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Where does infiltrated stormwater go? Interactions with vegetation and subsurface anthropogenic features

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Abstract

The practice of stormwater infiltration is widely used to reduce the amount of urban stormwater runoff delivered to drainage systems and receiving waters. In theory, the practice recharges groundwater, leading to increased urban stream baseflow. In reality, however, little is known about the fate of infiltrated stormwater. Because urban groundwater pathways are numerous and the interactions with subsurface infrastructure (e.g. trenches, pipes, etc.) are highly complex, the spatial and temporal variability of the contribution of infiltrated stormwater to baseflow is difficult to predict. We tracked the fate of infiltrated stormwater out of an 1800 m² infiltration basin (3.5 % of its 5-ha impervious catchment) using a network of piezometers for over three years. We found that groundwater levels downslope of the basin were increased (by at least 4 m) while water levels in an array of reference piezometers lateral to the basin showed no change (dry at depths ranging 2-4 m). Monthly water balance calculations indicated that in summer, most of the infiltrated stormwater was evapotranspired by the vegetation downslope of the basin, and thus did not reach the receiving stream. In the colder months, some infiltrated stormwater did reach the stream as plant water use declined. Anthropogenic disturbances (a sewer pipe and stream re-alignment) interacted with the upper part of the plume of infiltrated stormwater, locally lowering the water table. The study provides evidence that the fate of infiltrated stormwater is complex, and that infiltrated stormwater does not always reach receiving streams as baseflow as is often assumed.

1. Introduction

As cities worldwide grow larger, native pervious soils are disturbed and sealed by largely impervious surfaces, such as roofs, roads, and pavement. This change in land surface dramatically alters the water balance of catchments, which can reduce evapotranspiration and infiltration and increase surface runoff, i.e. stormwater (Burns *et al.*, 2013). The conventional approach to manage this water has been to route it directly to receiving waters via stormwater drainage systems (Brown *et al.*, 2009). This, however, has led to the widespread erosion and ecological degradation of urban streams (King *et al.*, 2005). In response, alternative stormwater management strategies have become popular, with the aim of restoring the pre-development water balance by 1) restoring evapotranspiration through vegetated systems or mimicking it by stormwater harvesting and 2) promoting infiltration of stormwater (Fletcher *et al.*, 2014), theoretically recharging groundwater and stream baseflow. A range of technologies, such as infiltration basins (Dechesne *et al.*, 2005), infiltration trenches (Freni *et al.*, 2009; Campisano *et al.*, 2011), and porous pavement (Scholz and Grabowiecki, 2007; Mullaney and Lucke, 2014) has been used to promote the infiltration of stormwater into the ground.

Stormwater infiltration systems have proven effective at attenuating the magnitude and frequency of peak flows as well as decreasing the volumes of stormwater delivered to drainage systems at a range of scales: the site scale (~10-1000 m², e.g. Davis (2008); Hunt *et al.* (2012)), the streetscape scale (Jarden *et al.*, 2015; Wilson *et al.*, 2015) and even the catchment scale (Bhaskar *et al.*, 2016). In addition, infiltration systems theoretically

recharge groundwater, leading to increased baseflow in streams (Walsh, 2005). In low-density urban areas (typically, residential suburbs with 5-15 % impervious cover) where leakage from potable water and sewer pipes does not contribute substantially to groundwater recharge, urbanization leads to a net loss of stream baseflow, as a result of impervious areas precluding infiltration (Walsh *et al.*, 2012; Braud *et al.*, 2013). This depletion of baseflow causes a loss of in-stream habitat and changes the structure and function of stream ecosystems (Konrad and Booth, 2005). Managed stormwater infiltration and subsequent percolation to groundwater are hypothesised to compensate for the loss of recharge caused by impervious coverage, thus in theory helping to increase ecologically important baseflows. In some cases, stormwater infiltration is used to maintain high water levels to avoid rotting of wood pilings (Shoham, 2006; Beighley *et al.*, 2015; Boston Groundwater Trust, 2015).

In reality, little is known about the fate of infiltrated stormwater (Hamel *et al.*, 2011). This water could contribute to soil water and be depleted by evapotranspiration (Hamel *et al.*, 2012), or some component could recharge groundwater. The route taken by infiltrated stormwater and groundwater will control the effect that it has on groundwater storage as well as in-stream flow and water quality regimes (especially during dry weather). Understanding the fluxes and pathways of infiltrated stormwater is therefore an important pre-requisite to understanding the efficiency of stormwater infiltration as a strategy to recharge groundwater and increase stream baseflow.

Field-based evidence of stormwater infiltration influencing catchment scale hydrology is emerging. For example, some studies have linked stormwater infiltration to increased

stream baseflow (Loperfido *et al.*, 2014; Bhaskar *et al.*, 2016), while the study of Fanelli *et al.* (2017) found no effect of stormwater infiltration on baseflow. These studies use a “black-box” approach, i.e. do not look at the processes within the catchments, ignoring the route taken by infiltrated stormwater between the infiltration systems and the stream. The impact of stormwater infiltration on groundwater and stream hydrology is thus hard to predict and relies on assumptions rather than field observations (Hamel and Fletcher, 2014). Our inability to predict the fate of infiltrated stormwater reveals poor knowledge of groundwater pathways in urban catchments (Bonneau *et al.*, 2017). Disturbance of urban soils by pipes and gravel trenches containing utilities (such as sewers, potable water supply, etc.) can create preferential flow paths for groundwater and the pollutants it carries (Sharp *et al.*, 2003) which has been compared to an ‘urban karst’ (Kaushal and Belt, 2012).

In this study we aim to track the fate of infiltrated stormwater and quantify how much infiltrated stormwater contributes to stream baseflow. To do so, we monitored an infiltration basin and its surroundings using piezometers instrumented with water level probes. We tested the hypothesis that infiltrated stormwater recharges local groundwater and contributes to baseflow of a nearby stream through natural sub-surface pathways. We found that the fate of infiltrated stormwater was controlled by water use of the vegetation downslope and that the hypothesised recharge of groundwater by the infiltration basin was affected by sub-surface infrastructure between the basin and the stream.

2. Methods

2.1. *System and catchment description*

Wicks Reserve Infiltration Basin (hereafter “the infiltration basin”) is located in the eastern suburbs of Melbourne, in South-Eastern Australia (Lat -37.857°, Long 145.321°). Built in 2011, the basin is 1,800 m² in surface area and was built to achieve several objectives: 1) reduce the frequency and magnitude of high flows, 2) improve the quality of discharged stormwater, and 3) infiltrate stormwater locally with the aim of recharging groundwater and baseflow of the stream. The third objective is tested in this study. Topographically, infiltrated stormwater is expected to travel through the clay soil (sitting on weathered rhyodacite) along the head gradient from the basin (elevation 161 m) to the stream, Dobsons Creek, some 75 m downslope (elevation 153.7 m).

The infiltration basin receives stormwater from 5 ha of impervious areas (house roofs, driveways and roads) which amount to 15% of the system’s total catchment area. Mean annual rainfall of the catchment is 730 mm, reasonably evenly distributed over the year, with a winter-spring bias (averaging 73 mm month⁻¹ from June to November and 62 mm month⁻¹ from December to May). Mean annual potential evapotranspiration (PET) is 1050 mm (BoM, 2016). This means that during the warmer months, water demand from the vegetation will often exceed recharge rates. Mean monthly minimum temperatures range between 6-14°C while mean monthly maximum temperatures range between 13-26°C, and the catchment did not experience freezing during the monitoring period (2015-2018).

Impervious areas in the catchment are drained by a conventional, separated stormwater drainage system, discharging into the basin through two pipes (750 mm and 525 mm diameter). Stormwater is filtered as it percolates down the 0.8 m deep (0.4 m loamy sand-based overlaying 0.4 m of scoria gravel) filter media of the basin. There is a slotted underdrain at the base of the infiltration basin, which discharges through an elevated orifice in a discharge pit. The orifice is elevated by 0.5 m from the invert of the basin, thus creating a submerged zone to promote infiltration: when the water level in the basin is below the orifice level, no water leaves through the underdrain and only infiltration and evapotranspiration contribute to emptying the basin. For large rainfall events, excess water leaves the basin non-filtered through an overflow weir. The basin is planted with a mix of plants, including swamp grasses (e.g. *Centella cordifolia*, *Amphibromus nervosus*), sedges (e.g. *Carex appressa*), prickly shrubs (e.g. *Acacia vertillata*, *Epacris impressa*) and common spike rush (e.g. *Eleocharis acuta*). There have been historic attempts to drain the site where the basin is located (in the 1940s) and some underground constructed drainage remains. Thus, the upslope side of the basin was lined so these constructed drains do not impact the basin.

The underdrain and the overflow weir of the infiltration basin discharge into Dobsons Creek, a perennial, flashy peri-urban stream. While annual PET > Rainfall, data from forested nearby streams (similar catchment size, geology, climate) indicates that streams are perennial in this environment (Li *et al.*, 2017), though urbanization leads to the depletion of baseflow and the need to re-infiltrate stormwater (Bonneau *et al.*, 2018). Topographic contours and historical documents indicate that at this location the stream was re-aligned (for agricultural purposes) and is therefore out of its natural streambed position

(Supplementary Figure 1), which is not unusual in urban and rural catchments (Brookes *et al.*, 1983; Benke, 1990).

