including I/I. A particular emphasis of the consultation was the occurrence of I/I in new sewer construction [42]. Based on this consultation, the factors identified that drive the occurrence of excessive I/I in new construction include:

- General lack of understanding by the industry of the various factors during construction that represent I/I risk;
- Failure to construct private- and public-side sewers according to construction codes, standards, and guidelines in force at the local level;
- Failure to apply testing, quality assurance, and acceptance practices, as outlined in codes, standards, guides, and specifications;
- Conflicts of interests related to which party performs the site inspection (e.g., developer vs. municipal representatives);
- Limited inspection of the private side of the pipe system (these include prescribed notices only);
- Lack of clarity and guidance in construction codes with respect to constructing leak-acceptable sewer infrastructure;
- Jurisdictional issues and silos [42].

Surveys of municipal staff managing wastewater systems in communities with new subdivisions reporting high rates of I/I indicated that many manufacturer-recommended practices and construction code requirements concerning sewer system construction and inspection were not being conducted [38]. Ongoing surveying of the municipal respondents indicated no testing or very low rates of feeler gauge testing for installed pipe gaskets (0% of ~100 municipalities). The respondents further indicated that, though mandatory, sewer testing methods, including leak testing, mandrel, and CCTV inspections, were conducted infrequently (Figure 1).

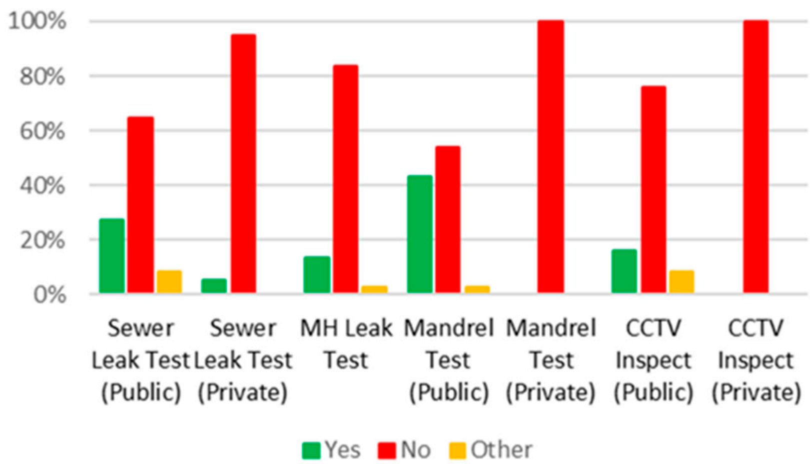


**Figure 1.** Performance of required sewer inspection/testing. Based on surveys conducted by Norton Engineering Inc. between 2015 and 2019 [40].

On the public side, maintenance hole infiltration or exfiltration tests may be rarely conducted (17% of 35 municipalities reported the performance of these tests), and CCTV inspections of public-side lateral sewers and connections were rarely conducted (14% of 35 respondents reported this type of test) [40]. Additional factors affecting the occurrence of I/I in new construction are outlined in Table 5.

Municipal staff across Canada have reported multiple factors driving the limited application of recommended or required inspection practices. These include: actual or perceived pressure from the development industry and/or pressure from the senior management in local governments to approve new sewage works quickly; compartmentalization (existence of "silos") between the staff/departments/organizations responsible for building and sewer construction and inspections [42,84]; lack of experience in the construction and inspections sectors with respect to appropriate practices for the construction, inspection, and acceptance of public- and private-side sewer systems; and resource limitations, including limited staffing for inspection and oversight [42]. While more experienced municipal engineering staff may oversee the inspection and testing of public-side sewer infrastructure, sewer and drainage systems on the private side of the property line are only "spot-checked" by local building code inspection staff, who may lack plumbing system expertise and who may have limited consideration for the lifecycle issues associated with private-side sewer system performance and the implications of I/I [42].

**Table 5.** Factors affecting I/I in new sewer construction, municipal-side [1].

| | |
|---|---|
| Planning, design, and construction | • Location of sewer systems, including buried pipe systems in areas prone to surface flooding and/or high groundwater tables. |
| Construction | • Quality control and construction issues leading to pipe defects and cross connections. |
| Inspections and acceptance | • Limited knowledge by inspections staff of the factors driving I/I and their implications for the lifecycle costs of operating and maintaining sewer infrastructure and related systems.<br>• Lack of experience of municipal inspectors.<br>• Lack of appropriate inspections to verify the leak-acceptable status of buried pipe infrastructure, including visual inspections to verify construction practices at different stages of construction (e.g., embedding and haunching), the infiltration and/or exfiltration of pipes after backfill, CCTV inspections, and mandrel testing.<br>• Failure to refer to the performance-based standards for sewers stated in sewer regulations governing the design, construction, and inspection of sewer systems.<br>• Conflicts of interest between the proponent's desire to complete construction quickly and the owners' (e.g., municipality) desire for long-term pipe performance. |

[1] [42].

