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# The Effectiveness of Exfiltration Technology to Support Sponge City Objectives

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**Abstract:** Urban stormwater management is essential to improve the management of floodwaters in municipalities in urban areas. However, relying on sponge city options for site planning in an attempt to decrease the impacts of flooding is challenging due to the magnitude of flooding in urban China. The merits of exfiltration technology being used in Canada are described as having significant potential; this technology encourages passage from the stormwater pipe down to a second, lower pipe, to facilitate exfiltration to the vadose zone and, ultimately, to replenish groundwater. For example, for a small urban catchment, stormwater runoff from a 2-h long, 5-yearly storm, is demonstrated as being able to exfiltrate approximately 53% of the stormwater. Overall, the potential exists to exfiltrate stormwater from the lower pipe and it is estimated that 71% of the water entering the storm sewer is exfiltrated to the vadose zone, for a small catchment. The exfiltration pipe technology increases groundwater recharge which provides an opportunity to help manage subsidence in China. However, attention must be paid to the quality of the infiltrating water since, as true for any sponge city initiative, poor quality infiltrating water may deteriorate the quality of the groundwater.

**Keywords:** LID; sponge city; exfiltration; sewer system; exfiltration pipe; groundwater recharge; subsidence; Beijing; SWMM; water quality

## 1. Introduction

By 2050, it is projected that more than 70% of the human race will be in urban settings, with many of these urban settings located in mega-cities [1]. Challenges facing these large urban cities include two particular water-related dimensions, namely (i) urban flooding, in part due to the transformation of the landscape from pervious to significant levels of impervious land uses, plus the more intensive, heavy storms that are expected to occur as a result of climate change (e.g., References [2–4]), and (ii) in the search for sufficient supplies of water to satiate the burgeoning urban populations, large groundwater withdrawals may be resulting in land subsidence (e.g., see Reference [5]). Cities in northern China experience arid and semi-arid climates, with an average annual rainfall of less than 600 mm, with the precipitation concentrated within the rainy season from May to October. Severe water shortages are a major problem in these northern areas of China but, as noted above, the potential of land subsidence is also an important issue as well as the need to protect the integrity of water quality conditions in aquifers.

Another part of the response to these challenges facing large urban cities must be to move away from historical approaches which primarily focused on decreasing urban flooding by encouraging rapid stormwater runoff; an alternative approach in the appropriate circumstances stipulates the merits of efforts to encourage the recharge of groundwater and, at the same time, avoid problems of flooding, while also avoiding water quality impacts.

China has been focusing on widespread urban construction for the last 10 years but frequent inland flooding has shocked citizens. For example, more than 180 cities in China have annually incurred inland flooding caused by stormwater over a period of just three years from 2012 to 2014. In July 2012, Beijing faced the heaviest rainstorm in six decades, resulting in the deaths of 79 people [6]. This type of massive event has led to the country favoring 'green' rather than 'grey' and unordered, urbanization. This was shown in China's 12$^{th}$ five-year plan, which proposed to pay more attention to the issues of stormwater management [6].

Flooding has become a regular occurrence in China's cities; 62% of Chinese cities surveyed experienced floods and direct economic losses of up to $100 billion between 2011 and 2014 [7]. Over 200 people were killed and $22 billion in losses were incurred across China in 2016, affecting more than 60 million people. It is, thus, key that urban infrastructure is more resilient in response to the impacts of future climate change. It is clear that with the current design scenarios, the frequency of urban floods will increase over time. A survey conducted by the Ministry of Housing and Urban-Rural Development (MOHURD) [7] reported that 641 out of 654 Chinese cities have incurred frequent floods. In 2008–2010, 62% of 351 cities surveyed suffered from urban flooding and 39% experienced flooding on three or more occasions. Since 2008, the number of Chinese cities affected by floods has more than doubled, and at least 130 cities have experienced flooding nearly every year [8].

Severe weather is predicted to be one of the greatest reasons for higher costs in the future delivery of water services and managing infrastructure [9]. Intensifying concerns also occur in relation to subsidence, with consequences that exacerbate urban flooding problems, particularly in coastal zone cities such as Shanghai, Guangzhou, Zhangjiang, and Tianjin, to name a few [5]. One of the areas with the most severe land subsidence problems in China is Hangzhou-Jiaxing-Huzhou; by the end of 2010, the land subsidence area reached $4.2 \times 10^3$ km$^2$. Additionally, 66% of the Beijing plain has been affected by land subsidence (>50 mm) with a maximum subsidence of 1.23 m [10]. It is now known from the records of groundwater extraction, hydraulic head, and land subsidence, that land subsidence is the result of continual and excessive extraction of groundwater from deep confined aquifers (e.g., see Reference [11,12]).

As apparent from the above, China's cities are being forced to simultaneously consider issues of subsidence (as a result of groundwater over-extraction) as well as the problems of urban flooding while protecting against the potential deterioration of groundwater quality. The results of these sometimes-conflicting issues require effective environmental governance, necessarily entailing a holistic and sustained effort [13]. In December 2013, China's president first proposed to develop "sponge cities". From this moment on, there have been many policies and guidelines with the goal to help alleviate the adverse effects of urban construction and recycle 70–90% of stormwater in-situ by combining permeation, retention, storage, purification, and reuse before discharge by applying the green infrastructure concept [14]. As Wang et al. [15] reported, China has developed 30 pilot sponge cities thus far, replacing the approach of rapid drainage by using sponge city strategies. The Sponge City Project advocates for various forms of utilization of rainwater as water sources for cities.

As Xia et al. [6] pointed out, the sponge city construction will be a "hot topic in the future of China" and Li et al. [14] indicated that the Chinese government has been searching for viable options. In response, the focus of this paper is to demonstrate a potential technology option wherein emphasis in the design is to increase exfiltration to the vadose zone from the stormwater system itself and, hence, pursue two objectives, both to decrease flooding during storms and to increase contributions of stormwater to groundwater (while reflecting the need to assess the potential for deteriorating water quality in the groundwater). This technology, dubbed herein as the 'Etobicoke Exfiltration System' or EES, was created, designed and constructed (2.5 km in length) in the former city of Etobicoke (now part of Toronto) in 1993. The primary objective of EES was to restore elements of the natural hydrologic cycle in a built-up area of the City (e.g., see Reference [16]) while not conflicting with the desired surface land uses and providing the functionality of recharge to groundwater over all four seasons of the year. After 20 years of operation, the majority of the EES is still providing runoff control as well as recharge [17].