Soil cores were collected to a depth of 5 m from upgradient and downgradient of the basin and showed that this upper layer of soil is comprised of weathered grey silty clays with red-brown mottling formed from a weathered Devonian rhyodacite bedrock. Thus, the soil profile represents *in situ* weathered bedrock with a thin top soil (<1 m) (Figure 1). The weathered bedrock layer to 5 m depth has a clay matrix with very low hydraulic conductivity: it was measured *in situ* by conducting rising stage slug tests with the Bouwer-Rice method (Bouwer and Rice, 1976) and found to vary between $5\text{e}^{-8} \text{ m s}^{-1}$ and $5\text{e}^{-7} \text{ m s}^{-1}$ (0.005 m day^{-1} to 0.05 m day^{-1}), in bores downslope of the infiltration basin. Downslope of the basin is dominated by mature trees, mostly *Eucalyptus obliqua*, as well as dense understorey vegetation comprised of shrubs and ferns.

A sewer pipe is situated between the basin and Dobsons Creek, 35 m downslope of the infiltration basin. It runs parallel to the stream, perpendicular to the expected pathway of infiltrated stormwater (Figure 1). The sewer pipe has a 0.017 m.m^{-1} East-West gradient and flows into a pumping station which sends wastewater to a treatment plant. The sewer pipe sits in a 0.3 m wide gravel trench (measured $d_{10} \sim 0.25 \text{ mm}$), as it is standard construction practice to backfill the bottom of excavated trenches with gravel or sand. Rising stage slug tests were performed within the trench and its hydraulic conductivity was measured to range $0.9\text{--}2 \text{ m day}^{-1}$ ($1\text{e}^{-5} - 2.3\text{e}^{-5} \text{ m s}^{-1}$), some 20 to 400 times higher than the surrounding soil, similar to the findings of Sharp *et al.* (2003). An empirical formula based on grain size (Hazen formula) gave a hydraulic conductivity one order of magnitude higher, around $6\text{e}^{-4} \text{ m s}^{-1}$, even greater than the surrounding soil. Depths of the invert of the sewer pipe, measured

in manholes, are 2.3 m deep at the western end of the infiltration basin (“West Sewer”, Figure 3) and 1.2 m deep in manhole located in a transect approximately going through the centre of the basin (Transect 1, bore East Sewer, Figure 1).

2.2. *Monitoring set-up*

The basin and its surroundings were monitored to: (i) calculate the volume of infiltrated stormwater and (ii) characterise the pathway of infiltrated stormwater and test our hypothesis that infiltrated stormwater contributes to baseflow.

To track the plume of infiltrated stormwater and to monitor its impact on the water table, a network of monitoring bores was established around the basin (Figure 1). Three probes were located within the infiltration basin itself (probes Filter A, B, C). Four bores were located upslope of the basin (Upslope A, B, C, D, Figure 3) and two reference bores were located laterally away from the basin, outside of its area of potential influence (Reference A, B, Figure 3). Three extra, deeper, bores were added in July 2017 laterally away from the basin and one in the riparian zone of Dobsons Creek, away from the basin (respectively Reference C, D and East Creek, Figure 3), in order to access groundwater as previous reference bores remained dry. Two bores were located within the trench backfill and around the sewer pipe and the pumping tank to access groundwater (West Sewer and East Sewer on Figure 1). Finally, a transect of five monitoring bores located 17, 24, 30, 48 and 72 m downslope from the lower edge of the basin was installed to follow infiltrated stormwater along the expected topographic pathway to the stream. Among this down-

gradient transect of five bores, three bores were located between the basin and the sewer pipe (Bores Downslope 17, 24, 30 on Figure 1) and two bores between the sewer and the stream (Bores Downslope 48, 72 on Figure 1). This configuration allowed the impact of the sewer trench on the flow of groundwater to be observed.

Monitoring bores were 1.5-4 m deep, depending on available equipment and local constraints, and the screening interval was the bottom 0.8 m for each bore. Due to construction and administrative constraints, the bores did not penetrate to impervious bedrock and the full depth of a potentially perched aquifer (or a deeper unconfined aquifer). As a result, the bores did not record groundwater levels variations once the water level dropped below the base of each bore.

Water levels in the infiltration basin (probes Filter A, B, C) and groundwater levels were recorded respectively from March 2013 and January 2015, until October 2016. Monitoring was resumed in July 2017, to March 2018.

Water levels were monitored using capacitance probes (Odyssey Capacitance Water Level recorder, <http://www.odysseydatarecording.com/>, with a manufacturer-claimed accuracy of 0.8 mm, but a real-life accuracy around 2-3 mm). The accuracy of the probes (conductance probes) were not impacted by periods of drying. Water level in the bores was recorded every 6 minutes, with some blocks of data missing because of vandalism, flat batteries or faulty loggers (~ 25 % in total). Probes were calibrated before deployment in early 2013 (or July 2017, respectively) and again in March 2017. Over this period, the probes had a drift ranging 10-50 mm which was too small to impact the conclusions inferred. The

232 smallest calibration drift (9 mm over 4 years) was observed for the probe Filter B (Figure 3).
233 In addition, inflows and outflows of the infiltration basin were monitored every 6-min using
234 Hach Flow Sigma 950 flowmeters (www.hachflow.com/flow-meters/sigma950.cfm). These
235 recorded data were somewhat patchy, because sediments in the inflow pipes occasionally
236 interfered with the instruments. Flow data were therefore only used in this analysis to
237 detect periods with and without inflow/outflow.
238
239 Figure 1 here

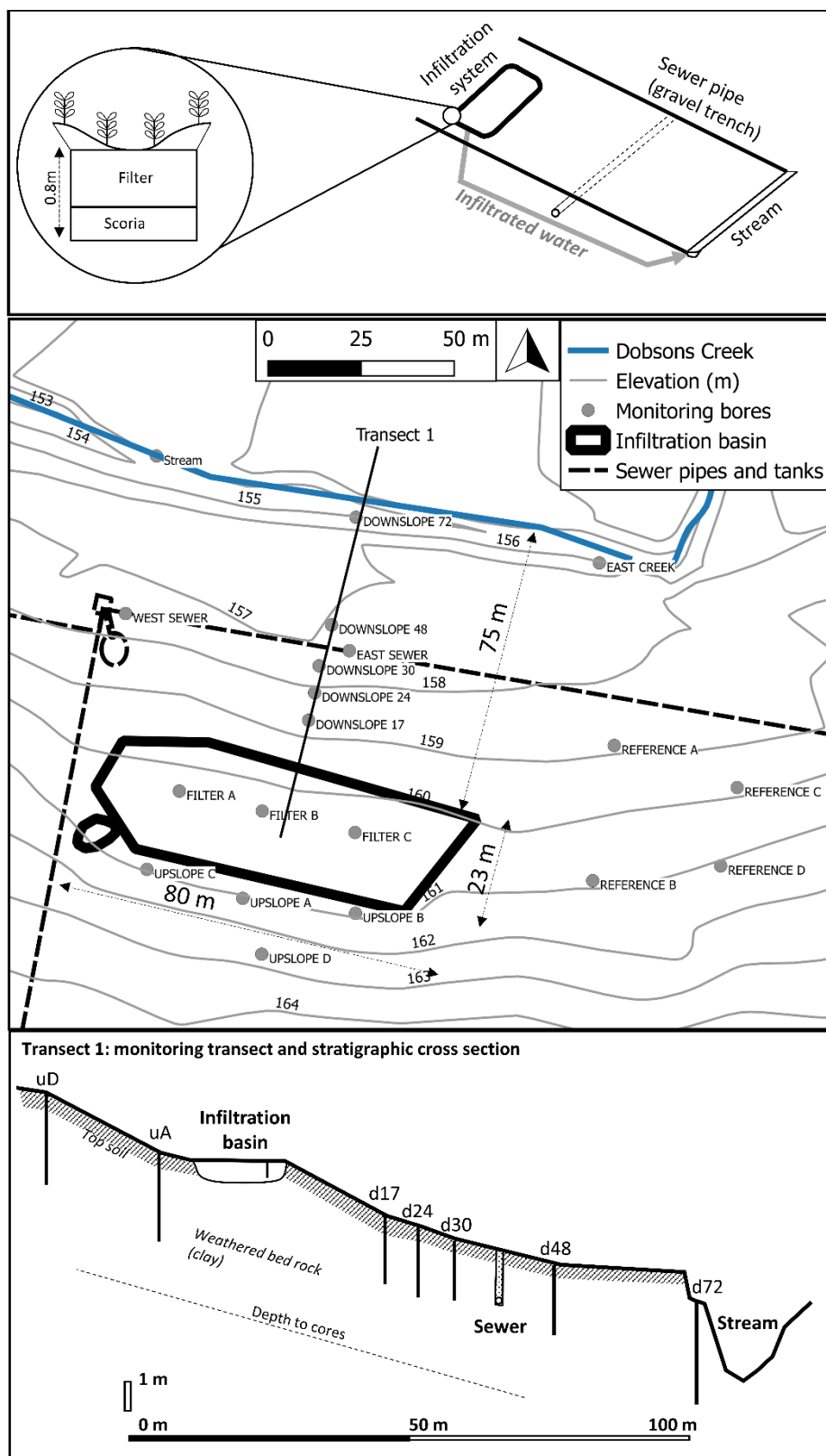


Figure 1: Infiltration basin and network of piezometers surrounding the basin. Elevation of the monitoring transect along the expected, topographic pathway of infiltrated stormwater and hydro-stratigraphic cross section.