A further jurisdictional issue relates to the responsibility for appropriate inspections of the connection between the municipal-side sanitary sewer "stub" (public-side lateral that extends toward the private property) and the private-side sewer lateral. This public/private-side connection has been identified as being at a high risk for I/I related defects due to the differential settlement, as the municipal-side infrastructure is constructed and buried before the private-side infrastructure is built [42]. Furthermore, although the same underlying construction standards specify the installation of the public- and private-side sewer pipe (e.g., PVC-pipe-manufacturer-recommended practices) [41,42], different regulatory requirements exist on the private and public sides of the property line (e.g., municipal guidelines for public-side construction and provincial construction codes for private-side construction), resulting in inconsistent construction practices for what is essentially a continuous pipe of consistent material [41].

With respect to new construction, flow monitoring allows municipalities to ensure conformance to performance-based specifications, providing real data that can be used in the process of verifying the acceptability of new infrastructure [13,42]. Providing notification to developers and contractors that flow monitoring will be in place and will be considered as part of the approval of new sewer infrastructure provides a strong incentive to ensure that recommended and required practices are in place and that I/I is managed to the extent possible. Flow monitoring, however, has not been routinely conducted for new sewer construction in Canada [42].

*Private-Side Issues*

The effective management of I/I should include considerations of managing sources of I/I on the private side of the property line. For example, [85] indicated that, based on a response of 26 reporting agencies, private-side contributions of I/I range from 7–80%, with an average contribution of 24%. Additional estimates of private-side contributions of I/I include 40% [86], 55% [87], and 35% [88]. Pawlowski et al. 2014 [88] further estimated that 98% of private-side I/I in a US case-study municipality were associated with foundation drain and downspout connections to sanitary sewers.

Multiple factors drive flood risk and I/I on the private side of the property line. These factors typically relate directly to the failure of property owners to maintain private sewers (e.g., building drains and laterals), as well as protective plumbing equipment (including pumped foundation drainage discharge systems and sewer backwater protection devices), lot grading, and the internal and external drainage features of buildings (see Table 6). As discussed above, partially separated/semi-combined systems are particularly problematic, and municipalities across Canada continue to report issues associated with the connection of foundation drainage and downspouts to sanitary sewers as significant drivers of I/I and the resulting urban pluvial flood/sewer surcharge risk [89].

**Table 6.** Factors affecting I/I in new construction, private-side [1].

| Element | Risk Factor |
|---|---|
| Planning and design | • Location of buildings and sewer connections in areas prone to surface flooding and/or high groundwater (inc. location of foundation drainage systems, floor slabs, footings, etc. below high groundwater tables) and/or failure to protect buildings from flood risks<br>• Building and drainage design that increase I/I and flood risk (e.g., reverse slope driveways, external area drains that may be cross connected to sanitary sewers, window wells, exterior basement stairwells, appropriate discharge of downspouts)<br>• Site factors that increase the risk of I/I (e.g., plantings that increase the risk of root penetration, the blockage of sewer connections and foundation systems, stormwater infiltration features that increase the risk of infiltration flooding, infiltration into sewer connections)<br>• Failure to incorporate backflow protection in pipe trench design |
| Construction | • Lack of application of industry-accepted bedding, haunching, and backfilling practices, inadequate pipe materials, improper pipe jointing practices<br>• Failure to seal water entry points in building foundations, basement floor slabs, utility penetrations |
| Inspection, testing, acceptance | • Limited application of industry accepted pipe testing approaches for leak testing, including the air pressure, infiltration, and exfiltration testing of private-side sewer connections in compliance with consensus-based standards (e.g., NSCs)<br>• Limited application of flow monitoring, consideration of flow monitoring results in the acceptance of new construction |
| Operation and maintenance | • Lack of maintenance of plumbing system and drainage systems, leading to failures (inc. sump pump system, foundation drain, sewer lateral connection pipe failures)<br>• Lack of inspection, maintenance, and repair of critical drainage features over the life of the building, including inspection and repair and the replacement of sewer connections and sump pump systems<br>• Lack of reporting of pertinent information to local authorities responsible for sewer systems—e.g., backups due to failed pipes, observations concerning flood occurrence and the mechanisms of flood (surface, seepage, sewer backup, other)<br>• Interference with critical drainage features on the property (e.g., alteration of lot grading and drainage) |

[1] [10,42,55].

