

Article (refereed) - postprint

Redfern, Thomas W.; Macdonald, Neil; Kjeldsen, Thomas R.; Miller, James D.; Reynard, Nick. 2016. **Current understanding of hydrological processes on common urban surfaces**. *Progress in Physical Geography*, 40 (5). 699-713. [10.1177/0309133316652819](https://doi.org/10.1177/0309133316652819)

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1 **Current understanding of hydrological processes on common urban surfaces.**

2

3 **Keywords:** urban hydrology, impervious surfaces, surface runoff, hydrological processes, urban
4 infiltration

5

6 **Abstract**

7 Understanding the rainfall-runoff behaviour of urban land surfaces is an important scientific and
8 practical issue, as storm water management policies increasingly aim to manage flood risk at local
9 scales within urban areas, whilst controlling the quality and quantity of runoff that reaches
10 receiving water bodies. By reviewing field measurements reported within the literature on runoff,
11 infiltration, evaporation and storage on common urban surfaces, this study describes a complex
12 hydrological behaviour with greater rates of infiltration than often assumed, contradicting a
13 commonly adopted but simplified classification of the hydrological properties of urban surfaces.
14 This shows that the term impervious surface, or impermeable surface, referring to all constructed
15 surfaces (e.g. roads, roofs, footpaths etc.) is inaccurate and potentially misleading. The
16 hydrological character of urban surfaces is not stable through time, with both short (seasonal) and
17 long-term (decadal) changes in hydrological behaviour, as surfaces respond to variations in
18 seasonal characteristics and degradation in surface condition. At present these changing factors are
19 not widely incorporated into hydrological modelling or urban surface water management planning,
20 with static values describing runoff and assumptions of imperviousness often used. Developing a
21 greater understanding of the linkages between urban surfaces and hydrological behaviour will
22 improve the representation of diverse urban landscapes within hydrological models.

23

24 **Introduction**

25 In the context of land-use and land cover change, urbanization describes the process by which
26 natural vegetated landscapes are replaced with constructed surfaces (Shuster et al., 2005). Urban
27 areas have expanded to provide the housing, transport and other infrastructure required by the
28 world's increasing urban population over the 20th and into the 21st Century, and so the coverage of
29 urban surfaces has increased and intensified in many parts of the world (Marshall, 2007).

30 During severe storm events, large volumes of water must navigate across the surface of towns and
31 cities before reaching a receiving water body (Wheater and Evans, 2009). Without careful
32 management surface water can accumulate resulting in the flooding of roads, homes and
33 businesses, often with considerable negative economic (Sušnik et al., 2014), social (Tapsell and
34 Tunstall, 2008) and health (Fewtrell and Kay, 2008) consequences for affected communities.
35 Historical engineering approaches to surface water management focused on constructing drains
36 that transfer runoff to receiving water bodies as quickly and efficiently as possible (Woods-Ballard
37 et al., 2007). However, directly connecting the catchment stream network to urban drainage
38 systems and runoff generating surfaces impacts on the hydrological functioning of a catchment
39 (O'Driscoll et al., 2010), potentially increasing flood risk downstream (Hollis, 1975; Kjeldsen et
40 al., 2013), whilst low flow regimes can be impacted by reductions in infiltration and groundwater
41 recharge (Chung et al., 2011) with consequences for water resources and hydro-ecology (White
42 and Greer, 2006).

43 Modern storm water management practices have developed away from the historical focus on
44 removing surface water as quickly and efficiently as possible, reflecting the need to address the
45 larger scale impacts of urbanisation on the hydrological cycle (Charlesworth et al., 2003). To
46 reduce runoff volumes and improve urban runoff water quality, contemporary storm water

47 management technologies aim to reduce and disconnect impervious surfaces from the storm water
48 drainage system (Walsh et al., 2005), use pervious areas and engineered surface features to
49 increase infiltration and therefore groundwater recharge (Hamel et al., 2013) and construct
50 artificial areas of storage within urban catchments (Woods-Ballard et al., 2007). The legacy of
51 extant urban developments combined with climate change and increasing imperviousness within
52 urban areas (urban creep) means retrofitting the existing built environment with modern storm
53 water management techniques has become a priority (MacDonald, 2011), both for local flood risk
54 management and for the mitigation of hydrological impacts in urbanised catchments.
55 Understanding the runoff generation processes and infiltration potential of diverse urban land
56 surfaces is therefore a priority for the design and implementation of storm-water management
57 policies and technologies (Salvadore et al., 2015).