The EES has been reported as being able to exfiltrate 90% of rainfall events and this groundwater preservation is important to the maintenance of uptake by vegetation that depends on groundwater during periods of drought [16]. Where groundwater provides stream recharge during low flow periods, this can also be very helpful via the augmentation of the baseflow in a river which will improve the surface water quality, including cooler temperatures of the receiving waterbody and, hence, help in maintaining terrestrial bio-diversity ([16,18,19], Harvey et al. 2017 [20]).

As a consequence of these outcomes in Ontario, Canada, EES types of systems are included as one of the low impact development practices for stormwater management as per TRCA/CVC [21], where it is stated that perforated pipe systems can be thought of as long infiltration trenches or linear soakaways [21] that are designed for both conveyance and infiltration of stormwater runoff. They are underground stormwater conveyance systems designed to attenuate runoff volume and, thereby, also reduce contaminant loads to the receiving waters. Perforated pipe systems are referred to under many terms including pervious pipe systems, exfiltration systems, clean water collector systems and percolation drainage systems. It is noted that there are conditions under which EES types of systems are undesirable due to the potential to deteriorate groundwater quality, as listed in Section 3.8 below and, hence, caution must always be reflected, particularly with regard to the quality of the stormwater, as well situations where the hydraulic conductivity of the ambient soils (e.g., exfiltration from the system may be limited due to ambient soil conditions not being sufficiently transmissive).

As apparent from the above, in the context of improving exfiltration to groundwater as a means of decreasing subsidence, while also decreasing surface flooding, this exfiltration option has several important dimensions. Examples of some of the beneficial impacts for this option are described using a mathematical modeling characterization applied to a hypothetical, small catchment in Beijing, China to illustrate some of the potential opportunities.

## 2. Material and Methods

### 2.1. The Concept of Exfiltration Pipe Technology

Basically, the exfiltration pipe approach involves the placement of one pipe for stormwater with a second (or more) pipe(s) placed beneath that of the stormwater pipe, as depicted schematically in Figure 1.

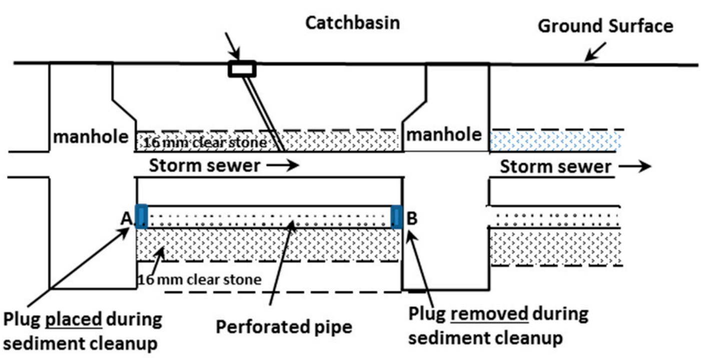


**Figure 1.** The schematic of the exfiltration pipe technology scenario.

In the modeling described herein, a single 300 mm diameter perforated pipe has been used (others have used two perforated pipes of 200 mm diameter, e.g., Reference [16]). A. M. Candaras Associates Inc. [22] indicates a cross-section of the constructed EES system in Etobicoke.

The intent is for the stormwater pipe to function in a manner similar to that of a typical storm sewer where the surface water discharges to the storm sewer with the additional dimension that the storm sewer system also provides vertical drainage conduits to allow runoff to drain into the lower pipe. The lower pipe has exfiltration perforations to allow recharge into the infiltration trench surrounding the lower pipe and, subsequently, to underlying groundwater. The perforations are intentionally placed to facilitate this exfiltration to the infiltration trench surrounding the perforated pipe and subsequently to the unsaturated soil around the infiltration trench. For exfiltration to occur from the infiltration trench, groundwater must be below the trench (for example, Tran et al. [16] indicated groundwater must be >1 m below the depth of the lower pipe). While this EES approach does involve incrementally larger costs to install (and maintain) the second pipe, if done at the time of installation (or replacement) of the storm sewer pipe, the costs are relatively modest (increasing the overall cost by ~15 percent (e.g., References [23–25] but, on the positive side, not requiring the use of space on the surface which would otherwise interfere with land use activities).

The components associated with the perforated pipe systems are located underground, resulting in a minimal surface footprint. This makes them of interest for high-density development contexts (i.e., ultra-urban areas), assuming the surrounding land use activities are residential and commercial, not industrial, and when being designed for new developments [21]. Many other systems such as ponds utilize space on the surface, and must also be maintained (e.g., see Reference [18]).

The perforated exfiltration (lower) pipe allows the temporary storage of stormwater and enhances exfiltration from the lower, exfiltration pipe to the surrounding infiltration trench and subsequently, to the underlying aquifer [26].

This paper provides results from computer modeling of a relatively simple example of the magnitudes of exfiltration which may be feasible when relying on the exfiltration pipe system.

### 2.2. Case Study Subdivision

The case study used to demonstrate orders-of-magnitude (a hypothetical area, but representative of residential and commercial areas of Beijing) is shown in Figure 2. The case study has three catch basins with a total area of 1.44 hectares (ha), with sub-area sizes contributing from 0.54, 0.48 and 0.42 ha each, respectively. The land use has been assumed as typical Chinese urban subareas with 75% impervious and a land slope of 0.5% toward each catch basin.

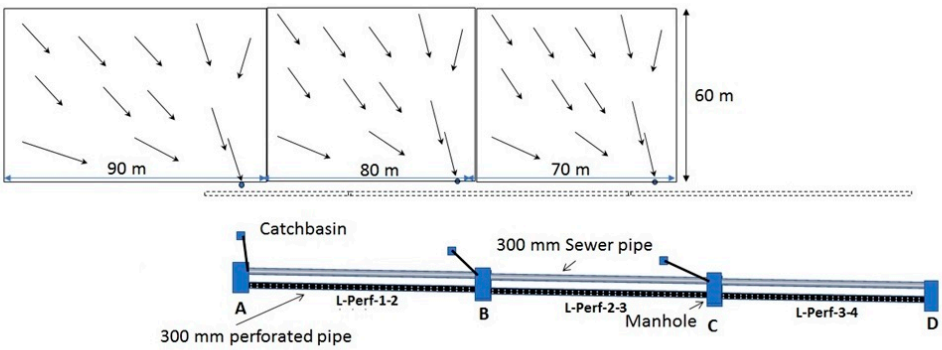


**Figure 2.** The schematic of the case study area.

The design scenario is evaluated with the perforated pipe placed between A to B (L-Perf-1-2), B to C (L-Perf-2-3) and C to D (L-Perf-3-4) (see Figure 2).