In existing/older sewer systems, building owners have significant control over the lot and building drainage characteristics that may affect the flood risk for the building and property, including foundation drain and downspout connections to sanitary sewers. Reflecting the influence of private property owners on system-level urban pluvial flood risk, municipalities across Canada have implemented multiple strategies to increase the engagement of residents in managing urban pluvial flood risk and I/I on the private side of the property line, including voluntary education and incentive programs. Successful engagement in these actions, however, remains elusive, with few programs resulting in the significant uptake of private-side action to control I/I [10].

New private-side construction is dictated by building construction code requirements (including building and plumbing codes), which are issued, in the majority of circumstances in Canada, by federal, provincial, and territorial governments. Local authorities may also regulate new private-side drainage works via local drainage and sewer use bylaws. In particular, sewer use bylaws regulate the common causes of significant inflow into sanitary systems, including restricting the connection of foundation drainage and downspouts to sanitary sewer connections [83]. Further, in many jurisdictions in Canada, provincial construction codes take precedence over local building bylaws. These provincial construction requirements may not clearly articulate requirements for the discharge of lot-side storm and groundwater and may, for example, permit the connection of foundation drains to sanitary sewers depending on local code enforcement and interpretation [39,90].

While foundation drain and downspout connections to sanitary sewers are typically restricted in Canada, it is widely reported that building owners make changes to their basement plumbing to avoid the use of sump pumps or to reduce existing flooding (including connecting or draining foundation drains to sanitary sewers) [90]. Further, municipalities face significant difficulty in monitoring and enforcing private-side I/I sources, as property owner permission may be required to access buildings and properties in order to evaluate cross connections. Post-inspection recommendations for the remediation of cross connections are typically disruptive and costly for households, further limiting households' involvement in I/I reduction [83].

Additional private-side factors that drive I/I and sewer surcharge risk include sewer connections that are in poor repair (e.g., poorly jointed, cracked, or with clean-out caps removed). The limited adoption of practices that reduce risk on the private side of the property line can drive I/I, as flood waters that enter buildings may then enter sanitary sewers via basement floor drains [55]. Further, foundation drainage system failures, the failure of sump pump systems due to power interruptions and/or the lack of maintenance, and the backing up of municipal stormwater systems into private-side drainage systems (e.g., where foundation drains discharge by gravity to municipal stormwater systems) may also drive private-side I/I risk [10,55]. The use of "reverse slope" driveways also represents a higher flood risk, as they direct surface water directly into buildings and then into sanitary systems via floor drains [91–94].

With respect to new construction, pipe manufacturers and construction guidelines and codes recommend specific installation and testing requirements to ensure the proper performance of installed sewer pipe. Specifically, the National Plumbing Code of Canada (NPCC) includes leak testing provisions (air and water testing, ball tests, and final tests for private-side drainage systems) and also includes specific pipe bedding practices to reduce the risk of penetration and the poor grading of pipes [95]. Construction codes also reference standards that are applied in public-side sewer construction [39]. Pipe manufacturers commonly reference consensus-based standards to outline the appropriate construction and inspection practices for buried pipe systems, including CAN/CSA B182.11 and ASTM D2321. These standards provide detailed information concerning the construction, installation, and testing of buried pipes for sewer conveyance systems. On the private side, however, these requirements are largely ignored [42].

## 5. Development of New Standards and Resources in Canada

As a result of significant losses derived from urban pluvial flood impacts, a number of new NSCs have been developed to help guide risk reduction associated with pluvial flooding and potential climate change impacts. Each of these standards includes specific guidance with respect to wastewater systems to manage the sewer surcharge and I/I components of urban pluvial flood risk. A high-level summary of the I/I considerations and requirements offered in these standards is provided in Table 7.

Two of the above standards focus on managing I/I in the context of urban pluvial flood risk on the public and private sides of the property line. Specifically, detailed measures required to manage urban pluvial flooding and I/I on the private side of the property line are outlined in CSA Z800-18: Basement Flood Protection and Risk Reduction Guideline. The guideline was developed by a technical committee comprised of local and national wastewater, stormwater, and buildings experts and includes details concerning the design and maintenance of private-side residential plumbing and drainage features that serve to mitigate urban pluvial flood and I/I risk. At the time of writing, a new NSC (BNQ 3682-320) concerning the management of inflow/infiltration in new sewer construction is under development [42,97]. This upcoming standard focuses on the most important drivers of I/I in new sewer construction, which have been identified by a wide cross section of municipal, provincial, and federal government professionals involved in sewer and building design and construction.

