



HAL
open science

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

Jeremie Bonneau, Tim D Fletcher, Justin F Costelloe, Peter J Poelsma,
Robert B James, Matthew J Burns

► To cite this version:

Jeremie Bonneau, Tim D Fletcher, Justin F Costelloe, Peter J Poelsma, Robert B James, et al.. Where does infiltrated stormwater go? Interactions with vegetation and subsurface anthropogenic features. *Journal of Hydrology*, 2018, 567, pp.121-132. 10.1016/j.jhydrol.2018.10.006 . hal-03557619

HAL Id: hal-03557619

<https://hal.science/hal-03557619v1>

Submitted on 4 Feb 2022

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

25 **Abstract**

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

45

46 1. Introduction

47

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

63

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

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

81

82 In reality, little is known about the fate of infiltrated stormwater (Hamel *et al.*, 2011). This
83 water could contribute to soil water and be depleted by evapotranspiration (Hamel *et al.*,
84 2012), or some component could recharge groundwater. The route taken by infiltrated
85 stormwater and groundwater will control the effect that it has on groundwater storage as
86 well as in-stream flow and water quality regimes (especially during dry weather).
87 Understanding the fluxes and pathways of infiltrated stormwater is therefore an important
88 pre-requisite to understanding the efficiency of stormwater infiltration as a strategy to
89 recharge groundwater and increase stream baseflow.

90

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

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

104

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

113

114 2. Methods

115 2.1. *System and catchment description*

116

117 Wicks Reserve Infiltration Basin (hereafter “the infiltration basin”) is located in the eastern
118 suburbs of Melbourne, in South-Eastern Australia (Lat -37.857°, Long 145.321°). Built in
119 2011, the basin is 1,800 m² in surface area and was built to achieve several objectives: 1)
120 reduce the frequency and magnitude of high flows, 2) improve the quality of discharged
121 stormwater, and 3) infiltrate stormwater locally with the aim of recharging groundwater and
122 baseflow of the stream. The third objective is tested in this study. Topographically,
123 infiltrated stormwater is expected to travel through the clay soil (sitting on weathered
124 rhyodacite) along the head gradient from the basin (elevation 161 m) to the stream,
125 Dobsons Creek, some 75 m downslope (elevation 153.7 m).

126

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

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

152

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

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

162 Soil cores were collected to a depth of 5 m from upgradient and downgradient of the basin
163 and showed that this upper layer of soil is comprised of weathered grey silty clays with red-
164 brown mottling formed from a weathered Devonian rhyodacite bedrock. Thus, the soil
165 profile represents *in situ* weathered bedrock with a thin top soil (<1 m) (Figure 1). The
166 weathered bedrock layer to 5 m depth has a clay matrix with very low hydraulic
167 conductivity: it was measured *in situ* by conducting rising stage slug tests with the Bouwer-
168 Rice method (Bouwer and Rice, 1976) and found to vary between $5e^{-8} \text{ m s}^{-1}$ and $5e^{-7} \text{ m s}^{-1}$
169 (0.005 m day^{-1} to 0.05 m day^{-1}), in bores downslope of the infiltration basin. Downslope of
170 the basin is dominated by mature trees, mostly *Eucalyptus obliqua*, as well as dense
171 understorey vegetation comprised of shrubs and ferns.

172

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

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

187

188

189 2.2. *Monitoring set-up*

190

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

194

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

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

212

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

219

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

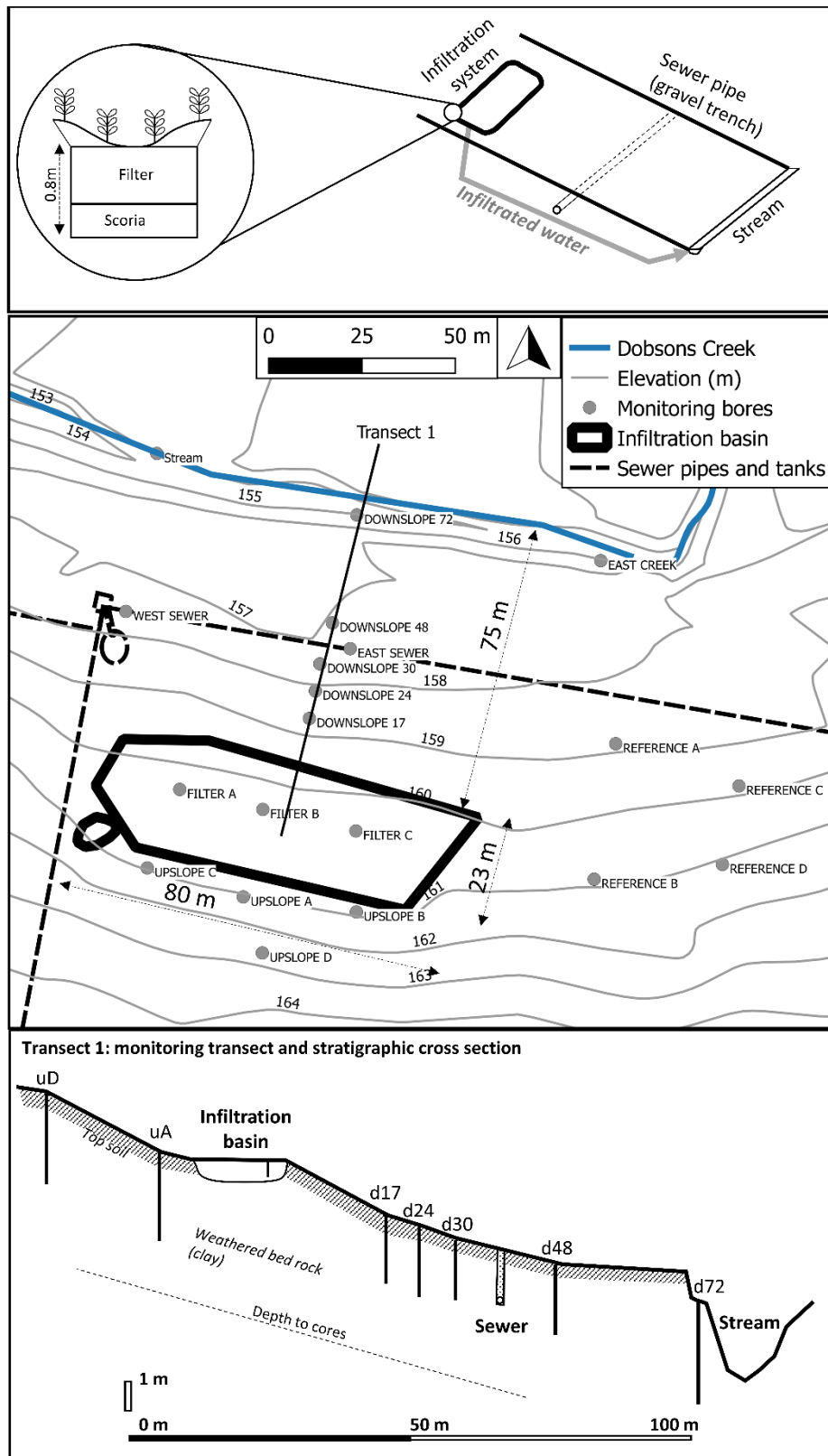
223

224 Water levels were monitored using capacitance probes (Odyssey Capacitance Water Level
225 recorder, <http://www.odysseydatarecording.com/>, with a manufacturer-claimed accuracy
226 of 0.8 mm, but a real-life accuracy around 2-3 mm). The accuracy of the probes
227 (conductance probes) were not impacted by periods of drying. Water level in the bores was
228 recorded every 6 minutes, with some blocks of data missing because of vandalism, flat
229 batteries or faulty loggers (~ 25 % in total). Probes were calibrated before deployment in
230 early 2013 (or July 2017, respectively) and again in March 2017. Over this period, the probes
231 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