In this design scenario, the perforated pipe is off-taking from the manhole and is connected to the downstream manhole (see Figure 1). Plugs are placed (a) at the downstream location at the manhole during normal operation, and (b) just before the manhole downstream, the plug is placed during sediment removal operations (as indicated in Figure 1). The alignment of the perforations in the lower pipe is intentionally at a 45° offset in the vertical, with a total of four perforations around the lower pipe. This approach assists the retention of sediments in the pipe, allowing periodic vacuuming removal of collected sediments to assist in protecting the quality of the groundwater and maintaining the exfiltration capacity. To evaluate the hydraulic performance potential of the system, a computer simulation of the hydraulic response is described below.

## 2.3. Methodology

### 2.3.1. Computational Structure

The computational structure includes a combination of stormwater management model (SWMM) and an Excel spreadsheet model, henceforth referred to as 'ExModel', to characterize the migration of stormwater to the lower pipe and subsequently, exfiltration from the lower pipe into the granular material within the infiltration trench, and finally, from the infiltration trench into the surrounding soil matrix. Although SWMM has a variety of options to model different LID practices (e.g., bio-retention cell, rain garden, green roof, infiltration trench, permeable pavement, rain barrel and vegetative swale), it does not have a modeling option for EES [27]. Liu [27] tried four different procedures, with the resulting conclusion that the Orifice-Pump-Storage method in PCSWMM was the best approach to model EES. In the modeling utilized in this case study evaluation, ExModel uses the same methodology as the Orifice-Pump-Storage procedure, namely, the seepage option from SWMM.

Sabrina [28] calibrated the MIDUSS model (Version 2.00, Rev. 200) to a historical event of 5–6 October 1995, where MIDUSS has the ability to model a specific event and includes a design option for EES. Sabrina [28] also reported that with the exception of a few, all of the catchment parameters were modified several tens of times until the runoff hydrograph was satisfactory and had a similar runoff volume, peak flow and distribution. Since MIDUSS is an event-based simulation model, it could not be used to simulate long-term runoff control performances [27] as needed for this research.

The steps used in the computations of ExModel (and the related SWMM) for this evaluation are indicated in Figure 3.

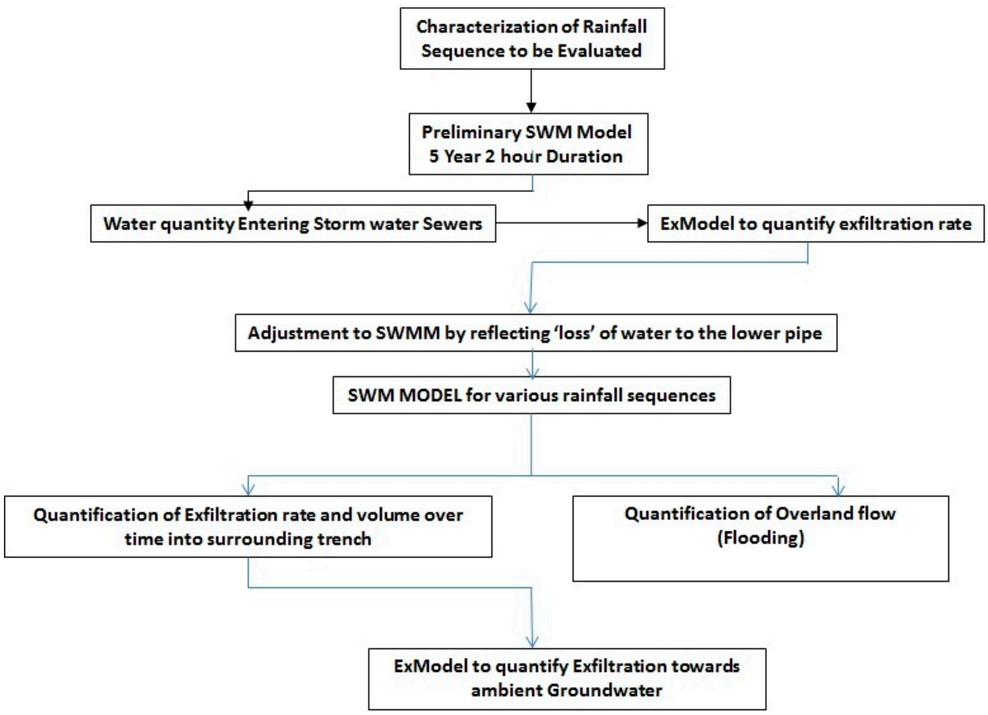


**Figure 3.** A flow chart detailing the computational structure of the EES technology.

### 2.3.2. Characterization of Rainfall Sequences

To determine the size of the storm sewer, a 5-year recurrence interval storm and rainfall duration time of concentration using the rational method was employed. The rainfall intensity duration and frequency relationship for Beijing-China was utilized (after Reference [29]):

$$I = 12.0 \times (1 + 0.811\ \mathrm{Log}_{10}\ (\mathrm{Tr}))/(D + 8)^{0.711} \text{ for } D < 120 \text{ min} \quad (1)$$

$$I = 13.9 \times (1 + 1.091\ \mathrm{Log}_{10}(\mathrm{Tr}))/(D + 10)^{0.759} \text{ for D from 120 to 360 min} \quad (2)$$

where 'I' is rainfall intensity in mm/min, Tr is the return period in years and D is the duration in minutes, as per Table 1.

**Table 1.** The intensity of rainfall for various time durations and return periods—Beijing. (after Reference [21]).

| Return Period | Years | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
|---|---|---|---|---|---|---|---|---|---|
| Duration | min | 5 | 10 | 15 | 30 | 60 | 120 | 180 | 360 |
| Intensity | mm/min | 2.74 | 2.23 | 1.91 | 1.37 | 0.92 | 0.59 | 0.46 | 0.28 |
| Intensity | mm/h | 164.50 | 134.07 | 114.40 | 81.90 | 55.02 | 36.98 | 27.62 | 16.59 |
| Rainfall Amount | mm | 13.71 | 22.35 | 28.60 | 40.95 | 55.02 | 73.96 | 82.86 | 99.54 |

### 2.3.3. Conceptual Stormwater Management Model (SWMM) for Case Study Area

SWMM was used to estimate the quantity of stormwater entering the storm sewers following sizing based on the rational method and subsequently evaluated using SWMM. SWMM was first used (without exfiltration or perforations in the lower pipe (exfiltration pipe) to estimate hydraulic depths (assuming negligible velocity head) versus time) as the standard approach. This computer run was then also used to obtain the needed information (using ExModel spreadsheet) to calculate the effective 'seepage loss' into the lower pipe and, subsequently, into the infiltration trench, and finally, exfiltration into the vadose zone.