**Table 7.** Consideration of wastewater systems and I/I in the National Standards of Canada targeted at urban pluvial flood risk reduction and climate change adaptation [1].

| Standard | Wastewater I/I System Considerations |
| --- | --- |
| CSA Z800-18 | • Comprehensive private-side I/I mitigation options for new and existing construction: Design, construction, maintenance, operation, and risk management considerations for private properties.<br>• Focus is on private properties and low-rise residential/small buildings. |
| CSA W204-19 | • New construction guidance to reduce the risk of urban flood events, with a focus on pluvial flood/stormwater management and other flood causes (e.g., riverine).<br>• Compliance requires: fully separated sewer systems, that sanitary sewers convey extraneous I/I without surcharging, and that surcharging should not occur during the design event specified by the authority with jurisdiction. Under extreme (1 in 100 year) I/I conditions, hydraulic grade lines shall be 0.3 m below the underside building footings.<br>• Additional compliance requirements include: the hydraulic design of sanitary sewer systems complying with storm sewer system requirements and that public-side maintenance holes not to be located in sags or be sealed when located in sags where stormwater ponding may occur. |
| CSA S900.1-18 | • Guidance for adapting wastewater treatment plants to the potential impacts of climate change, including vulnerability and risk assessments for plants under changing climate conditions and the development of adaptation options based on these assessments.<br>• Includes considerations for extreme precipitation events and implications for I/I and sensitivity analyses that consider the potential impacts of extreme precipitation events on I/I and the resulting plant design flows and peaking factors. |
| CSA W210-21 | • Urban flood risk management standard for older, built-up (mature) communities for application by local authorities with differing levels of resources/data available for assessments.<br>• Assessment of I/I factors depending on "[. . . ] technical maturity, staff capacity, and available resources [. . . ]," ranging from "foundational" or basic assessments using the era of construction to "advanced" assessments that include considerations such as sanitary sewer systems modelling and inspections of private laterals and cross connections.<br>• Comprehensive consideration of the factors that drive I/I and multiple types of sewer backup risk that affect buildings (e.g., storm, sanitary, combined, partially separated sewer backup risk) on the municipal and private sides of the property line for flood risk assessment. |
| CSA W211-21 | • Sanitary sewage collection, conveyance, and treatment systems "out of scope" for this standard.<br>• Includes some consideration of sanitary sewer systems in relation to flood (e.g., impacts on sanitary sewers where storm sewers are not maintained). |
| BNQ 3682-320 | • Under development at the time of writing, the standard is to provide comprehensive private- and municipal-side mitigation options for new and existing construction, including factors related to the design, construction, maintenance, and operation of public and private sanitary sewers.<br>• Considers the integration of flood types and that the protection of buildings from surface and infiltration flood reduces the risk of I/I (e.g., restricting use of reverse slope driveways to mitigate I/I during pluvial flood events).<br>• To include the consideration of the interaction between stormwater management features, such as features designed for stormwater infiltration, and sanitary sewer systems. |

[1] [44,45,55,69,96,97].

## 6. Discussion

Protecting sewer systems from I/I aligns directly with protecting buildings from urban pluvial flood impacts. As presented in Table 7, new NSCs concerning urban pluvial flooding include topics and considerations related to the management of I/I and sewer surcharge risk. Similarly, programs aimed at private-side flood protection simultaneously focus on the reduction of private-side contributions of I/I [10]. However, discussion concerning the management of I/I in the pluvial flood management literature is limited.

With respect to policy formulation, this discussion focuses on addressing key barriers in I/I management in both existing/older and new construction, as identified in consultation with practitioners across Canada [13,38–43,90] and in Technical Committee discussions leading to the development of new NSCs. Notably, the actions taken by building owners (on the private side) remain an ongoing impediment to the effective management of pluvial flooding and I/I specifically. There is also an identified need to strengthen the capacity of local governments to manage new construction in a manner that better addresses I/I. The improved education and coordination of the municipal staff involved in the inspection and approval of buildings and sewer infrastructure, backed by coordinated technical standards and regulations that clearly specify consistent standards for sewer systems and drainage on both the private and public sides of the property line, should be implemented. Improved technical regulation should rest upon improved administrative support, including the capacity for inspections and improved understanding on the part of building officials of the importance of appropriate sewer inspections and testing before the acceptance of new infrastructure. Improved technical and administrative requirements must also be backed by a better assessment of the benefits and costs of I/I management.