2.3. *Estimation of the volume and the fate of infiltrated stormwater*

2.3.1. How much water infiltrated?

The volume of infiltrated stormwater leaving the basin was calculated using the variations of the water level in the basin with known dimensions. Periods when piped inflow and outflow loggers recorded zero flow were isolated. At night (between 11pm and 3am) when ET was assumed to be zero in the sandy infiltration basin (Malek, 1992; Denich and Bradford, 2010), with neither inflow nor outflow, the change in storage in the basin was assumed to be entirely due to infiltration. These periods were used to establish a relationship between the volume of infiltrated stormwater (i.e. the change in storage) and the water level in the basin. Seasonality of infiltration rates was empirically observed, so one relationship for each of (a) low water table months (November - April) and (b) high water table months (May - October) was calculated. Resulting rating curves (Figure 2) therefore provided a relationship between an infiltrated volume at a given water level in the basin and were then applied to the whole dataset (as water levels within the basin were continuously monitored) to estimate the volume of infiltrated stormwater, rating curves were also fitted to the 10th and 90th percentile of data to provide both a lower and an upper estimation of the infiltrated volume.

Perhaps surprisingly, more water left the basin in summer, when the water level within the infiltration basin was at its lowest level, than in winter. This could be explained by (1) a higher water table in winter decreasing the head gradient compared to summer months; (2)

267 a wet soil limiting the storage capacity of the soil profile during winter; (3) lower
268 temperature reducing infiltration rates (Braga *et al.*, 2007).

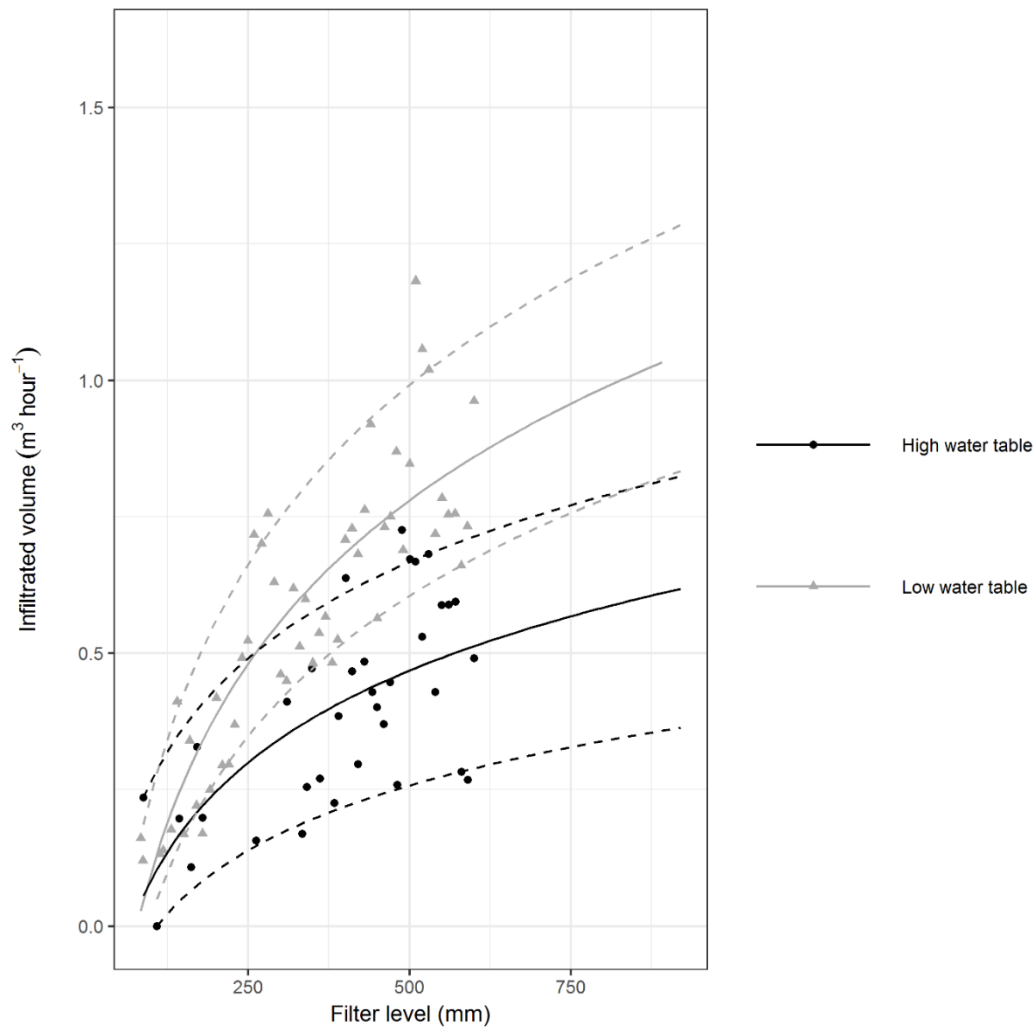


Figure 2: Relationships between the hourly change in basin storage for periods with no inflow, no outflow and no evapotranspiration (infiltrated volume) and basin level. Rating curves are formulated as $\text{Hourly volume (m}^3\text{)} = A * \ln(\text{Basin level}) + B$, with A and B being constants. Quantile regression to the 90th and 10th percentile was used to build upper and lower estimates of the infiltrated volume, in order to reflect scatter and uncertainty.

2.3.2. How much water was lost to evapotranspiration?

The volume of infiltrated stormwater consumed by the vegetation downslope of the basin, over a rectangular plane going from the edge of the basin to the sewer pipe and a width of a 100 m was calculated with a monthly water balance. When $ET > \text{Rainfall}$, rainfall could not satisfy the water demand by the vegetation, and the trees were assumed to access phreatic water (i.e. the plume of infiltrated stormwater and $ET - \text{Rainfall}$ was subtracted from the plume). Conversely, when $ET < \text{Rainfall}$, rainfall was assumed to be sufficient to satisfy the water demand by the vegetation, and excess rainfall was assumed to percolate down to the phreatic store, contributing a volume ($\text{Rainfall} - ET$) to the plume of infiltrated stormwater. Reference crop evapotranspiration was sourced from the Australian Bureau of Meteorology that use the Penman-Monteith equation (FAO56, Allen (1998)), with data from a nearby weather station (Australian Bureau of Meteorology Station 086266, Lat -37.87, Lon 145.35, 5 km from the site). Because the relationship between the reference crop ET and actual ET from the vegetation was unknown three varying crop factor coefficients were tested: 0.8, 1, 1.2 (Myers *et al.*, 1996; Worledge *et al.*, 1998)

2.3.3. How much water was lost to the 'urban karst'?

To test the possibility that infiltrated stormwater could seep into the sewer pipe through cracks and fissures, data of the sewer pump use from June 2004 to March 2018 was obtained from the local water authority (South East Water). Pump water use during night time (from 1:00 AM to 4:00 AM), when domestic use was minimal and the relative impact of

a leak would be the highest, was compared for periods before and after construction of the infiltration basin. A video inspection of the pipe was also conducted by the local water authority.

To test whether the high-permeability trench around the sewer pipe (backfill gravel) diverted infiltrated stormwater from its topographical pathway (Supplementary Figure 2), Darcy's equation was used to calculate the water fluxes within the gravel trench, perpendicular to the topographic pathway, using the piezometric data and measured hydraulic conductivity. In addition, two qualitative dye experiments were conducted, by placing, respectively, 60 L and 50 L of water with rhodamine (concentrations in excess of 1 mg/L) into the bore located just upslope of the sewer pipe (Bore Downslope 30 on Figure 1) on 27/01/2016 and 23/01/2018. Respectively 7 days later (02/02/2016) and 2, 23 and 29 days later (25/01/2018, 15/02/2018 and 21/03/2018), rhodamine concentrations were measured in bores upslope, downslope and within the sewer trench.

2.3.4. How much water contributed to baseflow?

From these estimations, the monthly volume of infiltrated stormwater available to potentially reach the stream (as baseflow) was calculated as (Equation 1, Figure 3):

$$Baseflow = Inf - ETf + Direct\ recharge - Diverted\ flows \quad (1)$$

Where:

- *Baseflow* was the volume of infiltrated stormwater potentially contributing to the stream baseflow (unknown).

- *Inf* the volume of water infiltrated from the basin (calculated with rating curves as detailed previously in Section 2.3.1.).
- *ETf + Direct recharge* was the volume of water either transpired from the plume by the vegetation or recharged to the plume by rainfall (as detailed previously in Section 2.3.2.)
 - When $Rainfall > ET$, $ETf = 0$ and $Direct\ recharge = Rainfall - ET$
 - When $Rainfall < ET$, $Direct\ recharge = 0$ and $ETf = ET - Rainfall$.
- *Diverted flows* represent any potential interception or diversion of infiltrated stormwater by the urban karst (as detailed previously in Section 2.3.3.).

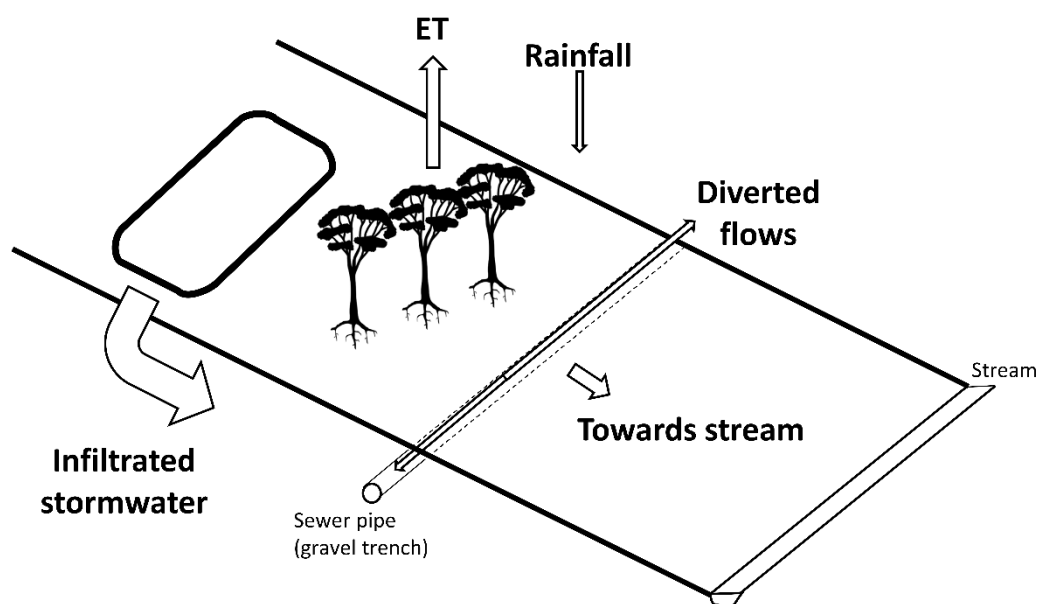


Figure 3: Conceptual water balance of the plume of infiltrated stormwater. Infiltrated stormwater will be consumed by downslope vegetation in dry months, or rainfall will contribute to the plume in wetter months. Some water seeps into the sewer network, and the rest is available to flow towards the stream.