58 Urban hydrology has been the subject of a considerable volume of research; as described in a
59 review by Fletcher et al. (2013). Topics of research have included detecting and quantifying
60 hydrological changes in urbanised catchments (Miller et al., 2014; Braud et al., 2013), accounting
61 for these hydrological changes within flood prediction models (Kjeldsen, 2009; Nirupama and
62 Simonovic, 2007), investigating the generation of surface water flood risk within urban settings
63 (Yu and Coulthard, 2015) and detecting the impacts of urbanisation on groundwater and base-flow
64 regimes (Kazemi, 2011; Shepherd et al., 2006). Where available, long-term flow series can be
65 analysed in combination with geospatial databases to attribute hydrological characteristics to urban
66 development patterns. However, long data series within urban settings are rare with the
67 hydrological behaviour of urban areas often predicted using hydrological modelling (Fletcher et
68 al., 2013).

69 The ability of hydrological models to accurately replicate the impacts of urbanisation on the
70 hydrological system is reliant upon the accurate representation, mathematical description and
71 parameterisation of rainfall-runoff processes on urban surfaces (Packman, 1980). However, no
72 universally accepted characterisation of urban surfaces for inclusion in hydrological models exists
73 (Shields and Tague, 2012) leading to a large number of hydrological models, with a high degree
74 of variability in the representation of hydrological processes in urban areas (Salvadore et al., 2015).
75 Commonly roads, roofs and other constructed surfaces are grouped together as *impervious*
76 *surfaces*, with estimates of their extent determined from aerial photographs, maps (Miller et al.,
77 2014) or remote sensing (see review by Slonecker et al. (2001)). Impervious surfaces are often
78 assumed to prevent precipitation from directly infiltrating into the soil, converting high proportions
79 of rainfall into direct runoff (Jacobson, 2011). Representing the hydrological behaviour of
80 impervious surfaces is often based on estimates e.g. percentage runoff = 70%, (Packman, 1980;
81 Kjeldsen, 2009), theoretical assumptions e.g. infiltration= 0% (Wiles and Sharp, 2008), or the
82 application of previously calibrated techniques linking the degree of imperviousness to
83 hydrological behaviour (Holman-Dodds et al., 2003). Other techniques include estimating the
84 hydrological characteristics of impervious surfaces as a function of proximity to the stream
85 network (Franczyk and Chang, 2009), or as a function of land use (Baker and Miller, 2013). This
86 list is by no means exhaustive and many other methods have been applied within the literature
87 (Salvadore et al., 2015). The outputs of hydrological models are therefore sensitive to the
88 determination of the extent of imperviousness, degree of connectivity to the surface water drainage
89 system (Roy and Shuster, 2009) and the definition of hydrological processes on urban surfaces
90 (Yao et al., 2016; Beighley et al., 2009). However, there is currently no thorough understanding
91 of hydrological processes occurring on extant urban surface types; as little research has assessed

92 the veracity of the underlying assumptions regarding the imperviousness of impervious surfaces,
93 or provided detailed assessments of the hydrological properties of other types of urban surface
94 (Evans and Eadon, 2007). The aim of this study is to review empirical measurements of
95 hydrological processes upon common urban surface types, through three objectives:

- 96 i. Review empirical measurements of hydrological processes on common urban surfaces
97 reported within peer-reviewed scientific literature and, where available, grey (engineering)
98 literature.
- 99 ii. Highlight surface types, features and processes that contribute to variability in urban
100 rainfall-runoff and infiltration behaviour.
- 101 iii. Discuss the implications of this review for hydrological modelling and storm water
102 management, identifying where current understanding is lacking and where future research
103 is required.