Subsequently, SWMM (with the seepage loss) was used for modeling in the storm-sewer pipe for the 5-year return period and 2-h storm duration using the seepage factor in SWMM (with the seepage factor magnitude as calculated by ExModel) to characterize flow conditions in the pipes, thereby providing the hydraulic impacts in the storm sewer system, reflecting the impacts (drainage down into the exfiltration pipes).

A schematic of the case study area in SWMM is shown in Figure 4.

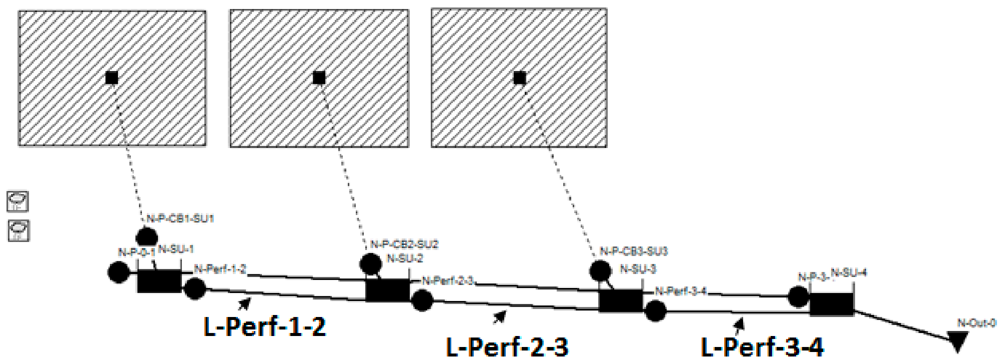


**Figure 4.** The schematic of the Stormwater Management Model (SWMM) in the case study area.

The initial runs provided the depths (hydraulic heads) of stormwater at the starting points of the perforated pipes and from this, the ExModel was employed (a table lookup function) to determine the exfiltration rate into the infiltration trench and, subsequently, into the surrounding vadose zone.

### 2.3.4. The Calculation of Exfiltration Rate and Quantity by the ExModel model

The ExModel was used to calculate the exfiltration rate from the lower pipe by assuming a constant head in the exfiltration (lower) pipes from step-2 for the 5-year storm (2-h duration). The following assumption is made: any sediment deposition in the perforated pipe is characterized by the blockage factor. EPA DDPIWE [30] recommends a blockage factor of 0.5 to 0.75 to be conservative to account for partial blockage of the perforations by the sediment deposits and the receiving media in the infiltration trench which is assumed as 15 mm of clear stone around the perforated pipe and is capable of absorbing the amount of water ex-filtrated from the perforated pipe.

To estimate the exfiltration rates through the perforations into the infiltration trench surrounding the lower, perforated pipe, orifice flow conditions and equations were employed (after Reference [30,31]). Calculations were then performed to determine the volume of stormwater which can exfiltrate from the perforated pipe 1.0 m below the main sewer pipe. An AASHTO Class 1 Perforated pipe of 300 mm diameter is assumed. As per ADS [32] for a 300 mm diameter perforated pipe with four rows of perforations, the total outlet area of perforation holes is 24.3 $cm^2/m$. The exfiltration rate is characterized by

$$Q_{exfiltration} = \sum(C_d \times A \times \sqrt{2} \times g \times H_i) \tag{3}$$

where

$Q_{exfiltration}$ = Exfiltration flow rate through holes ($m^3/s$)
$C_d$ = Coefficient of discharge = 0.60 as per ADS (2004)
A = Cross-sectional area of the inlet area of perforations of perforated pipe ($m^2$)
g = Gravimetric constant = 9.81 $m/s^2$
$H_i$ = Height of water above perforation, head (m) for $row_i$
$Q_{ex\text{-}filtration} = V_{ex\text{-}filtration\ 1} \times A_1 + V_{ex\text{-}filtration\ 2} \times A_2 + \ldots V_{ex\text{-}filtration\ n} \times A_n$
Total $Q_{exf}$ per meter with blockage factor of 0.5 = $Q_{ex\text{-}filtration} \times 0.5$
$Q_{exfiltration}$ Volume = Total $Q_{exf}$ per meter with blockage × time (seconds) × Length (m)

From the above, the exfiltration amount per unit length from the exfiltration pipe (to the bedding matrix) was characterized as 3900 mm/h. The exfiltration (or lower) pipe is not full all the time and, therefore, the exfiltration amounts (seepage rates) per unit length for heads of 290 mm and 280 mm (for a 300 mm diameter pipe) of water were calculated as 3600 mm/h and 3020 mm/h per unit length, respectively.

## 3. Results and Discussion

### *3.1. Calculation of Exfiltration Rate and Quantity by SWMM*

To employ SWMM, the exfiltration from the storm-sewer pipes thus determined was modeled using a seepage rate per unit length. The results for movement to the lower pipe as modeled by the seepage factor (in a manner similar to Liu [27] who reported that the seepage factor was the most accurate) from various runs of SWMM for a storm of a return period of 5-years and a duration of 2 h for various exfiltration rates per unit length were determined as 3600 and 3032 mm/h, producing total exfiltration amounts of 536 and 495 $m^3$ per event, respectively.

### *3.2. The Simulation Runs of SWMM for Rainfall Events of Various Return Periods*

SWMM was run for 1, 2, 5, 10, 25 and 50-year return periods and for half, one, two and six-hour duration storms with exfiltration rates of 3600 mm/h to estimate the quantities of stormwater entering the storm-sewer, the quantity of exfiltration, the quantity of overland flows (urban flooding) and the quantity of stormwater sewer outflows for the small system of pipes in Figure 2.

### 3.3. Quantification of (i) Exfiltration Rates and Volumes and (ii) Overland Flow (Flooding)

The analyses of results estimated the quantities of exfiltration and their percentages of total conventional outflows in storm sewers (% of water exfiltrated, thus, reducing the number of flows in the storm sewer). The results for a 2-h duration rainfall for various return periods are shown in Table 2.

**Table 2.** The quantities of exfiltration and their percentage of total stormwater sewer outflows for 2-h duration storms of various return periods.

| Return Period | Year | 1 | 2 | 5 | 10 | 25 | 50 |
|---|---|---|---|---|---|---|---|
| Duration | Minutes | 120 | 120 | 120 | 120 | 120 | 120 |
| Conventional Sewer System | | | | | | | |
| Overland Flow | $m^3$ | 0 | 0 | 0 | 2 | 37 | 179 |
| EES Type of System with Exfiltration Rate 3600 mm/h | | | | | | | |
| Exfiltration | $m^3$ | 476 | 514 | 536 | 545 | 552 | 555 |
| Overland Flow | $m^3$ | 0 | 0 | 0 | 0 | 0 | 0 |
| Exfiltration as % of Conventional Stormwater Sewer Outflows | % | 76.3% | 64.2% | 53.0% | 46.6% | 40.0% | 36.1% |

For a storm of 2-h duration with a five-year return period, 53% of the stormwater sewer flow is calculated as exfiltrating to the vadose zone.