240

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

244

245 2.3. *Estimation of the volume and the fate of infiltrated stormwater*

246

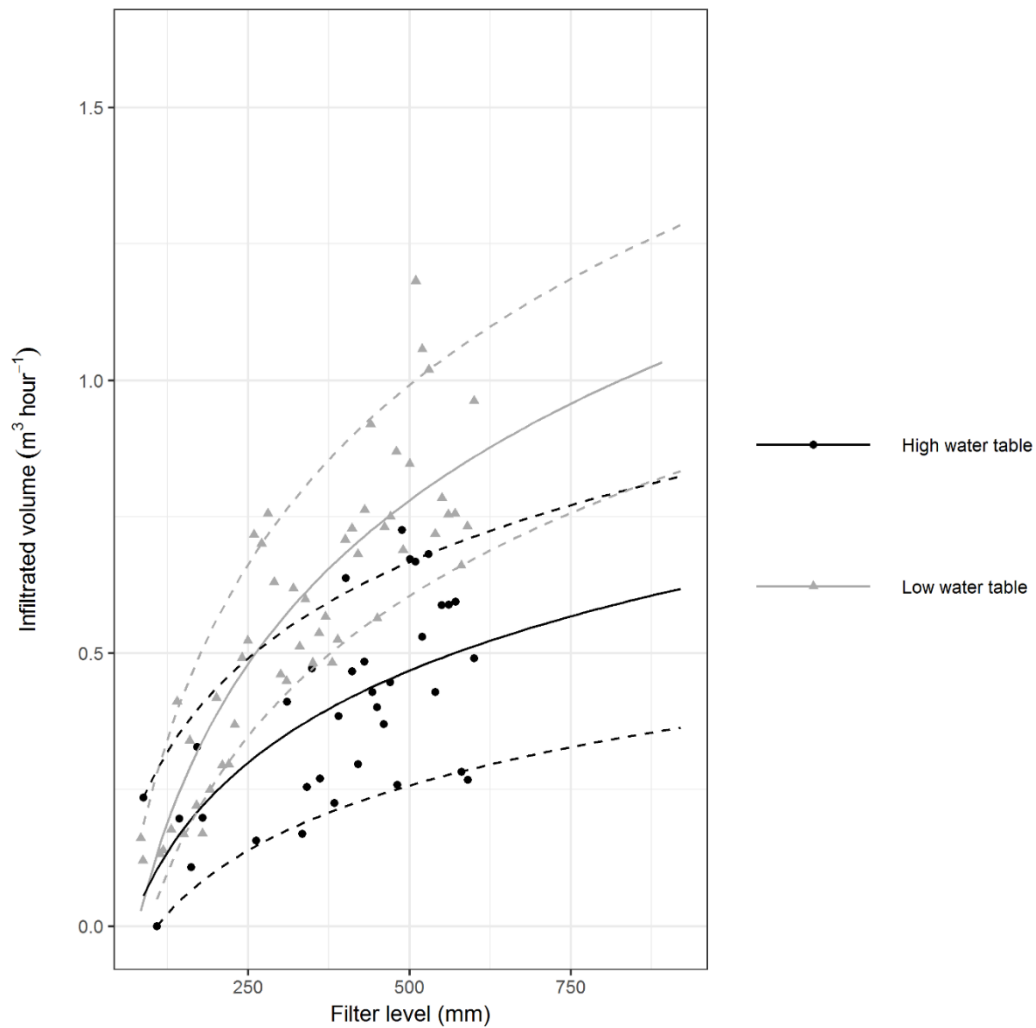
247 2.3.1. How much water infiltrated?

248 The volume of infiltrated stormwater leaving the basin was calculated using the variations of
249 the water level in the basin with known dimensions. Periods when piped inflow and outflow
250 loggers recorded zero flow were isolated. At night (between 11pm and 3am) when ET was
251 assumed to be zero in the sandy infiltration basin (Malek, 1992; Denich and Bradford, 2010),
252 with neither inflow nor outflow, the change in storage in the basin was assumed to be
253 entirely due to infiltration. These periods were used to establish a relationship between the
254 volume of infiltrated stormwater (i.e. the change in storage) and the water level in the
255 basin. Seasonality of infiltration rates was empirically observed, so one relationship for each
256 of (a) low water table months (November - April) and (b) high water table months (May -
257 October) was calculated. Resulting rating curves (Figure 2) therefore provided a relationship
258 between an infiltrated volume at a given water level in the basin and were then applied to
259 the whole dataset (as water levels within the basin were continuously monitored) to
260 estimate the volume of infiltrated stormwater, rating curves were also fitted to the 10th and
261 90th percentile of data to provide both a lower and an upper estimation of the infiltrated
262 volume.

263

264 Perhaps surprisingly, more water left the basin in summer, when the water level within the
265 infiltration basin was at its lowest level, than in winter. This could be explained by (1) a
266 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).



269

270 *Figure 2: Relationships between the hourly change in basin storage for periods with no*
 271 *inflow, no outflow and no evapotranspiration (infiltrated volume) and basin level. Rating*
 272 *curves are formulated as Hourly volume (m³) = A * ln(Basin level) +B, with A and B being*
 273 *constants. Quantile regression to the 90th and 10th percentile was used to build upper and*
 274 *lower estimates of the infiltrated volume, in order to reflect scatter and uncertainty.*

275

276

277 2.3.2. How much water was lost to evapotranspiration?

278

279 The volume of infiltrated stormwater consumed by the vegetation downslope of the basin,
280 over a rectangular plane going from the edge of the basin to the sewer pipe and a width of a
281 100 m was calculated with a monthly water balance. When $ET > \text{Rainfall}$, rainfall could not
282 satisfy the water demand by the vegetation, and the trees were assumed to access phreatic
283 water (i.e. the plume of infiltrated stormwater and $ET - \text{Rainfall}$ was subtracted from the
284 plume). Conversely, when $ET < \text{Rainfall}$, rainfall was assumed to be sufficient to satisfy the
285 water demand by the vegetation, and excess rainfall was assumed to percolate down to the
286 phreatic store, contributing a volume ($\text{Rainfall} - ET$) to the plume of infiltrated stormwater.
287 Reference crop evapotranspiration was sourced from the Australian Bureau of Meteorology
288 that use the Penman-Monteith equation (FAO56, Allen (1998)), with data from a nearby
289 weather station (Australian Bureau of Meteorology Station 086266, Lat -37.87, Lon 145.35,
290 5 km from the site). Because the relationship between the reference crop ET and actual ET
291 from the vegetation was unknown three varying crop factor coefficients were tested: 0.8, 1,
292 1.2 (Myers *et al.*, 1996; Worledge *et al.*, 1998)

293

294 2.3.3. How much water was lost to the 'urban karst'?

295

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

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

303

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

314

315 2.3.4. How much water contributed to baseflow?

316

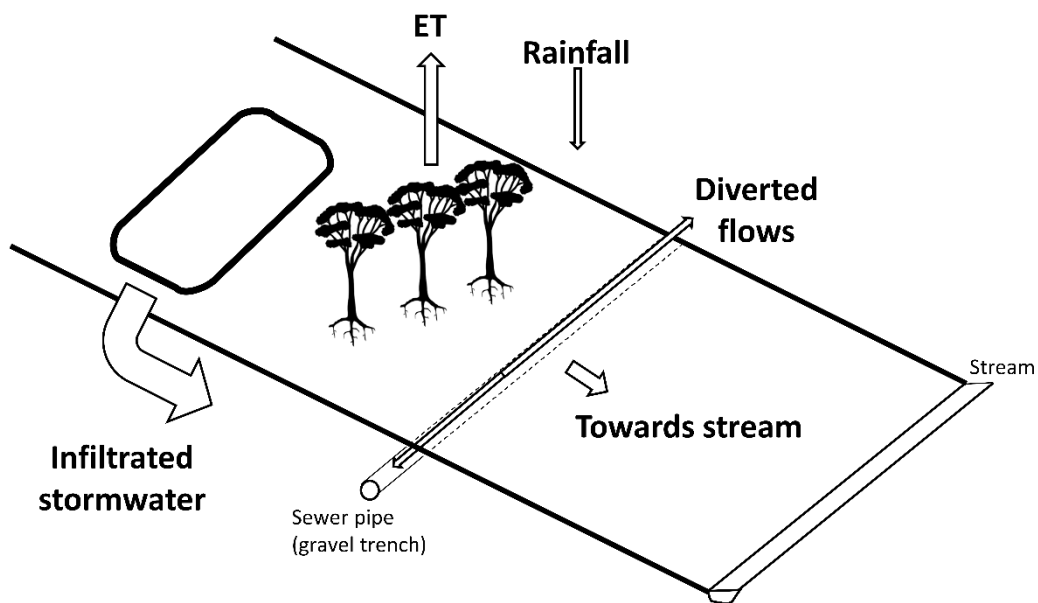
317 From these estimations, the monthly volume of infiltrated stormwater available to
318 potentially reach the stream (as baseflow) was calculated as (Equation 1, Figure 3):

$$319 \quad \textit{Baseflow} = \textit{Inf} - \textit{ETf} + \textit{Direct recharge} - \textit{Diverted flows} \quad (1)$$