104 A detailed evidence-based description of hydrological processes occurring on urban surfaces is
105 provided, informing future modelling and flood risk management research and policies. The aim
106 of this study is not to provide a comprehensive discourse on all available literature, but to highlight
107 and discuss the features, processes and variables likely to contribute to urban rainfall-runoff
108 response and infiltration, based on evidence extracted from analysis of observations rather than
109 predictions made using modelling systems.

110

111 **Review Methodology**

112 By focusing on empirical measurements of hydrological processes on common urban surfaces, this
113 study provides a novel approach to building understanding of the urban water cycle,
114 complementing recent hydrological reviews focussed on modelling techniques (Praskievicz and

115 Chang, 2009; Salvadore et al., 2015), management (Fletcher et al., 2013), impacts (O'Driscoll et
116 al., 2010; Shuster et al., 2005) and the detection of changes within urban catchments (Jacobson,
117 2011). This study provides details of the observed features and processes within urban catchments
118 that control urban rainfall-runoff response and thus offers a new insight into the hydrological
119 performance of perceived impervious surfaces, key to managing and understanding the urban
120 water cycle.

121 Relevant scientific studies and grey literature, identified through academic databases and web-
122 based search engines (which are more likely to identify grey literature e.g. Google Scholar), are
123 included in the review if they meet the following requirements:

- 124 i. Studies examining roads, pavements (not permeable paving), roofs (not green roofs),
125 driveways, paths and urban vegetated areas are targeted.
- 126 ii. Studies that aim to determine the physical features of urban surfaces that influence
127 hydrological behaviour (e.g. cracks, potholes, patches) are reviewed
- 128 iii. Empirical measurements of hydrological processes (infiltration, evaporation, runoff,
129 storage) on the urban surfaces are reported; whilst data inferred from large scale
130 monitoring or modelling studies are intentionally excluded from the review.
- 131 iv. Only those studies investigating surfaces within urban settings are included.
- 132 v. Priority is given to peer reviewed scientific journals or grey (engineering) literature.
133 Where relevant material was cited in a target paper outside of the available journals or
134 grey literature (i.e. PhD theses), the material was assessed for relevance and inclusion.
135 Inevitably the reviewed materials are English language based which could limit the
136 inclusion of some relevant studies. However, it is likely that the findings presented here
137 are applicable to those areas supported by non-English language based hydrological

138 communities and journals given the similarity in urban construction materials around
139 the world.

140

141 **The hydrological behaviour of roofs**

142 Roofs are typically drained via guttering to downpipes that either connect directly to the surface
143 water drainage system, drainage features within the soil (e.g. a soakaway) or to surfaces adjacent
144 to the building perimeter (e.g. garden, path etc.). Depending on downpipe discharge point, runoff
145 from roofs can directly contribute to catchment runoff (via the surface water drainage system),
146 local soil moisture and groundwater recharge or the wetting of local surfaces. Estimating the
147 proportion of roofs with a direct connection to storm water drains requires significant effort (Lee
148 and Heaney, 2003), which is difficult to extrapolate from catchment to catchment. Roofs have been
149 studied for their potential to provide water for domestic grey water uses (Villarreal and Dixon,
150 2005), their pollutant production potential (Davis et al., 2001) and in comparison to green roofs
151 (Bliss et al., 2009); but only a limited number of studies have specifically investigated and reported
152 roof runoff characteristics, limiting comparative analyses. Results published in the scientific
153 literature suggest that roofs typically convert a large proportion of rainfall into runoff, with
154 measurements of up to 92% of rainfall shown by Farreny et al. (2011), 77% by Ragab et al. (2003a)
155 and 57% by Hollis and Ovenden (1988b). Rainfall that is not converted to runoff in these studies
156 is assumed to evaporate. The materials of construction (Farreny et al., 2011), slope and orientation
157 (Ragab et al., 2003a) and total rainfall depth (Hollis and Ovenden, 1988b) influence roof rainfall-
158 runoff behaviour, meaning that performance is highly variable between roofs (see Tables 1 & 2).