Figure 5 shows the exfiltration percentages for a 5-year recurrence, 2-h duration storm.

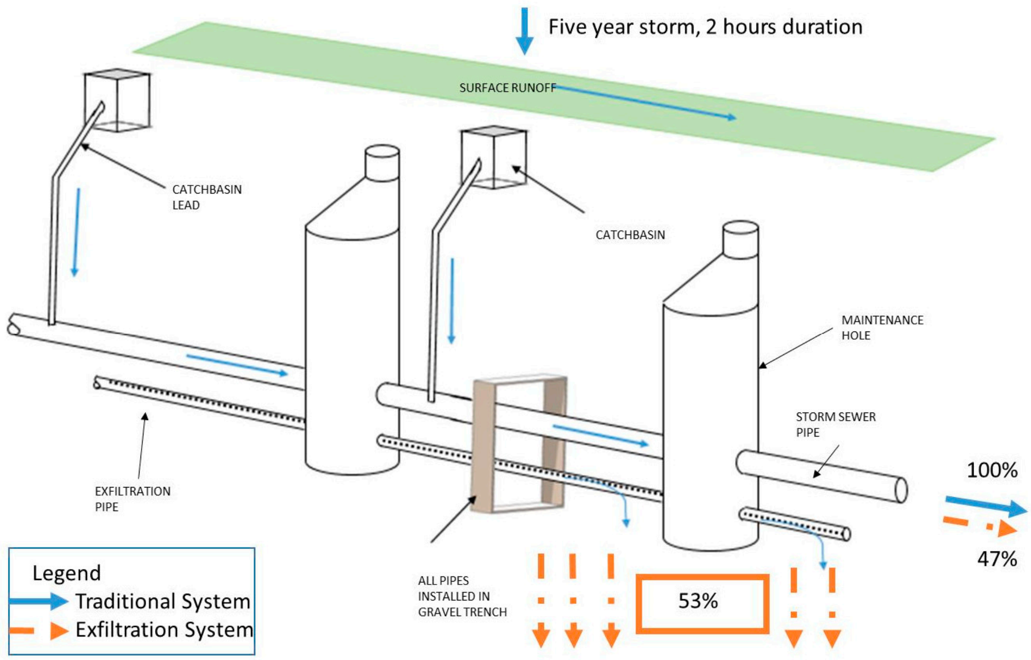


**Figure 5.** The percentage of exfiltration and runoff from the Exfiltration Pipe Storm Sewer for a 5-Year 2-h Duration Storm. Legend: Background of this figure as modified from SWAMP [33].

From these findings, the results show that the exfiltration pipe system provides extra space (assuming the sewer was designed for a 5-year recurrence storm). These results show that the exfiltration pipe system decreases urban flooding for more extreme events.

The results of the 30-min duration storm for various return periods are shown in Table 3.

**Table 3.** the quantities of exfiltration and their percentage of total outflows in sewers for a thirty-minute duration storm of various return periods.

| Return Period | Year | 0.5 | 1 | 2 | 5 | 10 | 25 | 50 |
|---|---|---|---|---|---|---|---|---|
| Duration | Min | 30 | 30 | 30 | 30 | 30 | 30 | 30 |
| Conventional Sewer System | | | | | | | | |
| Stormwater sewer Outflow | $m^3$ | 277 | 350 | 373 | 390 | 399 | 407 | 413 |
| Overland Flow (Urban Flooding) | $m^3$ | 0 | 17 | 87 | 191 | 274 | 387 | 474 |
| EES Type of System with Exfiltration Rate 3600 mm/h | | | | | | | | |
| Stormwater sewer Outflow | $m^3$ | 122 | 202 | 290 | 396 | 406 | 434 | 444 |
| Overland Flow | $m^3$ | 0 | 0 | 0 | 0 | 60 | 169 | 249 |
| Exfiltration | $m^3$ | 155 | 165 | 170 | 185 | 207 | 191 | 194 |
| Exfiltration as % of Outflow | % | 56.0% | 47.0% | 45.6% | 47.4% | 51.9% | 46.9% | 47.0% |
| Overland Flow Reduction % | % | 100.0% | 100.0% | 100.0% | 100.0% | 78.1% | 56.3% | 47.5% |

Considering a 30-min duration storm with a 5-year return period with a conventional storm sewer system, the storm sewer outflow from the case study area is 390 $m^3$ and there is urban flooding of 191 $m^3$, whereas from Table 3, there is no overland flow.

Figure 6 shows the results for both the 5-year 30-min duration and the 10-year 30-min storms, exfiltration, runoff and urban flooding percentages for the EES-type system.

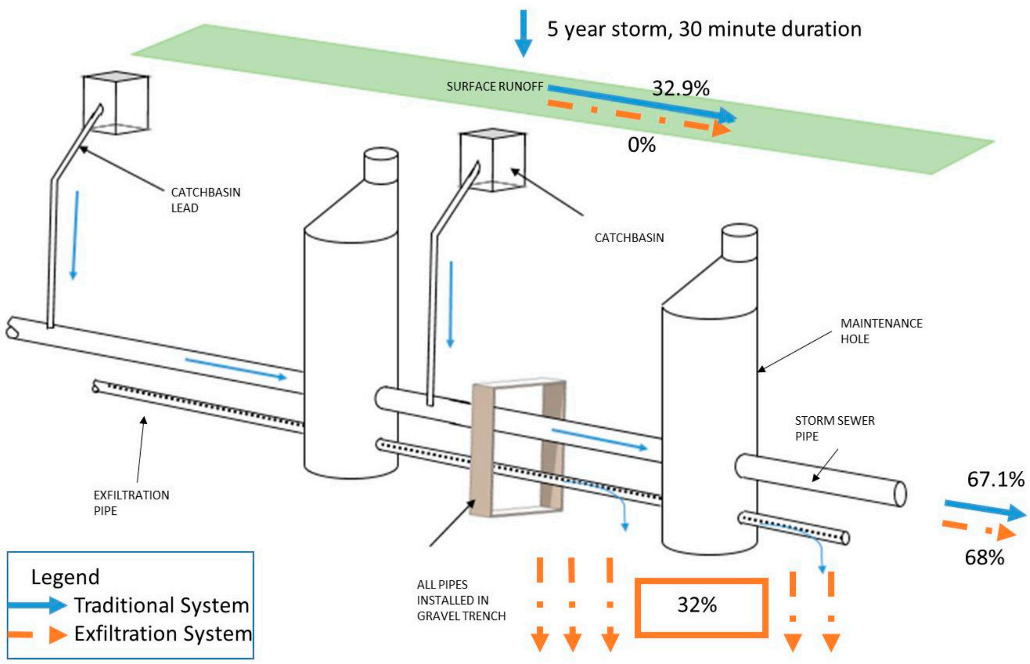


**Figure 6.** The mass balance (percentage of exfiltration, urban flooding and runoff, from exfiltration storm sewer) for 5-year 30-min duration storm.