320 Where:

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

- 323 • *Inf* the volume of water infiltrated from the basin (calculated with rating curves as
- 324 detailed previously in Section 2.3.1.).
- 325 • *ETf + Direct recharge* was the volume of water either transpired from the plume by
- 326 the vegetation or recharged to the plume by rainfall (as detailed previously in
- 327 Section 2.3.2.)
- 328 ○ When $Rainfall > ET$, $ETf = 0$ and $Direct\ recharge = Rainfall - ET$
- 329 ○ When $Rainfall < ET$, $Direct\ recharge = 0$ and $ETf = ET - Rainfall$.
- 330 • *Diverted flows* represent any potential interception or diversion of infiltrated
- 331 stormwater by the urban karst (as detailed previously in Section 2.3.3.).
- 332



333
 334 *Figure 3: Conceptual water balance of the plume of infiltrated stormwater. Infiltrated*
 335 *stormwater will be consumed by downslope vegetation in dry months, or rainfall will*
 336 *contribute to the plume in wetter months. Some water seeps into the sewer network, and*
 337 *the rest is available to flow towards the stream.*

338 3. Results

339 3.1. *Water level variations*

340

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

347

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

355

356 In contrast, water was consistently observed in the three bores located just downslope of
357 the basin (Downslope 17, 24, 30, Figure 1). In these bores, groundwater levels varied both
358 seasonally and with rainfall events, coinciding with variations of the water level in the basin.

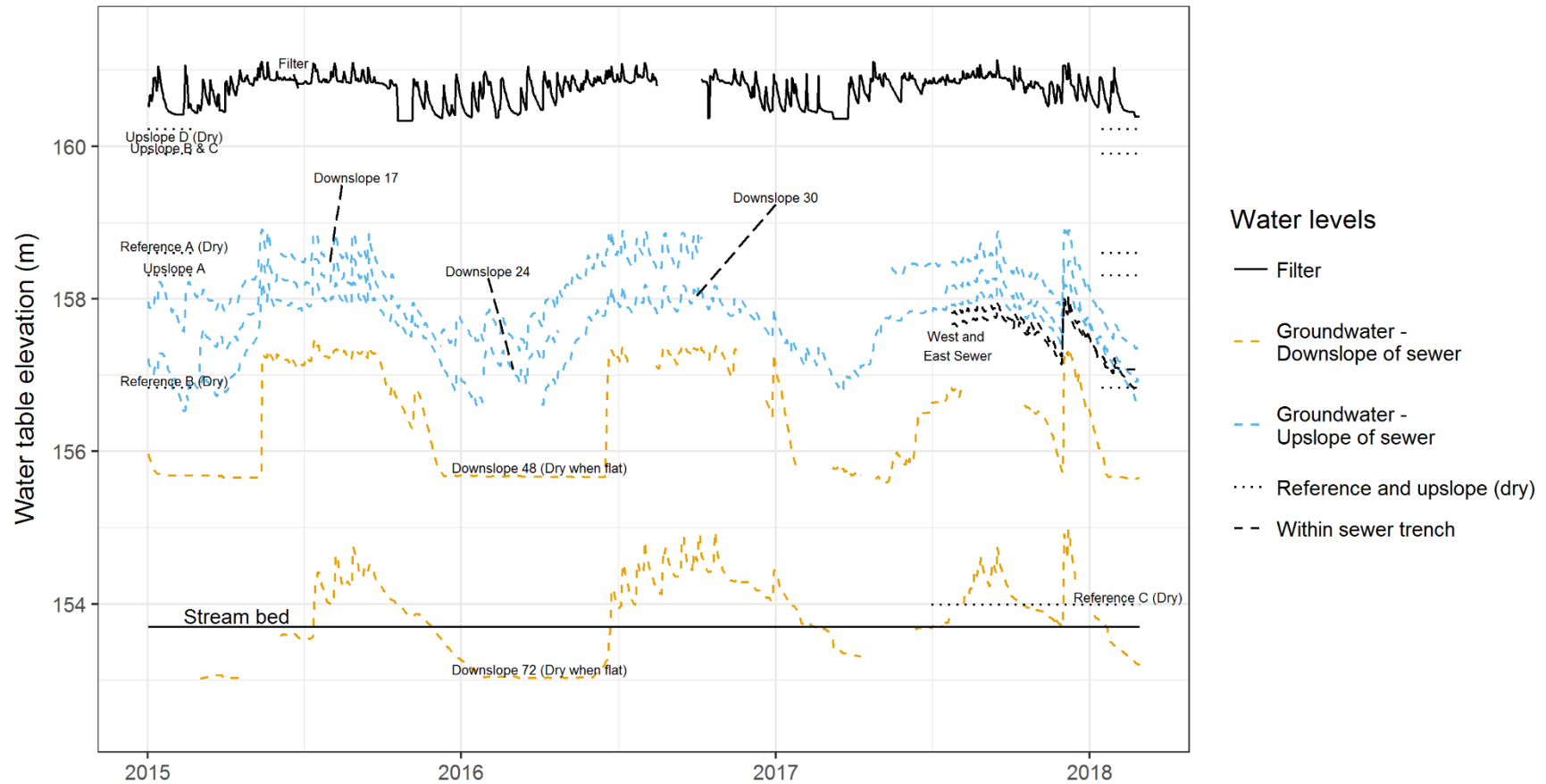
359 Similar variations were not observed in the reference bores laterally away or upslope of the

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

367

368 Figure 4 here (water levels).

369



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.*

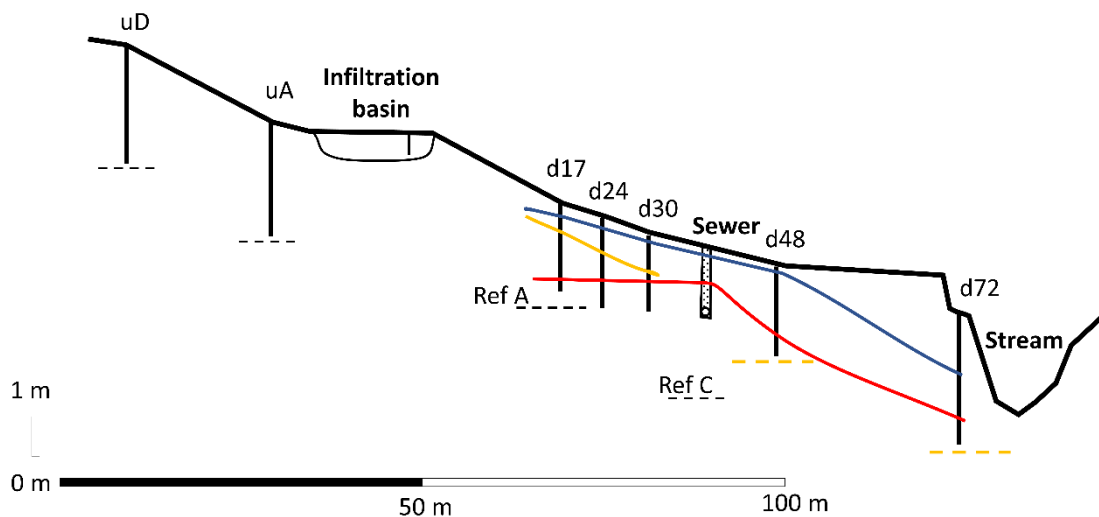
374 The groundwater level data in both bores located downslope of the sewer pipe (Downslope
375 48 and 72) gave zero values from January-February to May-June. Regular (weekly to
376 fortnightly) site inspections confirmed that the bores were dry and during this period the
377 water table was deeper than 1.9 m just downslope of the sewer pipe (Bore Downslope 48,
378 155.6 m). Bore Downslope 72, located in the riparian zone, was dry while the stream is
379 perennial and never stopped flowing. Conversely, in from May-June to November-
380 December, a seasonal increase of the water table resulted in groundwater being intersected
381 in the bores downslope of the sewer trench (Downslope 48 and 72, Figure 1 and 4), that
382 then also showed responses to individual rain events. The transition from dry bores to bores
383 intersecting the water table happened very rapidly. On 14/05/15, the water level just
384 downslope of the sewer pipe (bore Downslope 48) went from less than 155.92 m (dry) to
385 157.4 m in 6.2 hours (a > 1.48 m change). Similarly, on 20/06/2016, the water level went
386 from less than 155.92 m (dry) to 156.8 m in 16.6 hours. These rapid variations were not
387 consistent with seasonal groundwater variations as observed in bores located upslope of
388 the sewer trench, suggesting activation of preferential pathways carrying water rapidly. For
389 comparison, the seasonal water level rise of bores Downslope 17 and 30 took around one
390 month in 2015 and three months in 2016.