159

160 Table 1: Annual rainfall, runoff and evaporation estimates for six roofs studied by Ragab et al.
 161 (2003a) and average percentage runoff values recorded by Farreny et al. (2011).

	Roof	1	2	3	4	5	6	
Ragab et al. (2003a)	Slope	22.0	22.0	22.0	50.0	0.0	0.0	
	Orientation	N-S	E-W	E-W	N-S	N/A	N/A	
	Annual values	Runoff (%)	75.4	88.6	66.6	100.	9	70.5
		Evaporation (%)	24.7	13.6	33.4	56.2	9.3	32.2
	Monthly Values	Max (%)	84.7	104	86.1	121	81.6	71.0
		Min (%)	45.7	70.5	38.3	49.4	48.2	45.6
		Mean (%)	71.1	85.6	61	90.5	66.7	58.1
Farreny et al.	Roof material	Clay tiles (30° slope)	Metal sheeting (30° slope)	Polycarbonate plastic (30° slope)	Flat gravel			
	Annual average percentage runoff (%)	0.84 ± 0.01	0.92 ± 0.00	0.91 ± 0.01	0.62 ± 0.04			

162

163 Table 2: Mean and monthly percentage runoff values recorded by Hollis and Ovenden (1988b) for
 164 roads and roofs in the south east of the UK.

Month	For all storms		Storms >5mm	
	Mean for roads	Mean for roofs	Mean for roads	Mean for roofs
Jan	6.5	47.3	20.5	125.2
Feb	6.9	49.4	10.2	37.8
Mar	1.1	47.5		
Apr	18	60.9	25.3	75.1
May	17.4	42.4	36.2	97
Jun	9.7	65	36.9	91.9
Jul	10.2	71.5	33.2	154.8
Aug	36.6	86.3		
Sep	15.6	62.1	33.1	80.6
Oct	8.3	45.1	37.9	76.6
Nov	7.8	30.1	23.7	74
Dec	8.6	58.8	25.9	90.9
Mean	11.4	56.9	28.3	90.4

165

166 **The hydrological behaviour of roads**

167 Road infrastructure (e.g. roads, pavements, car parks) can represent a large proportion of urban
168 surfaces connected directly to a surface water drainage system i.e. Lee and Heaney (2003) report
169 that in a residential study area of Colorado (USA) 68% of directly connected urban surfaces are
170 transport related. Road surfaces typically consist of a number of layers of materials, whose
171 interlocking aggregates and binding materials provide a surface resistant to loading and
172 mechanical wear. Typically constructed of asphalt, concrete or tar-macadam, an important purpose
173 of the topmost layer (the wearing course) is to provide an impermeable barrier for water, as water
174 ingress and movement can rapidly degrade the integrity of supporting layers and compromise the
175 strength of a road (Dawson et al., 2009). Therefore, road surfaces are often assumed to be highly
176 impervious, allowing only limited infiltration of water into the soil (Wiles and Sharp, 2008).
177 Studies examining the hydrological performance of road related surfaces are available at a range
178 of scales from $<1\text{m}^2$ (Ramier et al., 2004) to $>100\text{m}^2$ (Hollis and Ovenden, 1988b); applying
179 methodologies that involve isolating individual surfaces and monitoring runoff in comparison to
180 meteorological parameters (such as rainfall or temperature).

181 At small spatial scales, total runoff can account for a large proportion of rainfall on common road
182 surface materials (Pandit and Heck, 2009). In tests by Mansell and Rollet (2006) on 300x300 mm
183 slabs of concrete paving, brick paving and tar macadam surfacing, runoff is reported to represent
184 a significant proportion of rainfall volumes for the continuous surfaces (Table 3) with slope and
185 gaps influencing the hydrological behaviour. Infiltration into the road structure itself is low for all
186 considered surfaces (2% or 0%), whilst the gaps between elements in the brick surfacing allowed
187 on average 52% of rainfall to infiltrate into the underlying soils.