### 6.1. Public Risk Perception and Risk Reduction Behavior

The private side of the property line is an important contributor to I/I in both new and existing construction. Local authorities across Canada have developed and implemented voluntary homeowner engagement programs to assist in the reduction of I/I and pluvial flood risk, including programs that provide direct financial incentives for sewer backflow protection and downspout and foundation drain disconnection.

The experience of wastewater system and urban pluvial flood managers in Canada to date suggests that it is difficult and expensive to address the factors resulting in I/I and urban pluvial flood risk post-construction. For example, the enforcement of I/I measures on the private side of the property line is politically unpopular [83], and voluntary programs targeted at property owners do not typically experience high uptake [10].

There exists considerable literature on household and public risk perceptions and risk reduction behavior related to natural hazards [98–111], with a substantial amount of the literature focusing on flooding specifically [112–123]. Further, studies have focused on the household response to pluvial flood events, including mitigation actions [27,124]. However, there exist few studies that comprehensively characterize the propensity of households and private property owners to engage in I/I and basement flood risk reduction, as these issues relate to pluvial flood [10]. While authors [27] have provided useful discussion concerning residents' propensity to engage in "medium" and "high" cost flood protection activities, these activities were consistent with protecting buildings from the direct impact of flooding (e.g., sewer backflow protection, relocating electrical systems to higher floor levels, flood barriers) rather than addressing the private-side drivers of sanitary sewer I/I that may contribute to flooding, including downspout and foundation drain connections.

It should not be expected that private property owners will choose to engage in risk reduction behavior in existing homes, especially in the case of significant drainage improvements (disconnecting foundation drains, replacing leaking buried sewer pipes, etc.), even where significant financial incentives are made available. Engaging private property owners, including households, in sewer maintenance and repair will require innovative practices that include inspections and maintenance requirements that are triggered during key windows of opportunity, including when permits are issued for private-side work concerning sanitary building sewers and drains and when private land parcels are redeveloped [83,125,126]. New sewer and drainage systems should be installed according to the best practices and manufacturer recommendations. The design, construction, and inspection of new systems should be conducted in a manner that will limit or eliminate the need to make significant changes to building drainage systems post-construction. Investments in the inspection and enforcement of new sewer construction can help offset the long-term issues with private-side systems that prove exceedingly difficult to address.

### 6.2. Improve Technical Standards & Regulation

In general, concerted effort to manage urban pluvial flood risk, including elements of risk related to wastewater systems, will require the regulation of I/I management practices on both the municipal and private sides of the property line. Through regulation, risk reduction methods concerning planning, design, construction, inspection, testing, and acceptance must become standard practice. Specific items that may require regulation on both the public and private sides of the property line are outlined in Table 8. Regulatory approaches to improving private-side construction are provided in Table 9.

With respect to the interface between private and municipal systems, there exist inconsistencies between private- and public-side technical requirements for sewer installation. In many instances, installation and inspection requirements for municipal-side sewers are more comprehensive, while key documents governing the private-side installation of sewers and drainage systems lack technical clarity with respect to restricting cross connections and ensuring proper installation procedures (e.g., gasketed connections for buried pipe, proper bedding, and backfilling procedures adhering to the manufacturer's requirements). Notably, with respect to sewer laterals extending onto private property, different local regulatory requirements may be in place for a continuous length of pipe. The requirements for the public- and private-side systems should be better aligned.

**Table 8.** Best practices concerning the design, construction, inspection, and acceptance of new sewer systems to reduce I/I risk, municipal-side [1].