3. Results

3.1. *Water level variations*

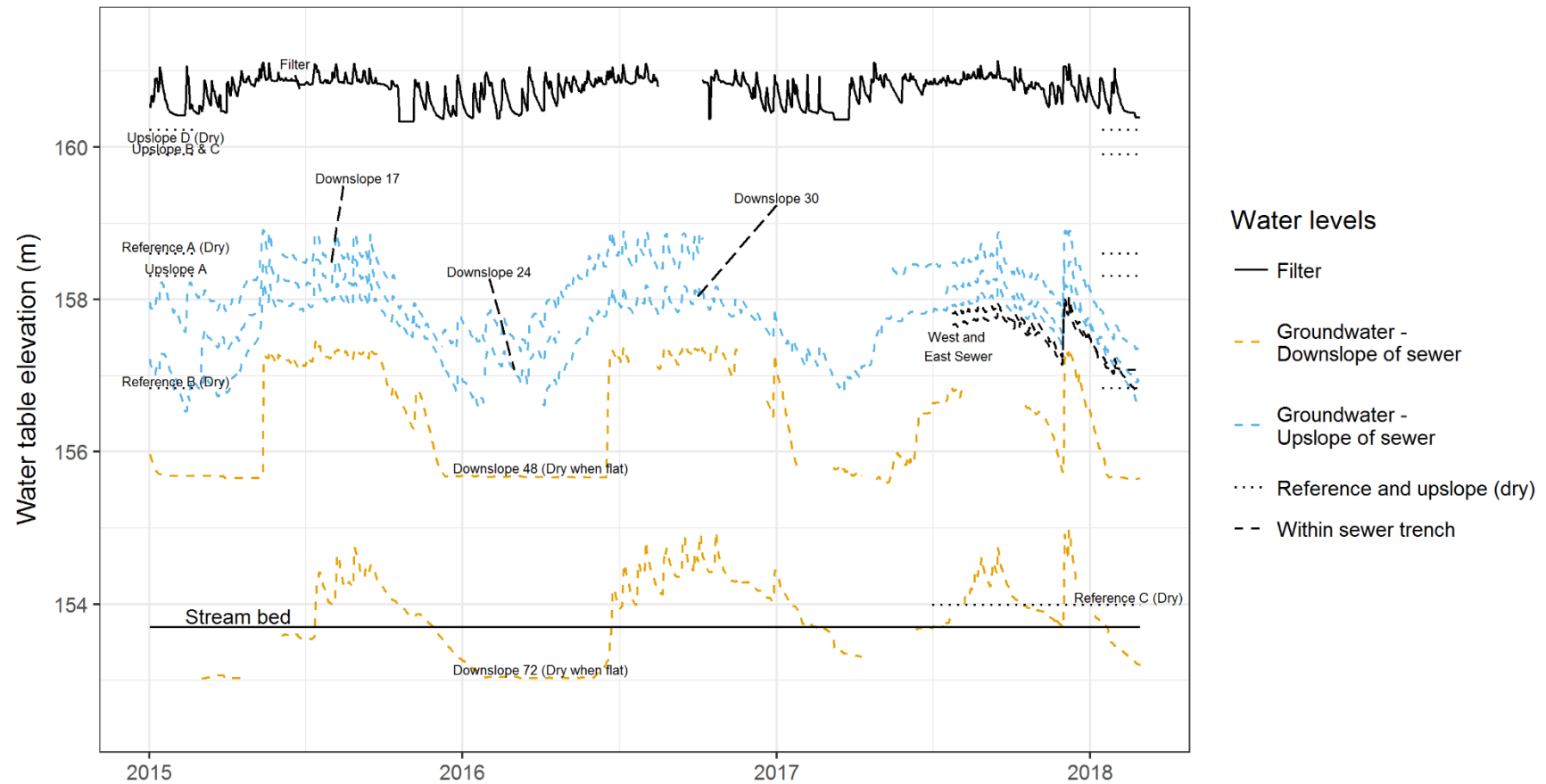
The water level within the infiltration basin showed both seasonal behaviour and responses to individual rain events (Figure 4). In summer (November-March, “low water level months”, Figure 4), the basin emptied over a few days after filling. In winter (April-October, “high water level months”, Figure 4), the basin never fully emptied, and the water level remained higher than 0.3 m deep, with some small peaks during rainfall events, resulting in permanent outflow to the stormwater network through the elevated underdrain.

Bores located upslope (Upslope D, Figure 1) and laterally (Reference A, B, C, D, Figure 1) away from the basin were not deep enough (ranging 1.5 – 4 m) to observe groundwater and were dry during the entire monitoring period. The other bores upslope of the basin (Upslope A-B-C, Figure 1) were mostly dry, except for the wetter months of the year when they showed flashy groundwater responses after rainfall. The rapid variations of the water level in these bores were responses to rainfall events (carried by underground constructed drains, a legacy of past land use) and were not seasonal variations of the local water table.

In contrast, water was consistently observed in the three bores located just downslope of the basin (Downslope 17, 24, 30, Figure 1). In these bores, groundwater levels varied both seasonally and with rainfall events, coinciding with variations of the water level in the basin. Similar variations were not observed in the reference bores laterally away or upslope of the

basin, which remained dry over the study period, inferring that infiltrated stormwater had raised groundwater levels downslope of the infiltration basin (Figure 4 and 5). In winter (April – October), the water table was as shallow as 0.5 m below the ground surface and reached depths between 0.1 m and 0.25 m below the ground surface during events. In summer (November – March), the water table fluctuated around 1.5 m below the ground surface. Infiltrated stormwater developed a permanent mound downslope of the basin for at least the first 30 m down-slope from the basin (Figure 5).

Figure 4 here (water levels).



370

371 Figure 4: Variations of groundwater elevation for the water level within the basin (Filter), bores downslope between the basin and the sewer
 372 trench (Downslope 17, 24, 30), and bores between the sewer trench and the stream (Downslope 48, 72), for which flat lines represent a dry
 373 bore. Dry reference and upslope bores levels are marked.

The groundwater level data in both bores located downslope of the sewer pipe (Downslope 48 and 72) gave zero values from January-February to May-June. Regular (weekly to fortnightly) site inspections confirmed that the bores were dry and during this period the water table was deeper than 1.9 m just downslope of the sewer pipe (Bore Downslope 48, 155.6 m). Bore Downslope 72, located in the riparian zone, was dry while the stream is perennial and never stopped flowing. Conversely, in from May-June to November-December, a seasonal increase of the water table resulted in groundwater being intersected in the bores downslope of the sewer trench (Downslope 48 and 72, Figure 1 and 4), that then also showed responses to individual rain events. The transition from dry bores to bores intersecting the water table happened very rapidly. On 14/05/15, the water level just downslope of the sewer pipe (bore Downslope 48) went from less than 155.92 m (dry) to 157.4 m in 6.2 hours (a > 1.48 m change). Similarly, on 20/06/2016, the water level went from less than 155.92 m (dry) to 156.8 m in 16.6 hours. These rapid variations were not consistent with seasonal groundwater variations as observed in bores located upslope of the sewer trench, suggesting activation of preferential pathways carrying water rapidly. For comparison, the seasonal water level rise of bores Downslope 17 and 30 took around one month in 2015 and three months in 2016.

The most downslope bore (bore Downslope 72, Figure 1, located in the riparian zone of the stream), recorded water levels deeper than the stream bed (Figure 4 and 5) and remained dry for extended periods of time. The infiltration basin therefore contributed no baseflow to the stream through the expected topographic pathway during February-June. During the rest of the year, the water table next to the stream was higher than the stream bed (Figure 4 and 5). The reference bore also located in the riparian zone but away from the basin (East

Creek, Figure 1) showed similar behaviour: water level below the streambed in summer and above the streambed in winter (Supplementary Figure 3). Groundwater levels in the riparian zone (bore East Creek, minimum observed 154.6 m, Supplementary Figure 3) were higher than the bottom of the deepest reference bore (Reference C, that remained dry at 154 m), indicating that water in the riparian bores was recharge from stream water (i.e. losing stream recharging the riparian zone) rather than groundwater from upper parts of the catchment, potentially with some contribution from the plume of infiltrated stormwater in Downslope 72.