In terms of the mass balance, the exfiltration system reduces the overland flow from 32.9% of the traditional system to 0.0% and exfiltrates 32% of the 5-year 30-min duration storm (Figure 6). For the 10-year 30-min storm, the exfiltration system reduces the overland flow from 40.7% of the traditional system to 9% and exfiltrates 31% of the storm.

For 30-min storms with return periods in the range 0.5- to 50-years, the exfiltration pipe accomplishes the following: (a) the stormwater volume flowing out in storm sewers from the study area is reduced from 56% to 47% as this amount of stormwater is exfiltrated to the vadose zone, (b) the urban flooding volume is reduced to 47% for thirty-minute storms of various return periods.

The results from this modeling approach are in line with Reference [28] for a system which had the available field measurements with a much longer perforation system.

### *3.4. Impacts on the Overland Flow*

Analyses to estimate the quantities of overland flow (urban flooding) avoided in the case study area due to the exfiltration pipe system showed that the quantities of overland flow (urban flooding) decreased due to increased availability of space in the EES type of system. The results are summarized in Table 4 for storm durations of 10-, 15-, 30- and 60-min storms and 5-year return periods. This finding is consistent with reporting in Reference [16], which indicated that except for the first length of the sewer, a reduction in the pipe size can be achieved due to this phenomenon, although reducing the pipe size often contravenes municipal standards.

**Table 4.** The quantities of overland flow (urban flooding) avoided due to increased availability of space in the sewer system because of the exfiltration pipe system exfiltration system.

| Return Period | Years | 5.0 | 5.0 | 5.0 | 5.0 |
|---|---|---|---|---|---|
| Duration | Min | 10.0 | 15.0 | 30.0 | 60.0 |
| Single Pipe Sewer System Overland Flow | $m^3$ | 126 | 165 | 191 | 90 |
| Overland Flow with Exfiltration Type of Sewer System | $m^3$ | 52 | 59 | 0 | 0 |
| Amount of Overland (urban flood) Volume Avoided with Exfiltration pipe with Exfiltration System | $m^3$ | 74 | 106 | 191 | 90 |

Table 4 shows the urban flooding volumes of the conventional single pipe storm sewer system avoided which demonstrates that considerable urban flooding for this case study site can be avoided by using the exfiltration type of system. The results demonstrate that for a storm of 30-min duration and return period of 5 years, all urban flooding amount is avoided.

### *3.5. Storage Volume Available Within the Clear Stone Pipe Bedding*

Clear Stone (gravel) bedding is a standard requirement in Canada to support storm sewers and to provide the horizontal and vertical alignment for pipes. The selected material must have two properties: (a) The ability to store exfiltration sewer water volume; and, (b) A high transmissive capacity to pass on the water to the vadose zone. Gravel bedding such as 19-mm clear stone has a very high infiltration rate in the range of 3600 mm/h [16]. The following equation was used to determine the amount of storage volume available within the clear stone pipe bedding [34].

$$V = LWD \times n \times f \tag{4}$$

where L is the length of the pervious pipe and stone, W is the width, D is the depth, n = 0.4 (void space for clear stone), and f = 0.75 (longevity factor based on native soil). Values used in the modeling are summarized in Table 5.

**Table 5.** The storage volume available for the ex-filtration amount for various lengths.

| Attribute | Value with Unit |
|---|---|
| Width | 3.0 m |
| Depth | 1.5 m |
| f (longevity factor) | 0.75 |
| n (porosity) | 0.4 |
| Length | 240 m |
| Storage Volume | 324 $m^3$ |

For a 5-year 2-h duration storm, the total exfiltration volume is less than the storage volume available within the clear stone pipe bedding infiltration trench. However, the resulting accumulated water in the infiltration trench will be exfiltrating to the vadose zone. A volume of 534 $m^3$ of exfiltrated water will be accumulated in ~2 h. However, during this time, the 324 $m^3$ volume space within the clear stone pipe bedding infiltration trench will be exfiltrating to the vadose zone. At one point in time, it can store 61% of the infiltrated amount.

### *3.6. Outflows from Infiltration Trench*

The outflow from the Infiltration trench to the vadose zone is calculated based on (after Reference [34])

$$Q = f \times (P/3{,}600{,}000) \times (2LD + 2WD + LW) \times n \quad (5)$$

where f = 0.75 (longevity factor); P = 50 mm/h (assumed native soil percolation rate); L in m (total length of the infiltration trench; D in m (depth of water in the infiltration trench); W in m (width of each infiltration trench); n = 0.4 (void space in the infiltration trench clear stone). Values used in the modeling are summarized in Table 6.

**Table 6.** The outflow from pipe bedding to the vadose zone.

| Attribute | Value with Unit |
|---|---|
| W | 3.0 m |
| D | 1.5 m |
| Length | 240 m |
| Outflow | 0.006 $m^3/s$ |

Comparing the number of 0.006 $m^3/s$ with the total exfiltration rate/m of 0.0012 $m^3/s$ shows that the infiltration trench is able to accept the volume of water exfiltrating from the lower pipe (i.e., larger than the rate of exfiltration from the perforated pipe).

### *3.7. Exfiltration Amounts on Annual Basis*

An analysis was conducted for Beijing from daily data [35] for the daily rainfall data from 1951 to 2016. Average annual numbers of rainy days falling in various total daily rainfall amount categories are listed in Table 7 and Figure 7. The average numbers of rainy days above 0.7 mm precipitation were 53 in the total historical record although, in the last five years, it increased to 78 days.