391

392 The most downslope bore (bore Downslope 72, Figure 1, located in the riparian zone of the
393 stream), recorded water levels deeper than the stream bed (Figure 4 and 5) and remained
394 dry for extended periods of time. The infiltration basin therefore contributed no baseflow to
395 the stream through the expected topographic pathway during February-June. During the
396 rest of the year, the water table next to the stream was higher than the stream bed (Figure
397 4 and 5). The reference bore also located in the riparian zone but away from the basin (East

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

406



407

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

413

414

415 3.2. *Volume and fate of infiltrated stormwater*

416

417 3.2.1. How much water infiltrated?

418

419 An average of 395 m³ month⁻¹ (≈ 12 % of annual rainfall, or 8 mm month⁻¹) infiltrated from
420 the infiltration basin to the ground, with some seasonal variations (averaging 361 m³ month⁻¹
421 ¹ from November to April and 430 m³ month⁻¹ from May to October, Panel A, Figure 6). The
422 minimum monthly volume happened in March 2017 (216 m³, or 4 mm of runoff, as the
423 basin was closed for half of the month) and the maximum in December 2017 (614 m³, or
424 12.2 mm of runoff). Upper and lower estimates of the rating curves resulted in monthly
425 infiltrated volumes being on average, respectively 37 % higher or 36 % lower than the mean
426 estimate (pink ribbon, Panel A, Figure 6).

427

428 3.2.2. How much water was lost to evapotranspiration?

429

430 For months when ET was higher than rainfall (typically from October to March), the
431 vegetation downslope of the infiltration basin accessed phreatic water (i.e. the plume of
432 infiltrated stormwater) to satisfy the fraction of the water demand rainfall could not supply.
433 This volume (ET – Rainfall) averaged 164 m³ month⁻¹ (3.3 mm month⁻¹, 5.2 % of annual
434 rainfall) and ranged 20-380 m³ month⁻¹, nearing the volume of infiltrated stormwater at the
435 height of summer (Panel B, Figure 6). The percentage of infiltrated stormwater consumed by
436 the vegetation downslope, in summer, averaged 42 % with large monthly variations (4 -
437 100%).

438

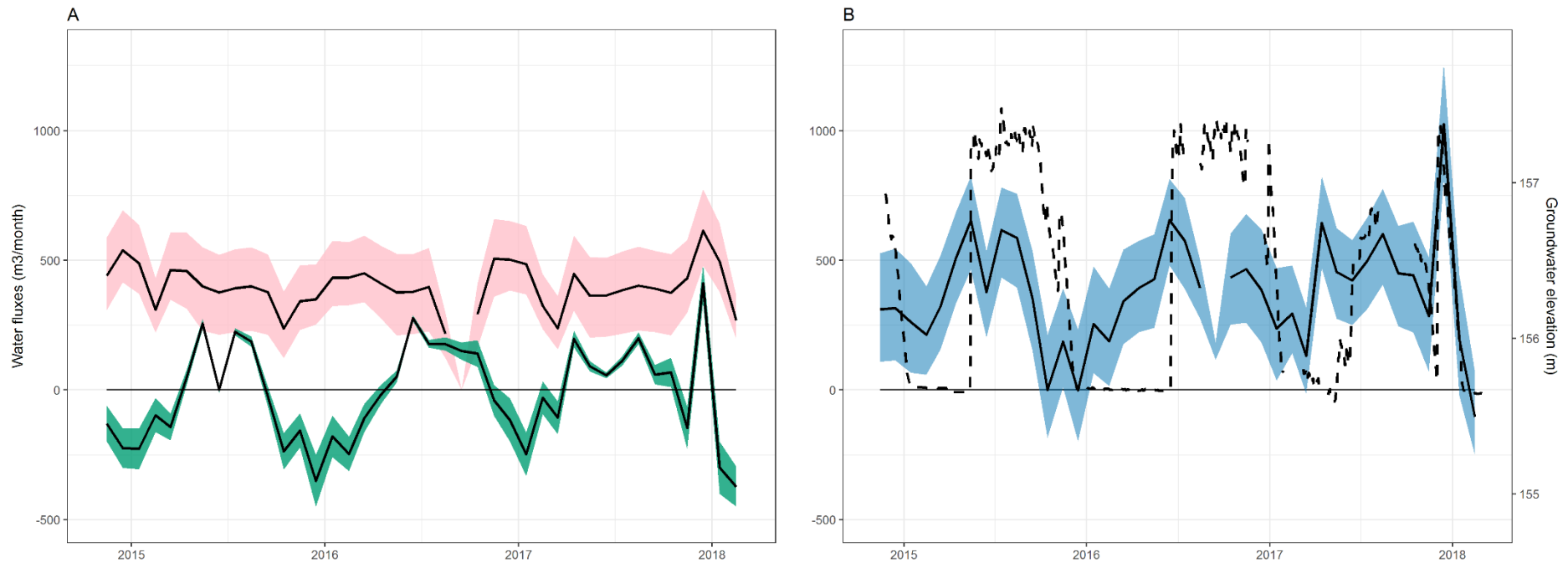
439 In contrast, for months with rainfall higher than ET (typically from April to September-
440 October), the contribution of rainfall recharge to the area influenced by the plume of
441 infiltrated stormwater averaged $138 \text{ m}^3 \text{ month}^{-1}$ (2.8 mm of runoff) and ranged 0-410 m^3
442 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



452

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

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

461

462

463 Analysis of the sewer pump water use showed a significant increase in the night time
464 pumping time (i.e. the time when the pump is running, at night, from 1AM to 4AM) since
465 the construction of the basin (Panel A, Figure 7). Pump running time from 1AM to 4AM
466 averaged 9 min in 2004-2011, while it averaged 12 min in 2013-2018 (t-test p-value <
467 0.001). The median pump running time was 7 min for 2004-2011 and 12 min for 2013-2018
468 (Mann-Whitney p-value < 0.001). While this difference did not appear major, 5 extra
469 minutes of pumping at a rate of the order of magnitude 1-10 l s⁻¹ was high enough to
470 suggest leakage into the pipe and to impact the water balance of the plume of infiltrated
471 stormwater. The video inspection conducted by the local water authority indicated no
472 seepage, possibly because volumes of infiltrated stormwater leaking into the pipe are much
473 smaller than total volumes of wastewater flowing down the pipe, or possibly because the
474 video did not inspect the locations of leakage.

475

476 Water levels within the gravel trench showed the presence of a small head gradient,
477 variable with surrounding groundwater levels, within the gravel trench (~0.1 m, Panel B,
478 Figure 7). The equivalent Darcian flow rate was 1.6 e⁻⁷ m³ s⁻¹ or 0.01-0.02 m³ month⁻¹. The
479 gradient was mostly one direction (going East to West) but reversed in response to a large
480 rainfall event. The inconsistent flow directions were likely due to the sewer trench following
481 the local topography which did not show a clear gradient laterally away from the infiltration
482 basin (Figure 1).

483

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.