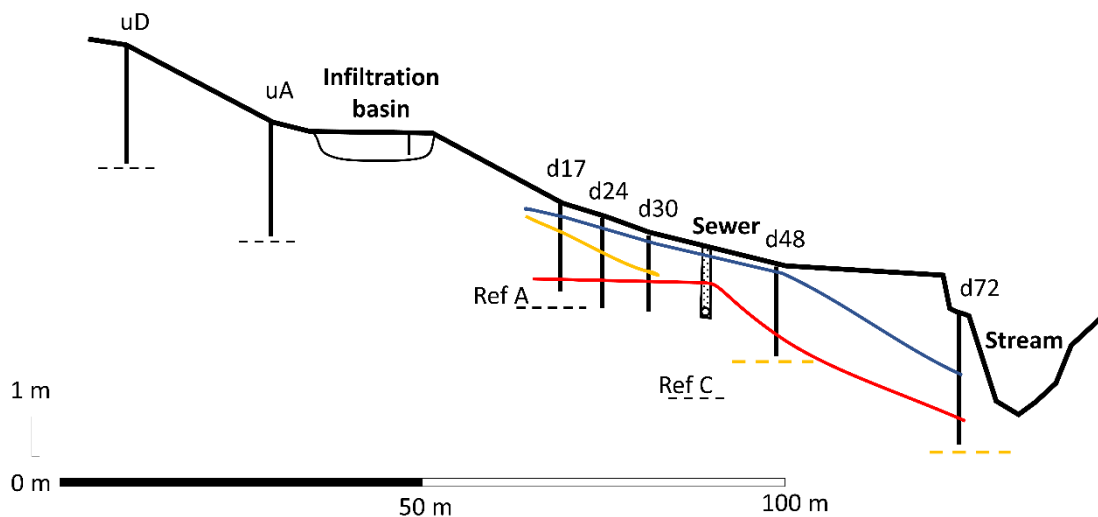


Figure 5: Transect from the infiltration basin to the receiving stream with water levels observed during high water conditions on 14/09/2016 (blue line), during low water conditions on 10/05/2016, (yellow line), and for the lowest recorded level in Downslope 17 on 25/01/2018, (red line). Water was not observed upslope or away from the basin and downslope of the sewer trench during low water conditions.

3.2. *Volume and fate of infiltrated stormwater*

3.2.1. How much water infiltrated?

An average of $395 \text{ m}^3 \text{ month}^{-1}$ ($\approx 12 \%$ of annual rainfall, or 8 mm month^{-1}) infiltrated from the infiltration basin to the ground, with some seasonal variations (averaging $361 \text{ m}^3 \text{ month}^{-1}$ from November to April and $430 \text{ m}^3 \text{ month}^{-1}$ from May to October, Panel A, Figure 6). The minimum monthly volume happened in March 2017 (216 m^3 , or 4 mm of runoff, as the basin was closed for half of the month) and the maximum in December 2017 (614 m^3 , or 12.2 mm of runoff). Upper and lower estimates of the rating curves resulted in monthly infiltrated volumes being on average, respectively 37% higher or 36% lower than the mean estimate (pink ribbon, Panel A, Figure 6).

3.2.2. How much water was lost to evapotranspiration?

For months when ET was higher than rainfall (typically from October to March), the vegetation downslope of the infiltration basin accessed phreatic water (i.e. the plume of infiltrated stormwater) to satisfy the fraction of the water demand rainfall could not supply. This volume ($\text{ET} - \text{Rainfall}$) averaged $164 \text{ m}^3 \text{ month}^{-1}$ ($3.3 \text{ mm month}^{-1}$, 5.2% of annual rainfall) and ranged $20\text{-}380 \text{ m}^3 \text{ month}^{-1}$, nearing the volume of infiltrated stormwater at the height of summer (Panel B, Figure 6). The percentage of infiltrated stormwater consumed by the vegetation downslope, in summer, averaged 42% with large monthly variations ($4 - 100\%$).

438

439 In contrast, for months with rainfall higher than ET (typically from April to September-
440 October), the contribution of rainfall recharge to the area influenced by the plume of
441 infiltrated stormwater averaged $138 \text{ m}^3 \text{ month}^{-1}$ (2.8 mm of runoff) and ranged 0-410 m^3
442 month^{-1} (0-8.2 mm month^{-1}). The resulting groundwater response (i.e. infiltrated
443 stormwater + rainfall recharge) was observed in bores downslope of the sewer trench
444 (Downslope 48 and Downslope 72). The three crop factors tested (0.8, 1, ,1.2) had little
445 impact on the calculations: the upper and lower estimates of ET resulted in evapotranspired
446 or recharged volumes within 4 %, on average, of mean values (green ribbon, panel A, Figure
447 6).

448

449 Figure 6 here (water balance graphics)

450

451

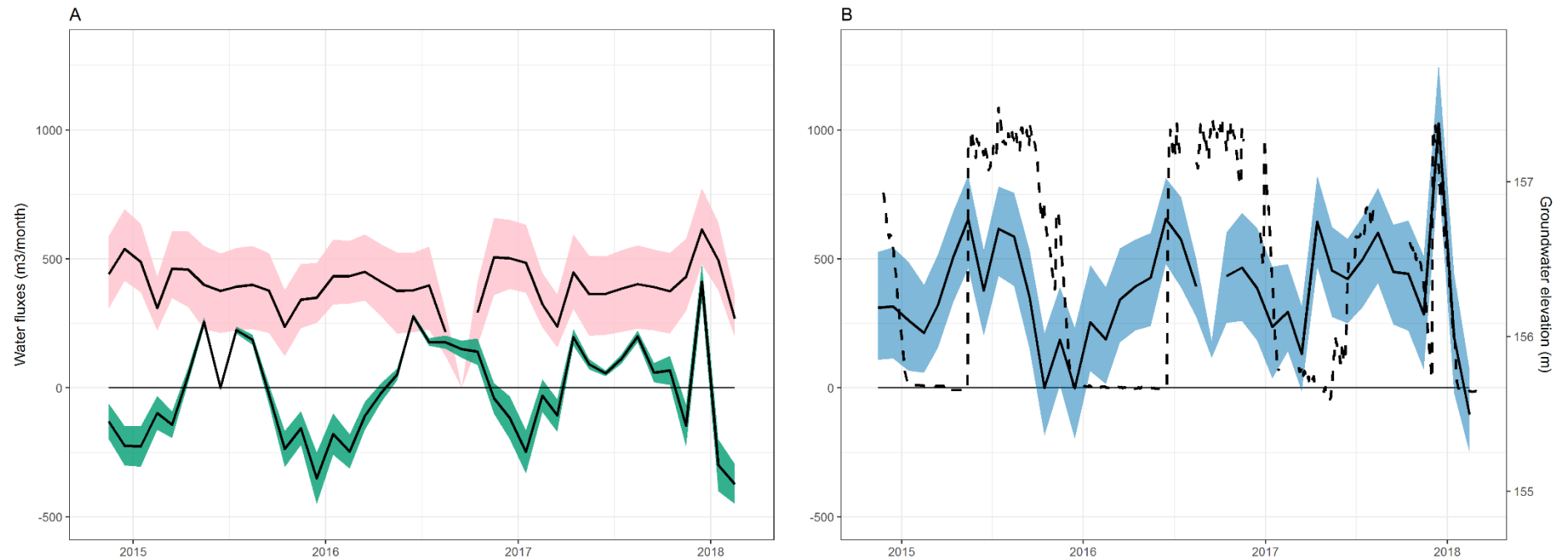


Figure 6: Panel A presents the monthly volume infiltrated from the basin to the surrounding environment (pink ribbon) and the monthly volume Rainfall – ET flux in $\text{m}^3 \text{ month}^{-1}$ (green ribbon). For comparison, 1000 m^3 is equivalent to 20 mm of runoff from 5 ha of impervious areas. The pink ribbon shows the range given by upper and lower rating curves. In green, positive values indicate recharge of rainfall to phreatic water, negative values indicate consumption of infiltrated water by the vegetation. Panel B shows the sum of the infiltrated volume and the recharge or consumption downslope of the basin (full line), as well as the daily water level downslope the sewer trench (dashed line). The blue ribbons present the higher and lower estimate of this volume. When the vegetation consumes most of the infiltrated stormwater, the bore downslope of the sewer trench is dry, whereas when tree consumption diminishes, infiltrated stormwater flows pass the sewer trench towards the stream.

3.2.3. How much water was lost to the 'urban karst'?

Analysis of the sewer pump water use showed a significant increase in the night time pumping time (i.e. the time when the pump is running, at night, from 1AM to 4AM) since the construction of the basin (Panel A, Figure 7). Pump running time from 1AM to 4AM averaged 9 min in 2004-2011, while it averaged 12 min in 2013-2018 (t-test p-value < 0.001). The median pump running time was 7 min for 2004-2011 and 12 min for 2013-2018 (Mann-Whitney p-value < 0.001). While this difference did not appear major, 5 extra minutes of pumping at a rate of the order of magnitude $1\text{-}10\text{ l s}^{-1}$ was high enough to suggest leakage into the pipe and to impact the water balance of the plume of infiltrated stormwater. The video inspection conducted by the local water authority indicated no seepage, possibly because volumes of infiltrated stormwater leaking into the pipe are much smaller than total volumes of wastewater flowing down the pipe, or possibly because the video did not inspect the locations of leakage.

Water levels within the gravel trench showed the presence of a small head gradient, variable with surrounding groundwater levels, within the gravel trench ($\sim 0.1\text{ m}$, Panel B, Figure 7). The equivalent Darcian flow rate was $1.6\text{ e}^{-7}\text{ m}^3\text{ s}^{-1}$ or $0.01\text{-}0.02\text{ m}^3\text{ month}^{-1}$. The gradient was mostly one direction (going East to West) but reversed in response to a large rainfall event. The inconsistent flow directions were likely due to the sewer trench following the local topography which did not show a clear gradient laterally away from the infiltration basin (Figure 1).