| Element | Approach |
|---|---|
| Planning and Pre-Design | • Direct new sewer construction away from surface flood hazard areas, groundwater, or areas with site conditions that exacerbate I/I risk, including stormwater infiltration features.<br>• Where construction in flood-prone areas is unavoidable, incorporate I/I and flood risk reduction mitigation options (e.g., apply more restrictive, leak-proof standards for sewer pipe design to reduce the risk of infiltration over its lifespan). |
| Design | • Ensure that systems can achieve minimum design flushing velocity.<br>• Design sewage pumping stations to operate under all flow conditions.<br>• Locate maintenance holes away from surface ponding areas, use riser rings in manholes.<br>• Design according to site conditions: e.g., leak-proof joints are required in areas exposed to groundwater.<br>• Appropriate differentiation of storm and sanitary sewer pipe materials to reduce the risk of cross connections (e.g., with respect to the size, color, and placement of pipes).<br>• Accommodate flow monitoring in system design (e.g., place manholes at the downstream end of new sewer systems serving subdivisions). |
| Construction | • Install flow monitors at the downstream end of new subdivisions when trunk systems are established so that conformance with existing performance-based standards can be confirmed.<br>• Increase education concerning I/I for municipal and consultant inspectors and enforce the generally required full-time inspection of pipe construction by the designated inspector. |
| Inspection and acceptance | • Inspect all new sewers using CCTV, compare written reports to CCTV recording, sign off on comparison.<br>• Provide written reports and report interpretation for sewer and maintenance hole leak testing and pipe deflection tests.<br>• Apply third party leak testing for manholes and sewers.<br>• Visually inspect manholes prior to acceptance.<br>• Provide acceptance packages that include all the items required by the standards, specifications, and regulations.<br>• Apply flow monitoring results to inform the acceptance of new sewers for all subdivisions. |

[1] [39].

**Table 9.** Best practices concerning the design, construction, inspection, and acceptance of new sewer systems to reduce I/I risk, private-side [1].

| Element | Approach |
| --- | --- |
| Planning and Pre-Design | • New buildings should not be located in areas exposed to surface flood risks, groundwater, or areas with site conditions that exacerbate I/I risk, including stormwater infiltration features. Where construction in these areas is unavoidable, apply flood and I/I mitigation options (e.g., construct buildings without basements).<br>• Private-side connections into public-side municipal stubs should be located above seasonally high groundwater tables.<br>• Building foundation drains, floor slabs, and foundation footings should be located above seasonally high groundwater tables. |
| Design | • Apply surface, groundwater, and infiltration flood hazard protection to reduce the risk of building flooding that can contribute to I/I, including site grading and drainage and all aspects of lot grading (reverse slope driveways are prohibited, basement windows, exterior stairwells are used only where necessary).<br>• Do not permit the cross-connections of private-side drainage features to sanitary sewers (including downspouts, area drains, foundation drainage systems).<br>• Use appropriate sewer pipe materials for buried applications, gasketed pipe joints, and appropriate pipe strength.<br>• Sanitary sewer slope, protection of backfill through pipe trenches. |
| Construction | • Ensure appropriate application of construction practices for pipes (including bedding, haunching, and backfilling according to accepted construction standards), address common/recurring issues identified in new construction (including ensuring building air barrier systems remain intact and addressing infiltration and surface flood hazards). |
| Inspection and acceptance | • Visual inspections to ensure site grading and drainage complies with design requirements.<br>• Thorough inspections of the sewer connection (pre-backfill visual inspection of jointing, bedding, and haunching) and post-backfill (CCTV, pressure, infiltration and/or exfiltration testing, deflection testing).<br>• Acceptance depending on the inspection results and flow monitoring data. |

[1] [127].

NSCs concerning pluvial flood management and I/I, specifically CSA Z800-18 and the upcoming BNQ 3682-320 NSC (Table 7), emphasize restricting construction in areas known to be at risk of flooding, including regions prone to high groundwater and overland/surface flooding. In several regions of Canada, land use planning is in place to restrict development in known flood-prone areas [128]. Specifically, land use planning regulations in Ontario, Canada's most populous province, state that "development shall generally be directed [. . . ] to areas outside of [. . . ] hazardous lands adjacent to river, stream and small inland lake systems which are impacted by flooding hazards [. . . ]" [129] (p. 32). However, land-use planning restrictions across Canada are inconsistent, with several jurisdictions permitting development in flood prone areas. Further, non-river flooding, including surface stormwater flooding attributed to sags/topographical lows outside of riverine flood hazard areas, is typically not represented on official maps that are used to guide land use planning in Canada [130]. Thus, despite the recommendations in new NSCs that development be directed away from flood-prone areas, it is likely that many new sewer systems will be constructed in areas that are at risk of surface flooding. These eventualities are recognized in new NSCs, and the standards include accommodations with respect to building and sewer design to reduce the risk of damage should development be located in these areas (including constructing buildings without basements and applying additional sewer design methods to ensure that systems remain leak-acceptable).