**Table 7.** The average number of rainfall days of different daily rainfall amounts.

| Daily Rainfall Amount Range | Average No. of Days with Rainfall |
|---|---|
| **Mm** | **Number** |
| >0.7 to <2.5 | 24 |
| >2.5 to <5 | 10 |
| >5 to <10 | 5 |
| >10 to <15 | 5 |
| >15 to <20 | 2 |
| >20 to <30 | 2 |
| >30 to <40 | 2 |
| >40 to <50 | 1 |
| >50 | 2 |

Based on the average number of rainfall days of specified daily rainfall quantities from the analysis, an annual potential scenario was developed by assigning durations to the daily events of one, two and three hours based on the amount of daily rainfall amounts of those events. SWMM and ExModel were run for these selected events to calculate the quantities of stormwater entering storm sewers, the quantity of exfiltration and the quantity of storm sewer outflows on an annual basis which provides the approximate percentage of the water leaving the case study area on an annual basis. The results of the analysis are shown in Table 8 and Figure 8, with 8% of volume lost to evapotranspiration and surface infiltration.

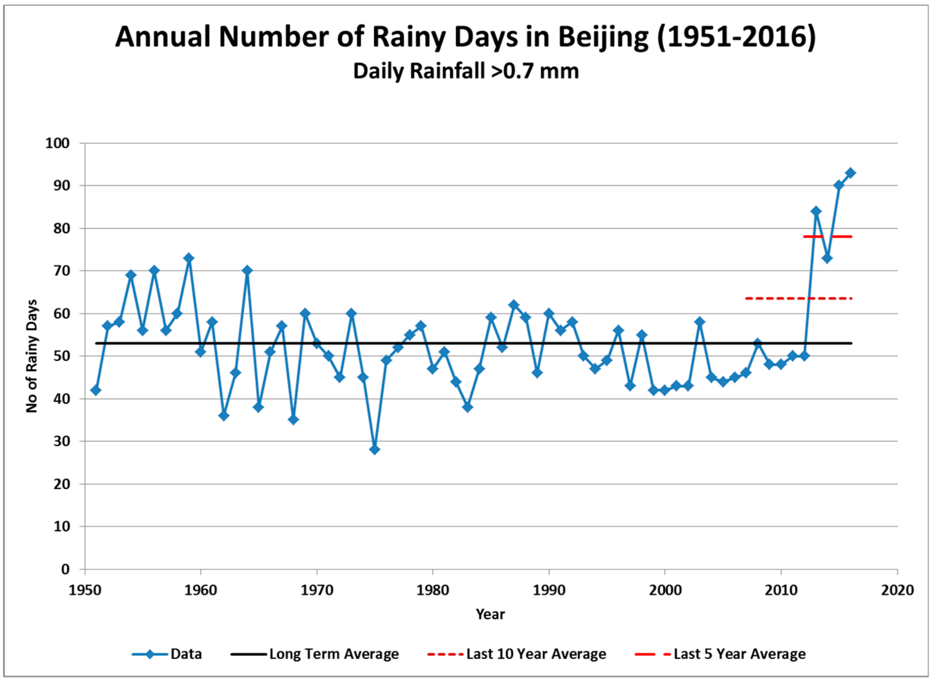


**Figure 7.** The annual number of rainy days with a precipitation of >0.7 mm in Beijing (1951–2016).

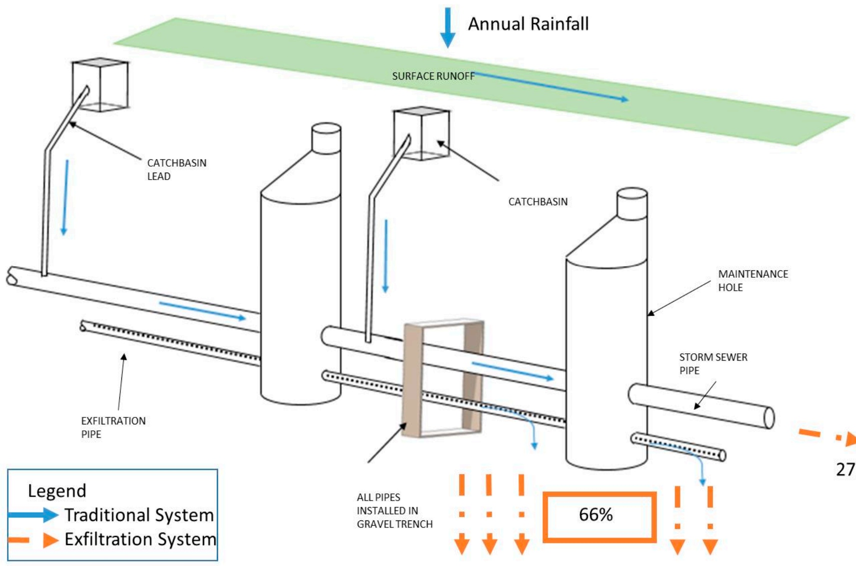


**Figure 8.** The approximate annual basin characterization of percentages of flows for the case study area (Beijing).

Table 8 shows that on an annual basis, the exfiltration system will reduce the stormwater outflow by ~66% by exfiltrating incoming stormwater inflows to the vadose zone for the case study area. Additionally, an amount of 5400 $m^3$ of stormwater is exfiltrated from the case study surface area of 14400 $m^2$. For Figure 8, overall, ~8% of the annual rainfall is lost through evapotranspiration and infiltration, ~66% of the stormwater is exfiltrated to the infiltration trench and subsequently to the vadose zone, and 27% passes through the sewer system. Hence, an estimated 71% of the water entering the storm sewer is exfiltrated to the vadose zone.

**Table 8.** The analysis of reduction in stormwater outflows leaving the case study area on an annual basis with the exfiltration pipe exfiltration system.

| One Event | | All Annual Events | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Precipitation | Duration | No of Events | Precipitation | Evaporation | Infiltration | Surface Runoff | Inflow (to Sewer) | Outflow | Exfiltration | Runoff Reduction |
| mm | min | | $m^3$ | $m^3$ | $m^3$ | $m^3$ | $m^3$ | $m^3$ | $m^3$ | % |
| 2 | 60 | 24 | 691 | 126 | 125 | 440 | 432 | 96 | 336 | 77.8% |
| 3.75 | 60 | 10 | 540 | 58 | 59 | 423 | 420 | 110 | 320 | 76.2% |
| 7.5 | 60 | 5 | 540 | 30 | 31 | 478 | 480 | 125 | 350 | 72.9% |
| 12.5 | 60 | 5 | 900 | 31 | 32 | 837 | 835 | 120 | 715 | 85.6% |
| 17.5 | 60 | 2 | 504 | 13 | 13 | 478 | 478 | 90 | 388 | 81.2% |
| 26.5 | 60 | 2 | 763 | 13 | 13 | 737 | 738 | 238 | 500 | 67.8% |
| 36 | 120 | 2 | 1037 | 18 | 17 | 1002 | 1002 | 190 | 812 | 81.0% |
| 46 | 120 | 1 | 662 | 9 | 8 | 645 | 645 | 181 | 464 | 71.9% |
| 90 | 180 | 2 | 2592 | 23 | 21 | 2546 | 2548 | 1034 | 1514 | 59.4% |
| | | Annual Basis ($m^3$) | 8230 | 321 | 321 | 7588 | 7578 | 2184 | 5399 | 71.2% |
| | | Annual Basis (%) | 100% | 4% | 4% | | | 26.4% | 65.6% | |

It is noted that the findings reported herein agree with Reference [28] in that while this technology exfiltrates sizable numbers of rainfall events to the vadose zone (e.g., 90% in the Toronto area as per [28]), this is not the same as exfiltrating 90% of the volume of annual rain (i.e., less than 90% of the actual rainfall volume).