484 In spite of the water fluxes within the trench being small, the dye tests suggested some flow
 485 of infiltrated stormwater in the gravel trench surrounding the sewer pipe during the
 486 summer period (low water table), albeit with complex patterns. The 2016 test was followed
 487 by a period of rising water levels in the surrounding bores in response to a 48 mm rainfall
 488 event and dye was then observed in the sewer trench (bore West Sewer) but not in the
 489 downstream bores (Table 1). The 2018 test was completed during a period of falling water
 490 levels and no dye was observed in the sewer trench or downstream bores, that were dry
 491 (Table 1, Supplementary Figure 3), indicating no movement of water along the trench.

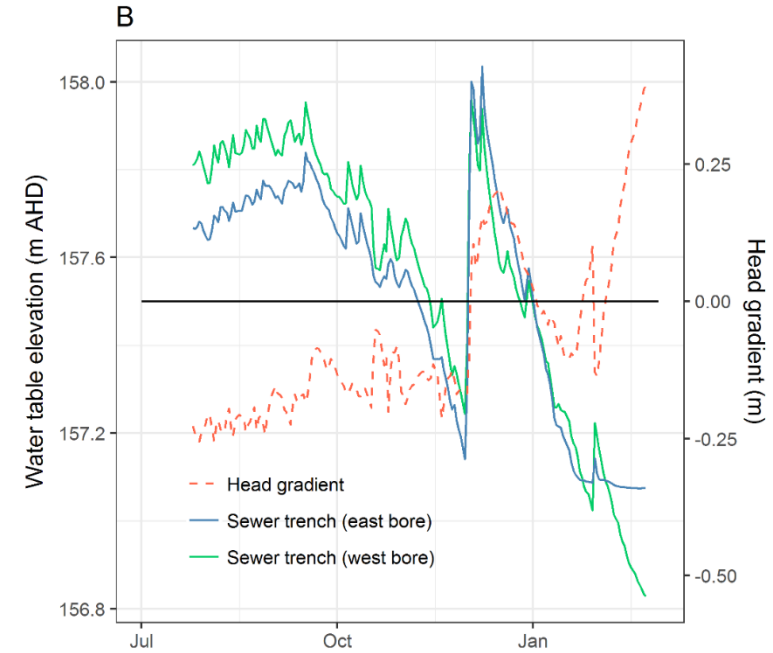
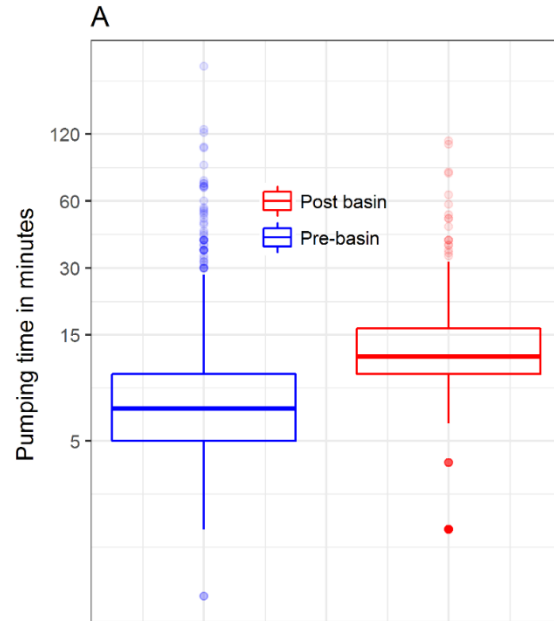
492

Rhodamine concentrations	First test: 2016		Second test: 2018			
	27/01	02/02	23/01	25/01	15/02	21/03
Upslope bores DS17, DS24	None	None	None	None	None	None
Input bore DS30	1000s $\mu\text{g/L}$	1000s $\mu\text{g/L}$	1000s $\mu\text{g/L}$	1000s $\mu\text{g/L}$	1000s $\mu\text{g/L}$	Dry
ST East	None	None	None	Dry	Dry	Dry
ST West	None	32 $\mu\text{g/L}$	None	None	None	None
DS 48	Dry	Dry	Dry	Dry	Dry	Dry

493

494 *Table 1: Results of both dye tests. The dye was poured in bore Downslope 30 and*
 495 *surrounding bores were tested days after.*

496



497

498 *Figure 7: Panel A: Boxplot of the night pump use before-after the construction of the basin. Panel B: Water levels in the gravel trench*
 499 *surrounding the sewer pipe and equivalent head gradient from July 2017 to February 2018. The gradient alternates between East-West and*
 500 *West-East, depending on surrounding groundwater fluctuations.*

501 .

3.2.4. How much water contributed to baseflow?

The sum of monthly infiltrated volumes and evapotranspired or recharged volumes downslope of the basin, averaged $385 \text{ m}^3 \text{ month}^{-1}$ ($7.7 \text{ mm month}^{-1}$), ignoring the impact of sewer infrastructure. Upper and lower estimate, using respectively upper/lower rating curves and low/high crop factors were 63 % higher and 59 % lower, on average, than the mean estimate (blue ribbon, Panel B, Figure 6). These volumes, after subtraction of the volume that seeped into the sewer infrastructure, were in theory available for baseflow.

However, seasonality was strongly pronounced: from November to March (typically when ET depleted the plume) the volume of water available to flow downslope of the sewer trench averaged $296 \text{ m}^3 \text{ month}^{-1}$ ($5.9 \text{ mm month}^{-1}$), with estimates ranging $105 - 503 \text{ m}^3 \text{ month}^{-1}$. These volumes were not observed in bores Downslope 48 and 72 and did not contribute to baseflow. From April to October (typically when rainfall recharged the plume), these volumes averaged $451 \text{ m}^3 \text{ month}^{-1}$ (9 mm month^{-1}), ranging $303-594 \text{ m}^3 \text{ month}^{-1}$, and were sufficient to raise groundwater levels downslope of the sewer trench and water was observed in bores Downslope 48 and 72. The higher groundwater levels observed in bore Downslope 72 during this period were consistent with shallow groundwater supporting stream baseflow.

4. Discussion

4.1. *Contribution to baseflow and mechanisms at play*

The infiltration basin was designed with the assumption that some infiltrated stormwater would recharge groundwater and thus increase stream baseflow. This assumption was partly challenged by our data. Although infiltrated stormwater did produce a groundwater mound, infiltrated stormwater did not make it to the stream as baseflow for almost half the monitoring period (water table below the streambed, i.e. stream was losing). During these periods the plume of infiltrated stormwater was consumed by downslope vegetation and some water was diverted by the sewer infrastructure (pipe and trench). In winter, however, the assumption was validated. When plant water use was lower, the water table rose and saturated both the sewer trench and the possible leak into the sewer pipe, and infiltrated stormwater then flowed towards the stream. Groundwater levels were then above the streambed next to the stream, consistent with local baseflow being contributed by the infiltration basin. Water in the riparian bore (Downslope 72), however, was likely a mix between infiltrated stormwater from the basin, rainfall recharge and alluvial recharge from the stream.

At this location, the median streamflow is $0.0193 \text{ m}^3 \text{ s}^{-1}$ ($1167 \text{ m}^3 \text{ day}^{-1}$), and its 10th percentile is $0.0051 \text{ m}^3 \text{ s}^{-1}$ ($439 \text{ m}^3 \text{ day}^{-1}$), with peaks during rainfall events being one to two orders of magnitude higher. The stream and its tributaries are 7.2 km long, which result in linear baseflow contribution ranging $0.75 - 2 \text{ mm day}^{-1} \text{ km}^{-1}$. This contrasts with daily

infiltrated volumes ranging $10\text{--}20 \text{ m}^3 \text{ day}^{-1}$. (i.e. $0.2\text{--}0.4 \text{ mm}$) over a 100 m reach, i.e. a maximal potential contribution of $2 - 4 \text{ mm day}^{-1} \text{ km}^{-1}$. As such, any contribution of the basin to baseflow is a small fraction of streamflow, unlikely to be detectable by standard flow monitoring, but represents an increase in comparison to 'natural' conditions without an infiltration basin. While the magnitude of 'natural' baseflow contributions along this particular reach are unknown, the observed conditions (e.g. lateral bores to the infiltration basin being dry and riparian bores being below the streambed level during summer) suggest that this reach of stream would get little to no baseflow at any time of the year without the contribution of the plume of infiltrated stormwater. The groundwater plume contributing to increased groundwater levels in the riparian zone is evidence that along this reach, the infiltration basin increased baseflow per unit of stream length.

Our water balance model did not take into account any interception of rainfall by the canopy of the vegetation downslope of the basin. Doing so would reduce the amount of recharge to the plume of infiltrated stormwater and increase the amount of infiltrated stormwater consumed by the plants (because the vegetation would have access to less rain water to satisfy its demand). As a result, the sum infiltrated volume – consumption (or + recharge) would be even lower, which would further lower the available volume of infiltrated stormwater to contribute to baseflow.

4.2. *Evapotranspiration and local hydro-geological context*

Water use by the vegetation was the main control of water levels downslope of the infiltration basin and the fate of infiltrated stormwater. This contrasts with the work of Hamel *et al.* (2012) and Hamel *et al.* (2011) that found infiltrated stormwater to have little impact on local ET. Their infiltration system was adjacent to shallow rooted grass whose evapotranspiration rates were energy-limited, rather than water-limited. The combined effect of these two factors meant that the infiltration basin they studied had little impact on vegetation water use in all but the driest climatic conditions. In this present study, in the same climate, the infiltration basin was however upslope of deep-rooted, dense vegetation with mature trees whose water use was much higher than shallow-rooted grass and could also extract water from deeper soil layers. For most of the monitoring period, especially in summer months, plant water use reduced the volume of the plume of infiltrated stormwater. In summer, the volume lost to evapotranspiration neared the infiltrated volume and lowered groundwater levels. The seasonality observed in groundwater levels was mostly due to the catchment being in a water-limited environment. In a wetter, energy-limited catchment, shallow groundwater levels might have been even more consistent across the year. Similarly, the same infiltration basin, in the same soil, but upslope of shallow-rooted vegetation or impervious urban surfaces would have led to higher water levels all year round and higher baseflow contributions.