### *6.3. Improve Administrative Capacity for Local Authorities*

With respect to new construction, guidance for authorities with jurisdiction over the construction of sewer systems should extend beyond technical requirements, special provisions and drawings in construction documents, and sewer use bylaws, and it should consider administrative and enforcement provisions to ensure that existing technical requirements are adhered to. Administrative guidance should therefore be incorporated into technical standards concerning the design, construction, inspection, and operation of sewer infrastructure. Other municipal guidance documents not directly related to sewer design and construction should be written with a view to reducing I/I risk, including agreements with property developers and local government official plans. Best practices in the local regulation of sewer systems include ensuring that required inspection practices take place. Additional administrative approaches to managing I/I include education and awareness for those responsible for the installation, inspection, and management of sewer systems, including both professionals and private property owners (Table 10).

**Table 10.** Non-structural/administrative strategies, municipal- and private-side.

| Approach |
| --- |
| • Education and information for private-side building and plumbing codes inspection staff concerning I/I, its causes, and how proper construction and inspection techniques serve to limit I/I risk over the lifespan of sewer infrastructure.<br>• Education for public-side engineering staff working in I/I to help improve the understanding of private-side construction codes (i.e., building and plumbing codes) and the sections therein related to I/I risk.<br>• Application of local information concerning sewer system services as part of the maintenance, alteration, etc. of private-side drainage features.<br>• Provide information to local authorities concerning flood occurrence and its causes. |

### *6.4. Improve the Asessment of the Costs of I/I and the Benefits of Interventions to Reduce I/I*

Allocating the budget and resources to correct I/I remains challenging for sewer managers, as buried wastewater conveyance systems are out of sight, and I/I is typically invisible to the public and to decisionmakers. It is therefore necessary to ensure that available financial resources and existing data are used wisely to develop I/I management programs. As discussed above, the real, direct costs of I/I include sewer overflows at plants and pumping stations and the loss of sewer capacity that could be used to allow for additional development. Additional costs associated with I/I may include the need to upsize existing pipes/infrastructure to accommodate I/I flows, loss of the lifespan of the sewer, flooding of buildings and homes, treatment costs, the need to expand sewage treatment to help manage extraneous I/I flows, and legal risk to the municipality associated with flood and environmental damage, among additional negative impacts.

Traditional engineering studies (including Environmental Assessments or EAs) that determine whether to expand wastewater treatment plants, however, focus only on chemical and power costs when assessing the benefits of reducing I/I [13]. This approach is inadequate and does not account for the real costs of I/I, such as indirect societal, environmental, and economic costs. This approach has been applied because many of the known costs of I/I are difficult to calculate, as they are complex and depend on multiple factors, and limited resources are availed to practitioners (finances, time, and expertise) for detailed benefit–cost assessments. Nevertheless, a more comprehensive and systematic approach to estimating the costs of I/I is required, especially in light of increasing urban development and the risks posed by changing climate conditions.

A practical method to better assess the overall costs is to rely on the "user fees" charged by local authorities as a proxy for the overall costs of I/I. User fees are used to cover the costs associated with buried municipal systems, upsizing pipes due to lost capacity, replacing pipes that have not reached their design capacity, municipal liability for flood damage, and treatment plant expansion costs. These municipal costs are reflected in the rates charged to property owners, and these values may be more readily available to municipalities to assess the overall costs of managing I/I [13].

*6.5. Limitations, Future Research*

The limitations of this review include the lack of quantitative information on the relative contribution of different factors to I/I and how these factors directly or indirectly contribute to flood damage in buildings. Authors have identified private-side factors that drive damage [131] and have studied household perceptions and behavior related to pluvial flooding [27], but there has been a limited focus on physical flood mechanisms (i.e., the relative contribution to damage of different flood mechanisms). The relative contribution of private-side contributors to I/I has been studied [6,77,88], but a comprehensive understanding of public- and private-side factors that drive I/I during intense rainfall events is elusive. For example, quantitative information on the I/I benefits of properly installed/leak-acceptable sewer laterals is not typically sufficient to provide detailed benefit–cost assessment studies.

This review focused on providing an overview and discussion on the role of wastewater systems and I/I in the management of pluvial flood risk in Canada and on new approaches with respect to policy and regulation to reduce I/I, both as it relates to pluvial flooding in urban areas and to the multitude of additional negative impacts of I/I. This discussion did not focus on the mitigation of pluvial flood risk directly, including early public warning systems and blue-green or nature-based infrastructure, but rather on managing of the risk of I/I associated with pluvial flood events. Further, focusing on the wastewater component of pluvial flooding specifically, this review did not compressively address the issues associated with urban flooding, including flash flooding in urban basins [132,133]. The emphasis on wastewater and I/I reflects the input from practitioners across Canada that have struggled to manage this problem both in existing/older construction and in new construction and the dearth of discussion on wastewater systems and I/I in the pluvial flooding literature.