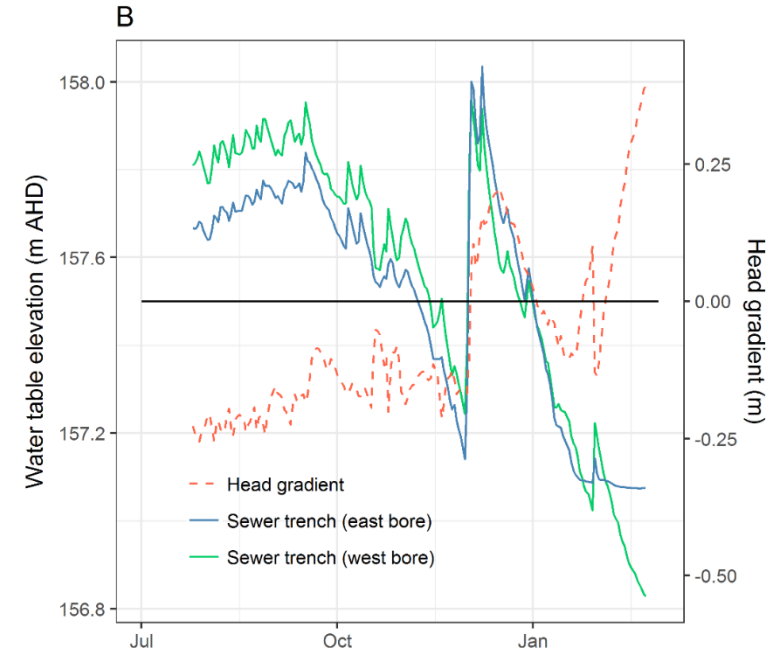
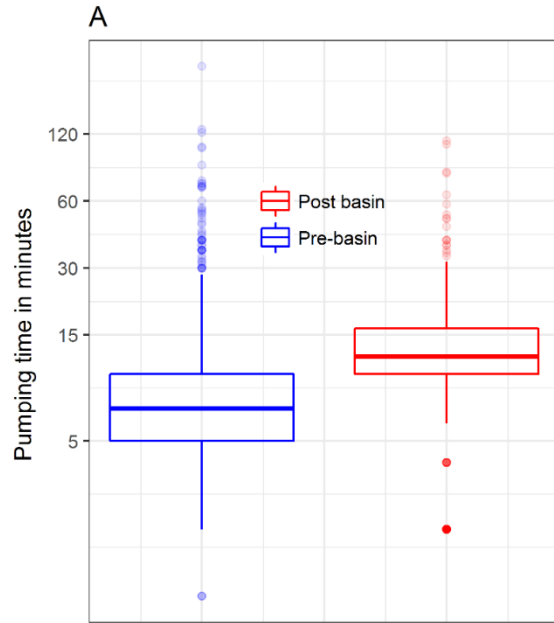
492

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 .

502 3.2.4. How much water contributed to baseflow?

503

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

510

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

521

522 4. Discussion

523 4.1. *Contribution to baseflow and mechanisms at play*

524

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

539

540 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
541 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
542 orders of magnitude higher. The stream and its tributaries are 7.2 km long, which result in
543 linear baseflow contribution ranging $0.75 - 2 \text{ mm day}^{-1} \text{ km}^{-1}$. This contrasts with daily

544 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
545 maximal potential contribution of $2\text{ - }4\text{ mm day}^{-1}\text{ km}^{-1}$. As such, any contribution of the
546 basin to baseflow is a small fraction of streamflow, unlikely to be detectable by standard
547 flow monitoring, but represents an increase in comparison to 'natural' conditions without
548 an infiltration basin. While the magnitude of 'natural' baseflow contributions along this
549 particular reach are unknown, the observed conditions (e.g. lateral bores to the infiltration
550 basin being dry and riparian bores being below the streambed level during summer) suggest
551 that this reach of stream would get little to no baseflow at any time of the year without the
552 contribution of the plume of infiltrated stormwater. The groundwater plume contributing to
553 increased groundwater levels in the riparian zone is evidence that along this reach, the
554 infiltration basin increased baseflow per unit of stream length.

555

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

563

564 4.2. *Evapotranspiration and local hydro-geological context*

565

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

584

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

588 other environments, with more permeable soils that promote vertical movement of
589 infiltrated stormwater, a shallow water table may not form, and infiltrated water would
590 percolate down to a deeper groundwater table, as is the case for infiltration basins in the
591 highly permeable glaciofluvial aquifers around Lyon, France (Foulquier *et al.*, 2009;
592 Mermillod-Blondin *et al.*, 2015) or the sandy aquifers of Perth, Australia (Locatelli *et al.*,
593 2016). In such environments, the lateral flow in the phreatic zone would likely be too deep
594 to interact with roots or any typical urban sub-surface infrastructure. This highlights the
595 importance of local context in the fate of infiltrated stormwater (in particular hydraulic
596 conductivities and depth to bedrock or the aquifer), as well as the importance of the
597 placement of systems to maximize performance in terms of groundwater recharge and
598 baseflow contribution.

599

600

601 *4.3. Impact of anthropogenic disturbances on groundwater levels and the* 602 *water balance*

603

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

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

623

624 This conceptual understanding of the fate of infiltrated stormwater assumes that most of
625 the flow of infiltrated stormwater is restricted to the upper layers of soil (first 5 m), based
626 on our cores that shown very low permeability soil at 5 m. At this depth, there are no roots,
627 and a significant amount of water could only find its way down through geological fractures
628 at the interface between soil and bedrock (Lachassagne *et al.*, 2011; Lachassagne *et al.*,
629 2014). These fractures are unknown to us, and were not detected during while coring.

630

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

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

638

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

654

655 4.4. *Management implications*

656

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

669

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

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

682

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

691

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

700 5. Conclusions

701

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

704 • The presence of the infiltration basin raised groundwater levels to around
705 0.25 – 1.5 m just downslope of the basin, in contrast to the upstream
706 reference depth of < 3-4m (Figure 5).

707 • The plume of infiltrated stormwater formed a shallow groundwater mound
708 in the low-permeability soil, and flowed along the expected topographic
709 pathway towards the urban stream for about 30 m.

710 • A significant amount of infiltrated stormwater was consumed by vegetation
711 downslope, especially in the warmer months (up to 100% for some months).

712 • As often in urban settings, the stream was locally realigned. In addition, the
713 upper part of the plume of infiltrated stormwater was intersected by
714 underground sewer infrastructure with potential seepage into the
715 wastewater network. In summer, the combination of tree water use,
716 realignment and sewer interactions resulted in no infiltrated stormwater
717 flowing towards the stream: the water table near the stream was below the
718 streambed.

719 • In winter, as ET decreased, groundwater levels increased, and infiltrated
720 stormwater flowed towards the stream: groundwater levels were then
721 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