The groundwater mound observed downslope of the basin was influenced by the local clay soil having low hydraulic conductivities and low specific yield, and thus not favouring rapid lateral or vertical flow. This situation favours mounding of water in shallow soil layers. In

other environments, with more permeable soils that promote vertical movement of infiltrated stormwater, a shallow water table may not form, and infiltrated water would percolate down to a deeper groundwater table, as is the case for infiltration basins in the highly permeable glaciofluvial aquifers around Lyon, France (Foulquier *et al.*, 2009; Mermillod-Blondin *et al.*, 2015) or the sandy aquifers of Perth, Australia (Locatelli *et al.*, 2016). In such environments, the lateral flow in the phreatic zone would likely be too deep to interact with roots or any typical urban sub-surface infrastructure. This highlights the importance of local context in the fate of infiltrated stormwater (in particular hydraulic conductivities and depth to bedrock or the aquifer), as well as the importance of the placement of systems to maximize performance in terms of groundwater recharge and baseflow contribution.

4.3. Impact of anthropogenic disturbances on groundwater levels and the water balance

During the monitoring period, the water level in the bore located upslope of the sewer trench (Downslope 30, Figure 1) sat constantly higher than the nearby sewer infrastructure (the pumping stations, pipes, pits, detention tanks, gravel trench). The water level data suggests an impact of the sewer pipe and trench on groundwater flow. Darcy's analysis showed that the flow within the gravel trench was not a major flux of water. However, pump use data (increased night consumption after the construction of the basin) indicates that a part of the plume might be seeping into the wastewater network and being pumped

out from the catchment, rather than contributing to streamflow. The sewer trench captured flow and filled up the trench: while the lateral flux away was not large, almost insignificant, the filled trench allowed leakage into the sewer pipe. This interaction between sewer infrastructure and the plume of infiltrated stormwater influenced the position of the unconfined water table, contributing to a local decrease of water level and dry bores downslope of the trench in summer months, a period when baseflow contributions are most critical. In winter months, when ET was low, the water level downslope of the basin rose and remained high and shallow. The high-water table quickly saturated the sewer trench and the seep, resulting in it having little influence on the groundwater flow to the bore just downslope (Downslope 48). This volume of water then flowed towards the stream, as the bore located next to the stream (Downslope 72) also recorded a sudden rise in water at the same time.

This conceptual understanding of the fate of infiltrated stormwater assumes that most of the flow of infiltrated stormwater is restricted to the upper layers of soil (first 5 m), based on our cores that shown very low permeability soil at 5 m. At this depth, there are no roots, and a significant amount of water could only find its way down through geological fractures at the interface between soil and bedrock (Lachassagne *et al.*, 2011; Lachassagne *et al.*, 2014). These fractures are unknown to us, and were not detected during while coring.

It is not known where the natural streambed of this reach of the stream should be. The local topography indicates that the stream should likely meander across a field 500 m downslope (Supplementary Figure 1), and that the current stream reach is an agricultural realignment across a clay profile. Realignment of the stream has potentially disconnected the stream

from its 'natural' water table, transforming this reach into a losing reach. In that case, it is likely that some groundwater flows below the streambed and below the monitoring set up, towards where the 'natural' streambed would lie.

While these observations (sewer infrastructure and stream re-alignment) may appear 'unique' to this one particular site, such complications very likely apply at most urban settings. Urban streams often have their trajectory re-aligned, transformed, altered, and are sometimes even buried or lined with concrete (Elmore and Kaushal, 2008). This modification of stream channels severely alters any interaction between surface water and the groundwater system. Underground gravel trenches and cracked pipes used to house utilities are also common to all urban settings, even low-density peri-urban areas. The field set-up in this study represents quite a simple scenario with only a single trench located perpendicular to a short topographic flow path, yet even in this simple set up urban features introduce some complexities in groundwater movement. Mechanisms of groundwater transport and pathways across urban catchments are likely to be highly variable, but the data presented herein provides evidence that the fate of infiltrated stormwater is likely to be different than expected from travel through natural, topographic pathways. Stormwater infiltration may not always lead to contributions to stream baseflow, as '*humans are geological agents*' (Sharp and Garcia-Fresca, 2003; Sharp, 2010).

4.4. *Management implications*

Shallow groundwater levels and sustained groundwater mounding suggest that this infiltration basin would not be ideal directly upstream of urbanization, given the geological context of low-permeability soils. An elevated water table could interact with building foundations and create stability issues. This issue has been demonstrated by modelling studies (Endreny and Collins, 2009; Roldin *et al.*, 2013). The data observed in this study provide evidence of raised, shallow water tables downgradient of infiltration basins. Groundwater mounding has been observed experimentally as a temporary and short-lived phenomenon (Nimmer *et al.*, 2009; Machusick *et al.*, 2011; Price *et al.*, 2013) with dissipation of groundwater peaks with distance to the infiltration systems (Nemirovsky *et al.*, 2015), though in the present case the mound was sustained over time. Substantial construction downslope of the basin should therefore consider high levels of groundwater and could require specific structural engineering.

The water quality impact of the plume of infiltrated stormwater remains untested and is an important area for future research. The basin will remove some pollutants (e.g. nutrients) through filtering in the sandy media, though some more mobile pollutants (e.g. heavy metals, herbicides) might travel with the plume of infiltrated stormwater. In addition, a constantly elevated water table and higher soil moisture downslope of the basin raise the risk of mobilisation of pollutants already present in the soil (Roy and Bickerton, 2012). Such a basin upslope of a decommissioned petrol station, for example, could pose a risk of aquifer and stream contamination. This work also has implications for wastewater treatment plants. Infiltrated stormwater seeping into the network might lead to increased

volumes of wastewater, potentially saturating treatment plants and networks as well as increasing costs. Groundwater seeping into sewer networks is a well-observed phenomenon (Wittenberg and Aksoy, 2010).

The results of this study suggest the need for careful consideration of type of stormwater control measures applied, and the location and scale of infiltration basins. Stormwater infiltration should not be considered as the sole means to return more natural flow regimes in urban streams; meeting these objectives requires a suite of technologies, including systems that reduce overall flow volume by means such as harvesting and use of the water for human purposes (Walsh *et al.*, 2015). Ideally this would leave only the “natural” proportion of rainfall to be infiltrated, rather than attempting to infiltrate the large additional runoff volume caused by impervious areas.

Designers of infiltration systems could ideally first undertake an analysis of geology and existing subsurface infrastructure in the surrounding area, in order to predict the likely pathway and fate of infiltrated water. Given the complications observed in this study, which took place in a tight clay environment not favouring infiltration, the question of appropriate scale of infiltration systems should form part of the design. For example, it may be preferable to build several smaller infiltration systems distributed throughout a catchment, rather than a large downstream system, to minimise the risk of major site-specific disturbance to the natural pathway of infiltrated water.

5. Conclusions

This study tracked a plume of infiltrated stormwater from an 1800 m² infiltration basin using an extensive network of piezometric data. It was found that:

- The presence of the infiltration basin raised groundwater levels to around 0.25 – 1.5 m just downslope of the basin, in contrast to the upstream reference depth of < 3-4m (Figure 5).
- The plume of infiltrated stormwater formed a shallow groundwater mound in the low-permeability soil, and flowed along the expected topographic pathway towards the urban stream for about 30 m.
- A significant amount of infiltrated stormwater was consumed by vegetation downslope, especially in the warmer months (up to 100% for some months).
- As often in urban settings, the stream was locally realigned. In addition, the upper part of the plume of infiltrated stormwater was intersected by underground sewer infrastructure with potential seepage into the wastewater network. In summer, the combination of tree water use, realignment and sewer interactions resulted in no infiltrated stormwater flowing towards the stream: the water table near the stream was below the streambed.
- In winter, as ET decreased, groundwater levels increased, and infiltrated stormwater flowed towards the stream: groundwater levels were then higher than the (altered) streambed and likely contributed to baseflow.

722 Improving our understanding of the fate of infiltrated stormwater is crucial to improve our
723 understanding of urban stream hydrology and water quality. Ultimately, the success of
724 alternative approaches towards stormwater management which focus on stream protection
725 or restoration will rely on our understanding of these fluxes.