The authors here focused on the outcomes of consultations and opportunities for the better integration of new guidance documents and NSCs concerning sewer system and pluvial flood management in Canada. The consultation conducted since 2015 involved practitioners from local, provincial, and federal agencies concerning the management of sewer systems, and thus, the recommendations and discussion provided here focused on the needs and interests of sewer practitioners.

There is a growing literature and increased emphasis on the topic of climate change adaptation in urban areas, including a particular emphasis on urban stormwater management and pluvial flooding [19,134–137]. The administrative and behavioral aspects of infrastructure design, construction, inspection, and acceptance, however, remain a gap in the literature. As discussed above, recurring barriers to effective pluvial flood protection, including wastewater and I/I components, include property owners' behavior, the activities and behavior of those responsible for the installation and inspection of new sewer infrastructure, and limited administrative and regulatory capacity to ensure that new sewer infrastructure is installed according to industry requirements and best practices. "Siloization," or the compartmentalization of responsibilities for urban water services, identified in previous studies, results in "[. . . ] misaligned strategic goals" [136] (p. 13). This review further identified the compartmentalization of responsibilities for municipal- and private-side sewer infrastructure, contributing to the inconsistent application of technical standards and best practices, as well as to the inconsistent inspection and acceptance requirements for sewer infrastructure. Future research should explore practical methods for ensuring appropriate infrastructure governance that supports the consistent application of technical standards and best practices.

## 7. Conclusions

Urban pluvial flooding, resulting in flooded residential buildings, is one of the most significant drivers of disaster loss in Canada. As a result of historical impacts and an expected increase in the intensity of urban pluvial flood events, practical guidance documents and resources have been developed for infrastructure and property managers in Canada to help mitigate risk. Increasingly, the role of wastewater systems and their contribution to both flood damage and additional negative flood impacts (social, environmental, and financial impacts to communities) are recognized and are being incorporated into the standards oriented toward urban pluvial flood management.

The conclusions of this review include:

1. Though there is extensive literature on pluvial flooding and I/I, the literature on managing I/I as part of pluvial flood risk management is limited. The experience in Canada indicates that I/I is a significant contributor to pluvial flood risk, and greater emphasis should be placed on managing I/I as part of pluvial flood risk management. I/I's role in urban pluvial flooding should be factored into the multitude of additional negative impacts of excessive, chronic I/I to better motivate the management of I/I.
2. I/I is an ongoing issue in existing/older construction. In Canada, regions served by "partially separated" or "semi-combined" systems are particularly vulnerable to high inflow rates.
3. Extensive consultation across Canada has revealed that I/I is an issue in new sewer construction. The lack of administrative capacity to inspect and enforce sewer design requirements and the limited application of best practices in sewer design and construction—notably on the private-side—are key factors that affect the occurrence of I/I in new construction.
4. The engagement of property owners in I/I management and pluvial flood risk reduction, including the application of resource-intensive risk reduction options, remains an ongoing issue that has not been addressed through the engagement methods identified in the perception and behavior literature. New construction must be made as resilient as possible to avoid scenarios where the local authorities must revert to the education/voluntary compliance of property owners to mitigate I/I and pluvial flood risk.
5. New NSCs have been developed that focus both on the management of flood risk in urban areas (including pluvial flood) and on the management of I/I. The implementation of the practices outlined in these NSCs will require both adjustments to the technical aspects of the design, construction, inspection, and acceptance guidelines (e.g., as outlined in new NSCs) as well as administrative support to comply with and enforce improved standards. Improved understanding of the benefits and costs of reducing I/I, accounting for its myriad negative impacts, should support the implementation of the technical and administrative best practices.

The consultation of the relevant stakeholders across Canada has revealed the importance of I/I as a significant contributing factor to urban pluvial flood risk and that I/I can occur in both new and existing sewer construction. Increased emphasis on the administrative aspects of managing I/I—including the collaboration between the practitioners involved in monitoring and regulating sewer construction on the public and private sides of the property line, aligning the regulatory requirements for sewer construction, the improved accounting of the costs and benefits of managing I/I, and applying innovative means of engaging private property owners in I/I management—will contribute to the management of urban pluvial flood risk in Canada.

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