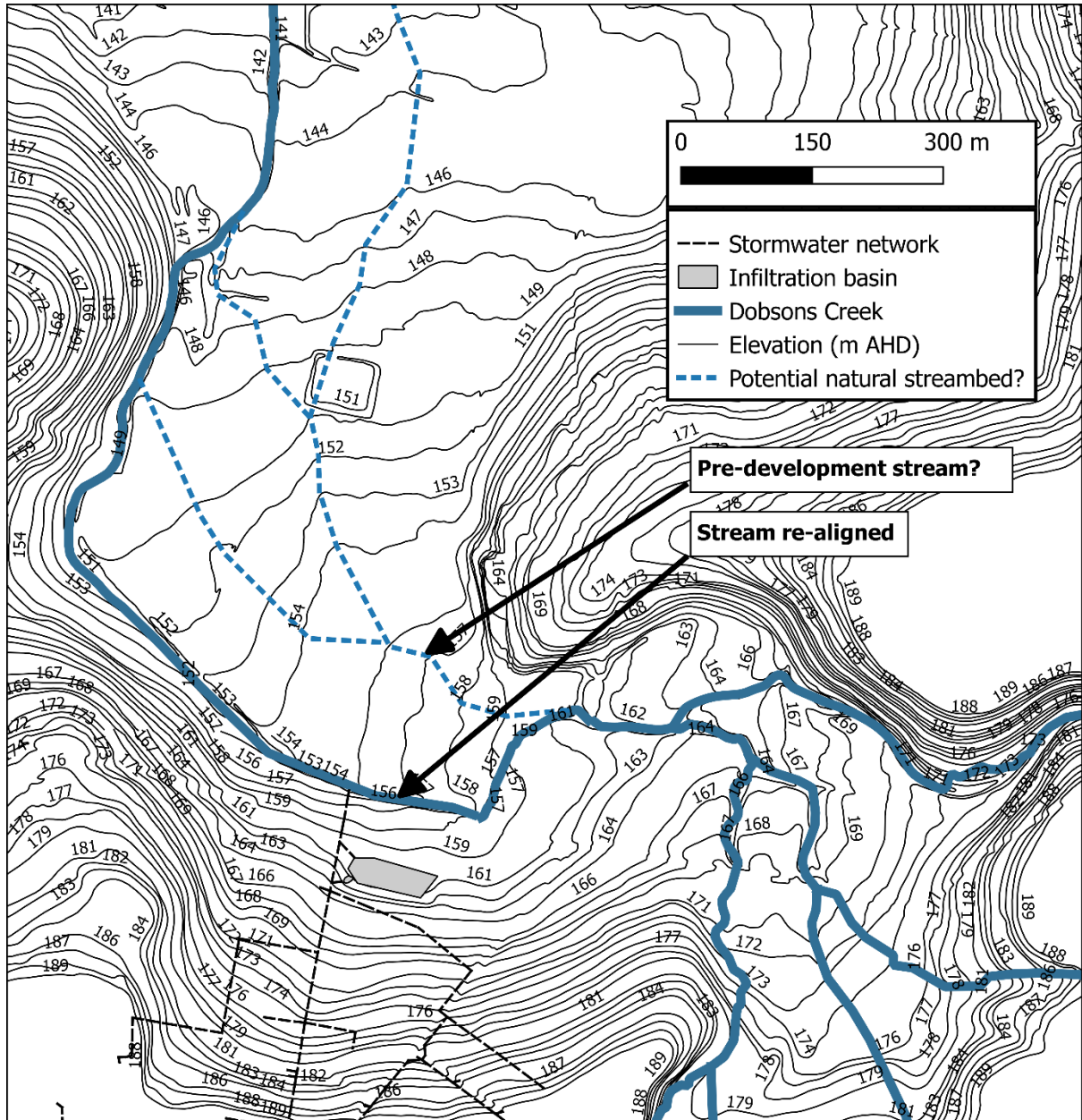
727

728 **Acknowledgments**

729 This article is a tribute to Justin Costelloe and his considerable contribution to science. Justin
730 was a tremendous contributor to his field of research and to this article, and to the
731 supervision of the PhD of the main author of the article. This work is supported by
732 Melbourne Water and Knox City Council. Prof. Tim Fletcher was supported during part of
733 this work by the Australian Research Council's Future Fellowship scheme (FT100100144) and
734 the work is supported indirectly by ARC Linkage Project (LP130100295). We thank
735 anonymous reviewers whose comments have contributed to a great improvement of the
736 manuscript. Chris Walsh, Jasper Kunapo and Mike Timms made many insightful comments
737 on the present text.

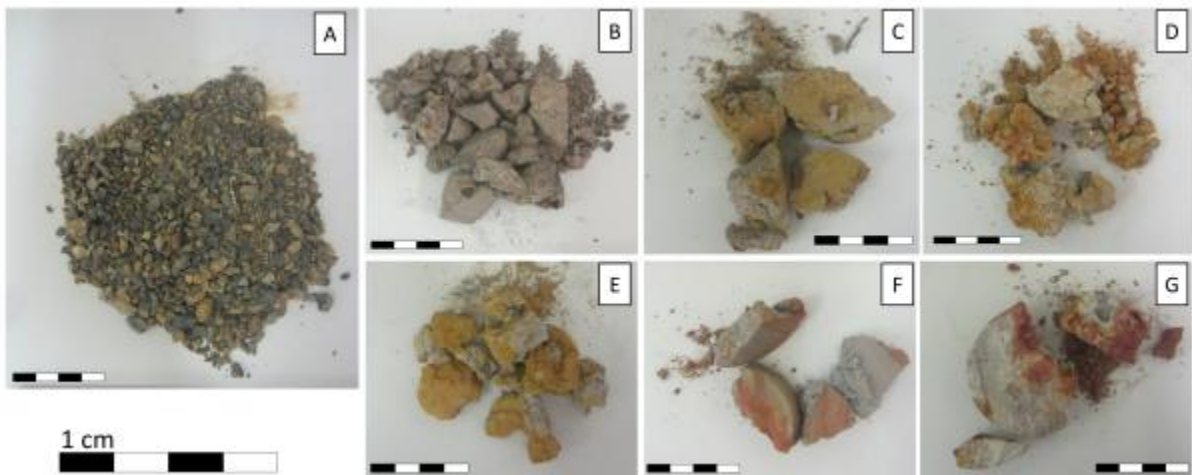
Supplementary material

Supplementary Figure 1:



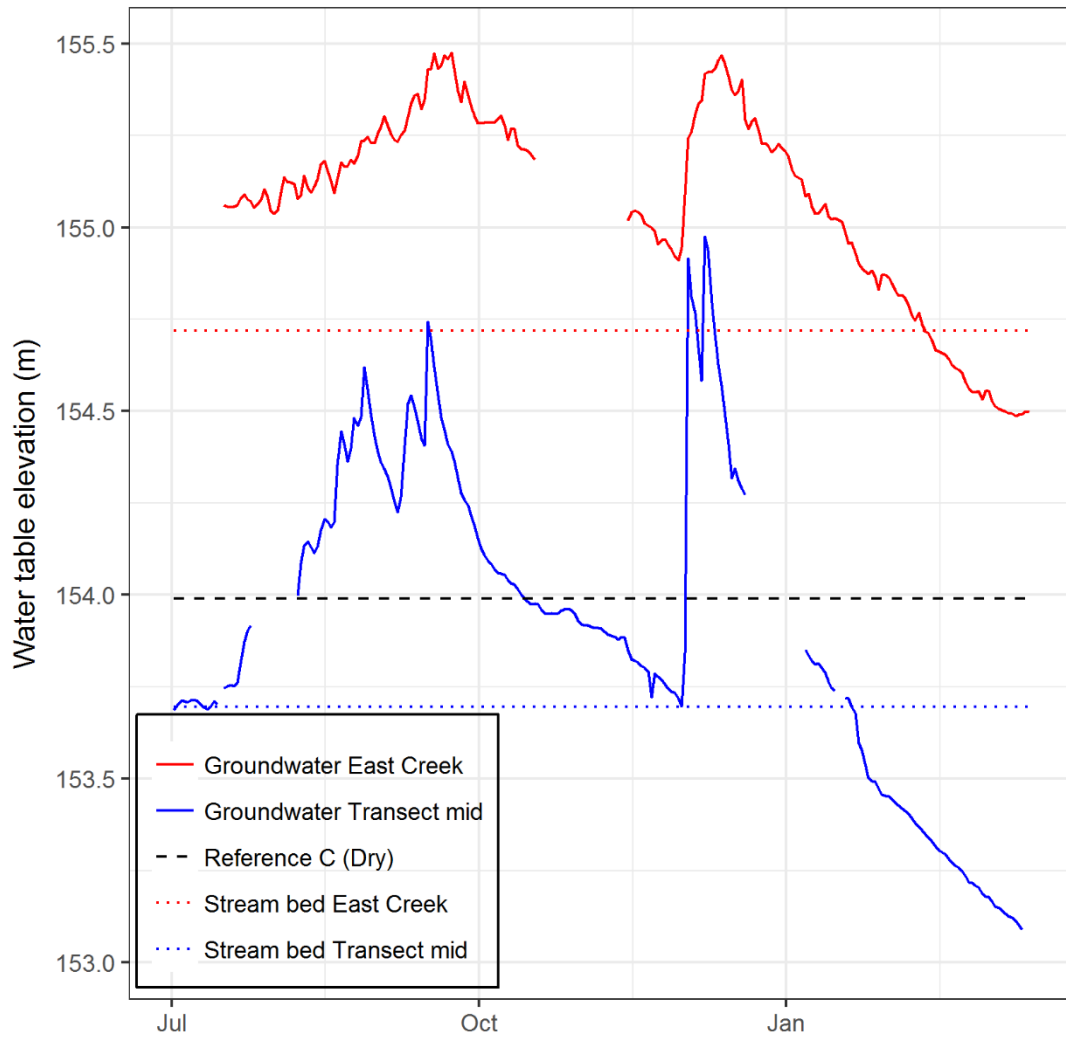
Topographic contours of the area with the infiltration basin (grey polygon), the stormwater network (black dotted lines) and the current stream bed trajectory (full blue lines). Dotted blue lines are proposed pre-development streambeds based on topographic contours, as the reach near the infiltration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