726

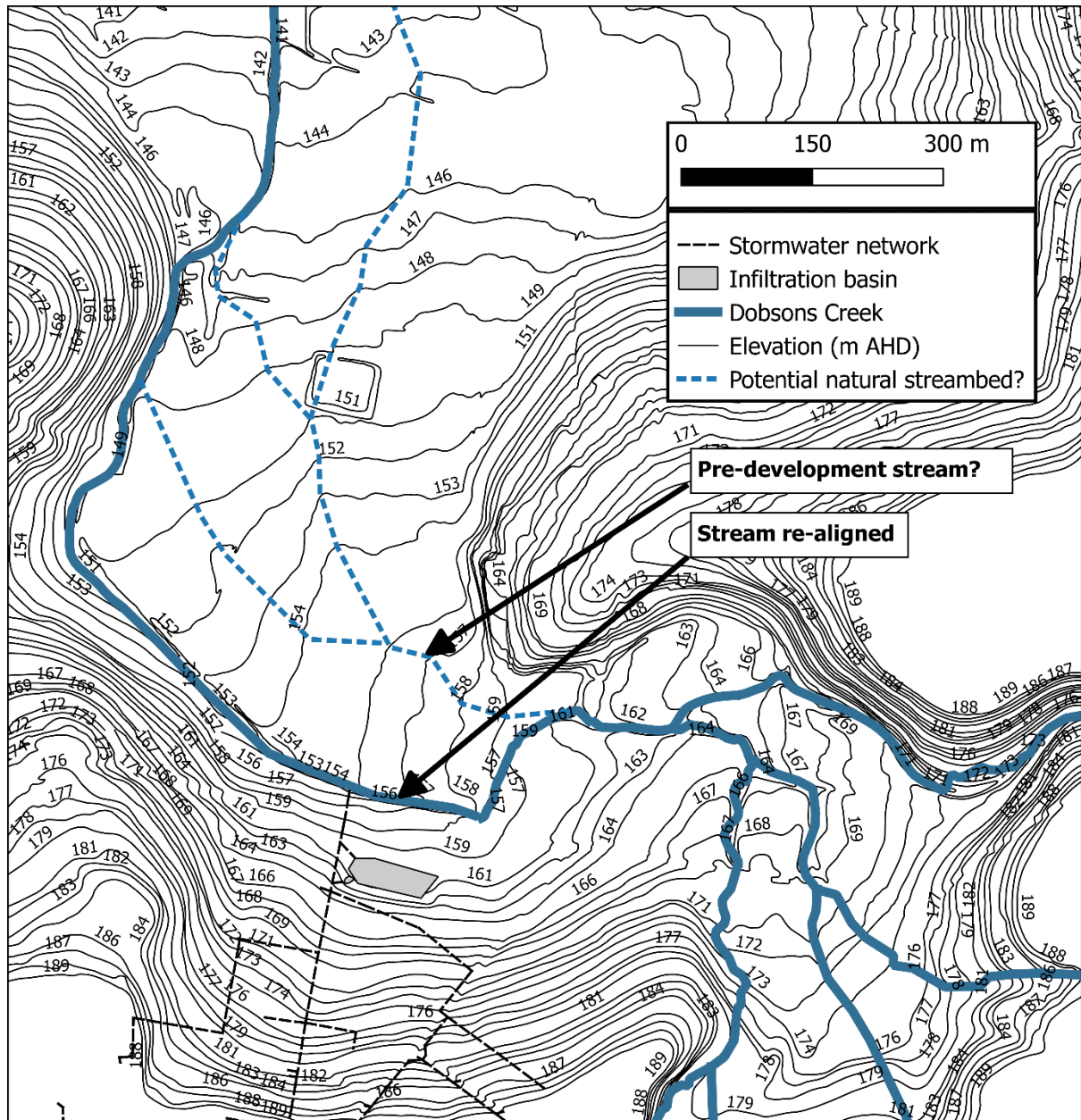
727

728 **Acknowledgments**

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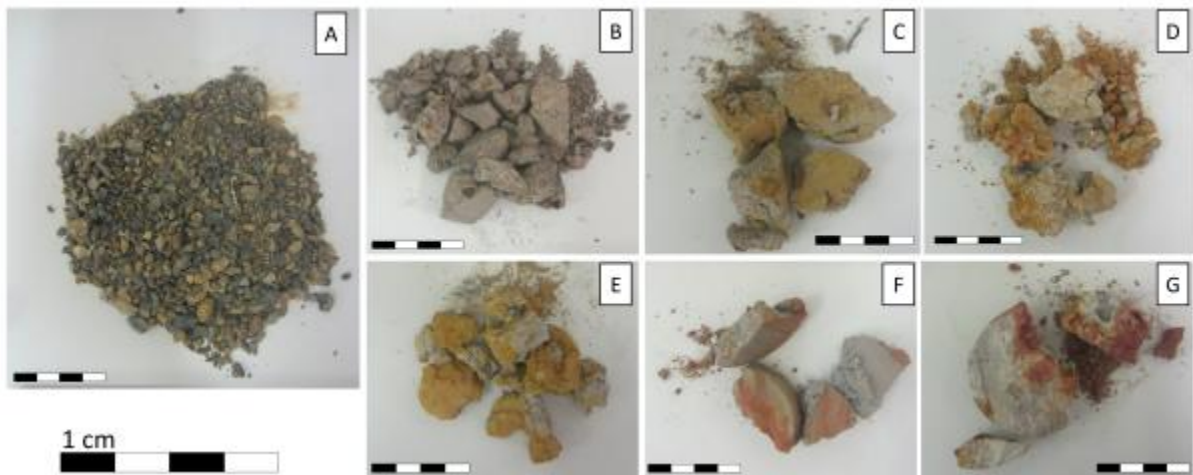
Supplementary material

Supplementary Figure 1:



Topographic contours of the area with the infiltration basin (grey polygon), the stormwater network (black dotted lines) and the current stream bed trajectory (full blue lines). Dotted blue lines are proposed pre-development streambeds based on topographic contours, as the reach near the infiltration basin is likely a re-alignment dating back early European settlers in the area to use the land as farmland.

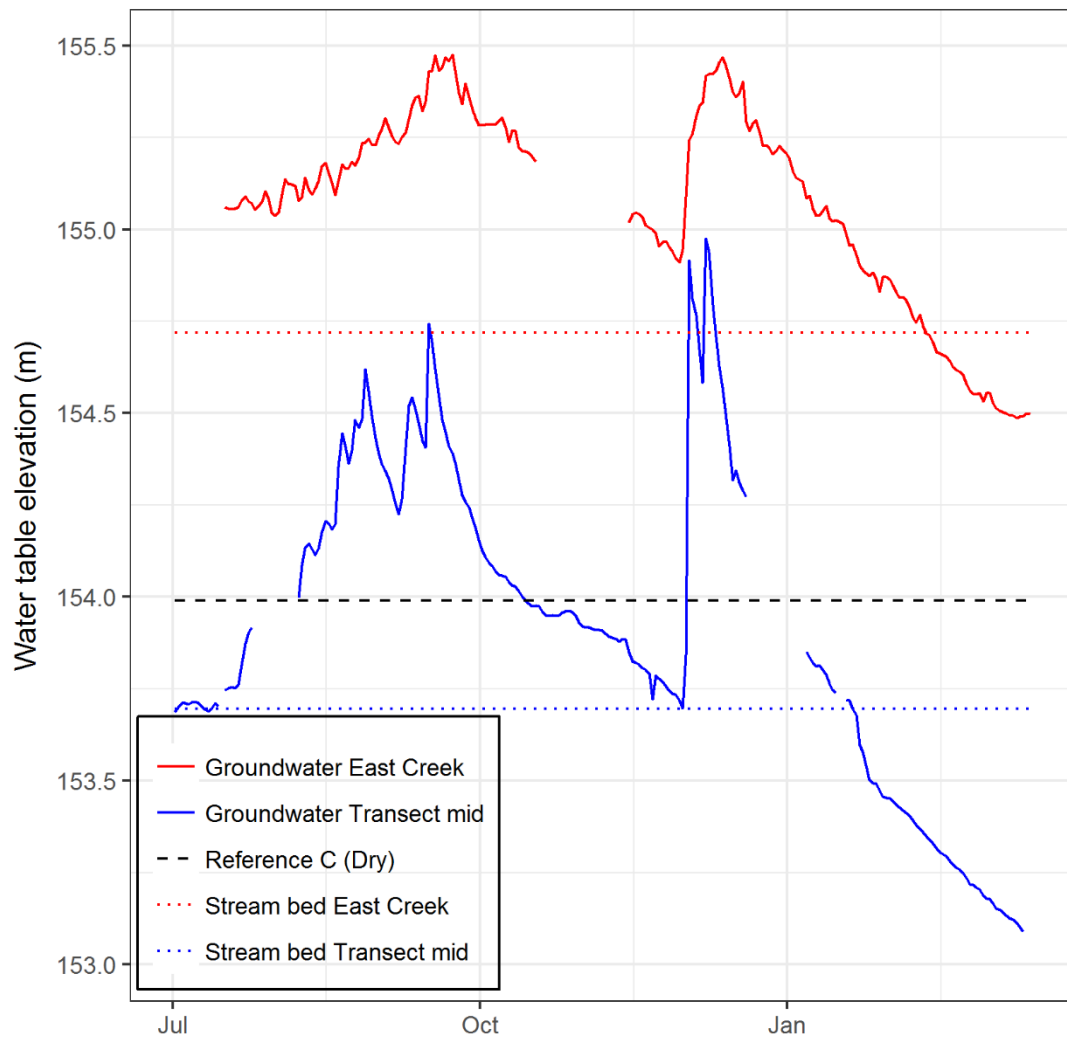
Supplementary Figure 2



Photograph of the gravels surrounding the sewer pipe (A), with a measured d_{50} of 2mm.

Other photographs are fragmented samples of the native clay soil at different depth of the soil profile: 0.5 m (B), 1 m (C), 2 m (D), 3 m (E), 4 m (F), 5 m (G).

Supplementary Figure 3:



Water level elevation in both bores located in the Riparian zone (full line) relative to their local stream-bed elevation (dotted line) and dry bore Reference C (black dashed line). Bore Downslope 72 is in blue and bore East Creek in red.

Figure 10 consists of two panels, A and B, each showing rainfall and elevation data. Panel A covers the period from January 25 to February 15, 2018, while Panel B covers the period from January 15 to March 15, 2018. Both panels include a rainfall bar chart at the top and an elevation line chart below. The elevation chart shows five data series: Downslope 17 (black squares), Downslope 24 (orange squares), Downslope 30 (light blue squares), Downslope 48 (green squares), and Sewer trench West (dark blue squares). Annotations indicate specific events such as 'Input', 'Sample', 'High', 'Dry', and 'None'.

44

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