### *3.8. Water Quality—Changes and Potential Challenges*

The success of this EES approach depends on the local conditions and cannot necessarily be transferred without appropriate consideration of possible water quality impacts. The EES type of infiltration practice should not be used in locations where it is not desirable for the reasons as described below and/or where the integrity of the groundwater quality cannot be preserved.

The main goals of Sponge City Initiatives (SCI) are to decrease urban flooding while accumulating, infiltrating and cleansing water naturally [15]. Consequently, the intent is to promote water purification and infiltration. Wang et al. (2018) [15] listed the primary technical initiatives of SCIs involving groundwater recharge as including pervious pavement, simple biodetention, permeation ponds, and artificial soil infiltration. Adoption of these SCI measures which involve infiltration, as well as the EES, can be considered for utilization but must involve the assessment of locations and appropriate measures to protect the integrity of the quality of the groundwater, e.g., to remove the pollutants from the water through urban runoff control (e.g., capture runoff from areas where the pollutants can be removed prior to entry into the storm sewer system such as filtering runoff water through vegetation to remove pollutants) and to avoid the implementation of SCIs, for example, where traffic and industrial inputs are high.

Further specific considerations regarding potential areas in which to avoid the EES type of system include:

(i) Reported results from different pieces of literature indicate that some areas should be avoided for high infiltration if there are some types of land uses which will include high levels of oil and grease and heavy metals. For example, from some areas of Guangzhou, oil and grease, suspended solids and heavy metals are reported as the dominant pollutants in stormwater [36]. Additionally, Zhang & Wang (2008) [37] reported high levels of cadmium, copper and zinc in areas of high traffic and industry and, hence, these types of areas should be avoided. However, this same study showed low metal concentrations from residential zones and parks. As Liu et al. (2005) [38] have indicated that the Total Nitrogen and Phosphorus, Total Organic Carbon and Suspended solids, are the primary stormwater pollutants in residential and commercial areas, not the heavy metals, oil and greases, etc.

(ii) Basically, areas of heavy traffic and industrial land use in metropolitan areas may aggravate pollution in stormwater (e.g., References [38,39]). Additionally, residential areas under construction should consider having remedial measures implemented during the periods of construction to restrict their potential for damage to an infiltration SCI.

(iii) For systems managing stormwater from roads in residential and commercial zones, there is need to consider the before-implementation of the infiltration of surface water runoff through consideration of differences between types of catchments as to their potential to deteriorate the groundwater quality (and this applies to all types of SCIs that infiltrate stormwater, including pervious pavements, etc., as referred above);

(iv) In addition to the above, road surface type influences stormwater quality and concrete surfaces tend to be better as they reflect source-limiting processes (as opposed to asphalt) (Liu, et al., 2014) [40].

(v) Additionally, attention must be given to areas where the surface runoff quality is poor and/or the soil is contaminated since the enhanced infiltration may result in the deterioration of the groundwater quality where there is significant potential for spills from trucks and/or hazardous spills which may cause deterioration in the groundwater quality and within wellhead protection zones.

(vi) Additional considerations related to infiltration SCIs need to be carefully evaluated prior to implementation for circumstances where ambient soils are poorly drained. EES will not work in clay soils, although lenses of granular soils may provide sufficient exfiltration opportunities to facilitate the ability for the infiltration trench to exfiltrate to ambient vadose zone and subsequently, to the groundwater. Additionally, where there are high groundwater tables; there must be free drainage to the vadose zone, in areas of steep slopes, in floodplains, and where tree root growth may be an issue [16].

With substantially lesser overland flow quantities and larger percentages of the stormwater flowing in the sewer and exfiltrating to the vadose zone, the water quality may be improved in the streams on the urban landscape by baseflow augmentation as indicated above.

## 4. Conclusions

There is widespread evidence of major flooding events in urban cities in China and, in many cases, there is groundwater extraction for water supply, resulting in land subsidence. An option that warrants consideration is the use of an exfiltration pipe system where substantial portions of the stormwater can be transferred to a lower, perforated pipe(s), and then exfiltrated to, at least in part, replenish groundwater, after ensuring that the infiltrating water will not result in damages to the water quality of the groundwater. The exfiltration type of the system decreases both flooding and subsidence. The exfiltration pipe system intentionally moves water into the environment to facilitate exfiltration from the lower pipe by ensuring large amounts of water are available for exfiltration.

There are clearly a number of benefits from the exfiltration pipe technology, (a) significant amounts of stormwater are exfiltrated to the vadose zone, (b) decreased overland flows occur, and (c) increasing recharge to a location experiencing declining groundwater aquifer.

Overall, from the computer modeling described herein, the net result for the case study area of Beijing using the exfiltration pipe design indicates the following:

I The exfiltration system substantially decreases overland flow and the lower (perforated) pipe would be able to capture, store and, subsequently exfiltrate ~53% of stormwater entering the storm sewer for the small catchment utilized for runoff from a 2-h duration, 5-year recurrence interval storm. Overall, the potential exists to exfiltrate water from the lower pipe, at levels of ~71% of the total annual rainfall for the small catchment utilized. This demonstrably increases vadose zone recharge and ultimately creates additional groundwater recharge which, in turn, will decrease subsidence in areas where this is a major concern (particularly related to coastal zone cities in China);

II Decreasing flooding from heavy storms can be accomplished (the so-called heavy storms that occur several times a year); and,

III The costs of placement of the second pipe increases the overall cost of the installation of this system (about 15%) which indicates, given the magnitudes of flooding and the resulting damages, this is a technology that warrants consideration.

Nevertheless, while there are many possible benefits of the exfiltration type of system, the utility of this technology for a particular location may be precluded due to a variety of conditions as outlined in the paper, including the potential to deteriorate the quality of the groundwater.

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