Supplementary Figure 2



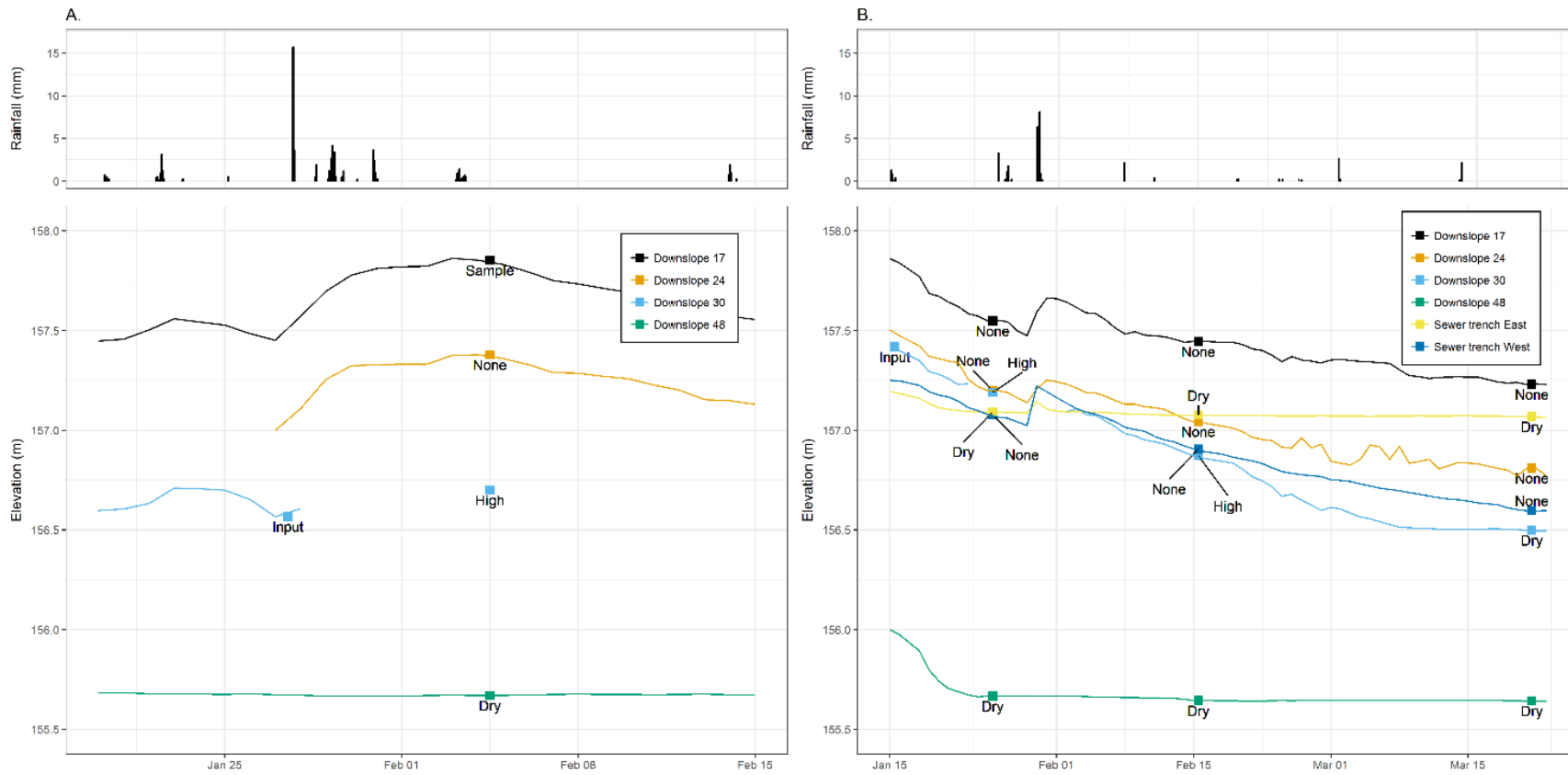
Photograph of the gravels surrounding the sewer pipe (A), with a measured d_{50} of 2mm. Other photographs are fragmented samples of the native clay soil at different depth of the soil profile: 0.5 m (B), 1 m (C), 2 m (D), 3 m (E), 4 m (F), 5 m (G).

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.

Supplementary Figure 4:



Water level elevations and rainfall in monitored bores during the two dye experiments (2016 in Panel A (left) and 2018 in Panel B (right)). Water samples and dye content are shown.

References

- Allen RG. 1998. Crop evapotranspiration - Guidelines for computing crop water requirements. In: FAO Irrigation and drainage paper 56, Food and Agriculture Organization of the United Nations.
- Beighley E, Laboy M, Onnis-Hayden A, Barbosa A, Coyle G, Abhishek J, Kline S, Li S, McNally M, Sullivan S, Normandi T, Ziola J, Whelpley D. 2015. Northeastern University - Recharging the City. EPA (ed.).
- Benke AC. 1990. A perspective on America's vanishing streams. *Journal of the North American Benthological Society*, **9**: 77-88.
- Bhaskar AS, Hogan DM, Archfield SA. 2016. Urban base flow with Low Impact Development. *Hydrological Processes*. DOI: 10.1002/hyp.10808.
- BoM. 2016. Rainfall in Victoria. Bureau of Meteorology.
- Bonneau J, Burns MJ, Fletcher TD, Witt R, Drysdale RN, Costelloe JF. 2018. The impact of urbanization on subsurface flow paths—a paired-catchment isotopic study. *Journal of Hydrology*.
- Bonneau J, Fletcher TD, Costelloe JF, Burns MJ. 2017. Stormwater infiltration and the 'urban karst'—A review. *Journal of Hydrology*, **552**: 141-150.
- Boston Groundwater Trust. 2015.
- Bouwer H, Rice R. 1976. A slug test for determining hydraulic conductivity of unconfined aquifers with completely or partially penetrating wells. *Water resources research*, **12**: 423-428.
- Braga A, Horst M, Traver RG. 2007. Temperature effects on the infiltration rate through an infiltration basin BMP. *Journal of Irrigation and Drainage Engineering*, **133**: 593-601.
- Braud I, Breil P, Thollet F, Lagouy M, Branger F, Jacqueminet C, Kermadi S, Michel K. 2013. Evidence of the impact of urbanization on the hydrological regime of a medium-sized periurban catchment in France. *Journal of hydrology*, **485**: 5-23.
- Brookes A, Gregory K, Dawson F. 1983. An assessment of river channelization in England and Wales. *Science of the Total Environment*, **27**: 97-111.
- Brown RR, Keith N, Wong TH. 2009. Urban water management in cities: historical, current and future regimes. *Water Sci Technol*, **59**: 847-855. DOI: 10.2166/wst.2009.029.
- Burns MJ, Fletcher TD, Walsh CJ, Ladson A, Hatt B. 2013. Setting objectives for hydrologic restoration: from site-scale to catchment-scale. NOVATECH 2013.
- Campisano A, Creaco E, Modica C. 2011. A simplified approach for the design of infiltration trenches. *Water Science & Technology*, **64**: 1362. DOI: 10.2166/wst.2011.170.
- Davis AP. 2008. Field performance of bioretention: Hydrology impacts. *Journal of Hydrologic Engineering*, **13**: 90-95. DOI: 10.1061//asce/1084-0699/2008/13:2/90.
- Dechesne M, Barraud S, Bardin J-P. 2005. Experimental assessment of stormwater infiltration basin evolution. *Journal of environmental engineering*, **131**: 1090-1098.
- Denich C, Bradford A. 2010. Estimation of Evapotranspiration from Bioretention Areas Using Weighing Lysimeters. *Journal of Hydrologic Engineering*, **15**: 522-530. DOI: doi:10.1061/(ASCE)HE.1943-5584.0000134.
- Elmore AJ, Kaushal SS. 2008. Disappearing headwaters: patterns of stream burial due to urbanization. *Frontiers in Ecology and the Environment*, **6**: 308-312. DOI: 10.1890/070101.
- Endreny T, Collins V. 2009. Implications of bioretention basin spatial arrangements on stormwater recharge and groundwater mounding. *Ecological Engineering*, **35**: 670-677. DOI: 10.1016/j.ecoleng.2008.10.017.
- Fanelli R, Prestegard K, Palmer M. 2017. Evaluation of infiltration-based stormwater management to restore hydrological processes in urban headwater streams. *Hydrological Processes*, **31**: 3306-3319. DOI: 10.1002/hyp.11266.
- Fletcher TD, Shuster W, Hunt WF, Ashley R, Butler D, Arthur S, Trowsdale S, Barraud S, Semadeni-Davies A, Bertrand-Krajewski J-L, Mikkelsen PS, Rivard G, Uhl M, Dagenais D, Viklander M.

2014. SUDS, LID, BMPs, WSUD and more – The evolution and application of terminology surrounding urban drainage. *Urban Water Journal*: 1-18. DOI: 10.1080/1573062x.2014.916314.
- Foulquier A, Malard F, Barraud S, Gibert J. 2009. Thermal influence of urban groundwater recharge from stormwater infiltration basins. *Hydrological Processes*, **23**: 1701-1713. DOI: 10.1002/hyp.7305.
- Freni G, Mannina G, Viviani G. 2009. Stormwater infiltration trenches: a conceptual modelling approach. *Water Sci Technol*, **60**: 185-199. DOI: 10.2166/wst.2009.324.
- Hamel P, Fletcher TD. 2014. Modelling the impact of stormwater source control infiltration techniques on catchment baseflow. *Hydrological Processes*, **28**: 5817-5831. DOI: 10.1002/hyp.10069.
- Hamel P, Fletcher TD, Daly E, Beringer J. 2012. Water retention by raingardens: implications for local-scale soil moisture and water fluxes. In: *WSUD 2012: Water sensitive urban design; Building the water sensitive community; 7th international conference on water sensitive urban design*, Engineers Australia, pp: 137.
- Hamel P, Fletcher TD, Walsh CJ, Plessis E. 2011. Quantifying the restoration of evapotranspiration and groundwater recharge by vegetated infiltration systems.
- Hunt WF, Davis AP, Traver RG. 2012. Meeting Hydrologic and Water Quality Goals through Targeted Bioretention Design. *Journal of Environmental Engineering*, **138**: 698-707. DOI: 10.1061/(asce)ee.1943-7870.0000504.
- Jarden KM, Jefferson AJ, Grieser JM. 2015. Assessing the effects of catchment-scale urban green infrastructure retrofits on hydrograph characteristics. *Hydrological Processes*: n/a-n/a. DOI: 10.1002/hyp.10736.
- Kaushal SS, Belt KT. 2012. The urban watershed continuum: evolving spatial and temporal dimensions. *Urban Ecosystems*, **15**: 409-435. DOI: 10.1007/s11252-012-0226-7.
- King RS, Baker ME, Whigham DF, Weller DE, Jordan TE, Kazyak PF, Hurd MK. 2005. Spatial considerations for linking watershed land cover to ecological indicators in streams. *Ecological applications*, **15**: 137-153.
- Konrad CP, Booth DB. 2005. Hydrologic changes in urban streams and their ecological significance. In: *American Fisheries Society Symposium*, pp: 157-177.
- Lachassagne P, Dewandel B, Wyns R. 2014. The conceptual model of weathered hard rock aquifers and its practical applications. *Fractured Rock Hydrogeology*: 13-46.
- Lachassagne P, Wyns R, Dewandel B. 2011. The fracture permeability of Hard Rock Aquifers is due neither to tectonics, nor to unloading, but to weathering processes. *Terra Nova*, **23**: 145-161. DOI: 10.1111/j.1365-3121.2011.00998.x.
- Li C, Fletcher TD, Duncan HP, Burns MJ. 2017. Can stormwater control measures restore altered urban flow regimes at the catchment scale? *Journal of Hydrology*, **549**: 631-653.
- Locatelli L, Mark O, Mikkelsen PS, Arnbjerg-Nielsen K, Deletic A, Roldin M, Binning PJ. 2016. Hydrologic impact of urbanization with extensive stormwater infiltration. *Journal of Hydrology*.
- Loperfido JV, Noe GB, Jarnagin ST, Hogan DM. 2014. Effects of distributed and centralized stormwater best management practices and land cover on urban stream hydrology at the catchment scale. *Journal of Hydrology*, **519**: 2584-2595. DOI: 10.1016/j.jhydrol.2014.07.007.
- Machusick M, Welker A, Traver R. 2011. Groundwater Mounding at a Storm-Water Infiltration BMP. *Journal of Irrigation and Drainage Engineering*, **137**: 154-160. DOI: 10.1061/(asce)ir.1943-4774.0000184.
- Malek E. 1992. Night-time evapotranspiration vs. daytime and 24 h evapotranspiration *Journal of Hydrology*, **138**: 119-129.
- Mermillod-Blondin F, Simon L, Maazouzi C, Foulquier A, Delolme C, Marmonier P. 2015. Dynamics of dissolved organic carbon (DOC) through stormwater basins designed for groundwater

- recharge in urban area: Assessment of retention efficiency. *Water Res*, **81**: 27-37. DOI: 10.1016/j.watres.2015.05.031.
- Mullaney J, Lucke T. 2014. Practical Review of Pervious Pavement Designs. *CLEAN - Soil, Air, Water*, **42**: 111-124. DOI: 10.1002/clen.201300118.
- Myers B, Theiveyanathan S, O'brien N, Bond WJ. 1996. Growth and water use of *Eucalyptus grandis* and *Pinus radiata* plantations irrigated with effluent. *Tree Physiology*, **16**: 211-219.
- Nemirovsky EM, Lee RS, Welker AL. 2015. Vertical and Lateral Extent of the Influence of a Rain Garden on the Water Table. *Journal of Irrigation and Drainage Engineering*, **141**. DOI: 10.1061/(asce)ir.1943-4774.0000799.
- Nimmer M, Thompson A, Misra D. 2009. Water table mounding beneath stormwater infiltration basins. *Environmental & Engineering Geoscience*, **15**: 67-79.
- Price WD, Burchell MR, Hunt WF, Chescheir GM. 2013. Long-term study of dune infiltration systems to treat coastal stormwater runoff for fecal bacteria. *Ecological Engineering*, **52**: 1-11. DOI: 10.1016/j.ecoleng.2012.12.008.
- Roldin M, Locatelli L, Mark O, Mikkelsen PS, Binning PJ. 2013. A simplified model of soakaway infiltration interaction with a shallow groundwater table. *Journal of Hydrology*, **497**: 165-175. DOI: 10.1016/j.jhydrol.2013.06.005.
- Roy JW, Bickerton G. 2012. Toxic groundwater contaminants: an overlooked contributor to urban stream syndrome? *Environ Sci Technol*, **46**: 729-736. DOI: 10.1021/es2034137.
- Scholz M, Grabowiecki P. 2007. Review of permeable pavement systems. *Building and Environment*, **42**: 3830-3836. DOI: 10.1016/j.buildenv.2006.11.016.
- Sharp J, Krothe J, Mather J, Gracia-Fresca B, Stewart C. 2003. Effects of urbanization on groundwater systems. *Earth science in the city: A reader*: 257-278.
- Sharp JM. 2010. The impacts of urbanization on groundwater systems and recharge. *Aqua Mundi*. DOI: 10.4409/Am-004-10-0008.
- Sharp JM, Garcia-Fresca B. 2003. Effects of urbanisation of groundwater resources, recharges rates, and flow patterns. *Geological Society of America*.
- Shoham T. 2006. Groundwater decline and the preservation of property in Boston. *Massachusetts Institute of Technology*.
- Walsh C. 2005. The urban stream syndrom: current knowledge and the search for a cure. *Journal of North American Benthological Society*, **24**: 706-723.
- Walsh CJ, Booth DB, Burns MJ, Fletcher TD, Hale RL, Hoang LN, Livingston G, Rippey MA, Roy AH, Scoggins M. 2015. Principles for urban stormwater management to protect stream ecosystems. *Freshwater Science*.
- Walsh CJ, Fletcher TD, Burns MJ. 2012. Urban stormwater runoff: a new class of environmental flow problem. *PLoS One*, **7**: e45814.
- Wilson CE, Hunt WF, Winston RJ, Smith P. 2015. Comparison of Runoff Quality and Quantity from a Commercial Low-Impact and Conventional Development in Raleigh, North Carolina. *Journal of Environmental Engineering*, **141**: 05014005. DOI: 10.1061/(asce)ee.1943-7870.0000842.
- Wittenberg H, Aksoy H. 2010. Groundwater intrusion into leaky sewer systems. *Water Science and technology*, **62**: 92-98.
- Worledge D, J.L. H, D.A. W, C.L. B, S.J. H. 1998. Scheduling irrigation in plantations of *Eucalyptus globulus* and *E. nitens*: A practical guide. *Tasmanian Forests*, **10**.