189 Table 3: Water balance components for common urban surface types from direct measurements
 190 reported by Mansell and Rollet (2006) and Ramier et al. (2004).

Study	Surface Type	Runoff (Av. % of rainfall)	Infiltration (Av. % of rainfall)	Evaporation (Av. % of rainfall)	Infiltration through joints (% of rainfall)
Rollet & Mansell (2006)	Flat Concrete				
	Slab	69	1	30	
	Inclined Concrete Slab	93	2	5	
	Brick Work	9	2	37	52
Mansell (2006)	Hot Rolled Asphalt	56	0	44	
	Dense Bitumen Macadam	36	0	64	
	Asphalt Concrete (deteriorated) (15% porosity)	16	58	26	
Ramier et al. (2004)	Asphalt Concrete (5% porosity)	74	3	23	
	Asphalt Concrete (5% porosity)	73	2	25	

191

192 The permeability of asphaltic mixtures is controlled by the size and interconnectivity of pore
 193 spaces (Dawson et al., 2009). Vivar and Haddock (2007) identified that increasing porosity (a
 194 function of aggregate mix) influences the permeability of new road surfaces in laboratory
 195 experiments, where porosities over 7% show rapid increases in permeability. The deterioration of
 196 condition of surface materials can increase the permeability of a road surface, reducing the
 197 proportion of rainfall converted to runoff. By applying a specially developed urban lysimeter,
 198 Ramier et al. (2004) measured components of the water balance on three samples of asphalt
 199 concrete, of the three samples tested, one surface was more porous than the other two (15%
 200 porosity rather than 5%) arising from a deteriorated condition. On the sample with increased

201 porosity (deteriorated condition), infiltration is reported to account for 58% of rainfall, runoff 16%,
202 with the remaining 26% lost to evaporation. The less porous (good condition) samples evidenced
203 infiltration rates of 2-3%, with runoff at 73-74% and evaporation at ~24% of rainfall (Table 3). In
204 summary, small samples of road surfaces and newly constructed materials can convert a large
205 proportion of rainfall into runoff, whilst infiltration is limited, but where surface condition has
206 deteriorated infiltration can occur.

207 The hydrological performance of actual in-situ roads is highly variable, both in space and time. In
208 an analysis of the rainfall-runoff performance of ten roads over 12 months, Hollis and Ovenden
209 (1988b) report average runoff values of 11.4% for rainfall events under 5mm in depth (Table 2),
210 with percentage runoff in individual months ranging from 1.1% for March to 36.6% for August.
211 For rainfall events over 5 mm in depth the annual average increases to 28.3%, ranging from 10.2-
212 37.9% for monthly average values. These results are surprisingly low given commonly held
213 assumptions of the impermeability of road surfaces and may relate to the initial loss of precipitation
214 to storage on the road surfaces (Kidd and Lowing, 1979). However, other studies have confirmed
215 the variable conversion of rainfall into runoff upon roads (Ramier et al., 2011; Rodriguez et al.,
216 2000). Ragab et al. (2003b) identified contradictory seasonal patterns of rainfall runoff behaviour
217 when compared to that recorded by Hollis and Ovenden (1988b), with 70% of annual rainfall
218 converted into runoff with a peak in winter (90%) and lower values in summer (50%). Comparing
219 Ragab et al. (2003b) and Hollis and Ovenden (1988b) suggests that rainfall - runoff processes on
220 urban surfaces are complex, with contradictory seasonal patterns exhibited between the two
221 studies. Each study measured urban rainfall and runoff within the south east UK; though Hollis
222 and Ovenden (1988b) worked within a permeable soils catchment, whilst Ragab et al. (2003a)

223 worked in an area dominated by clay soils, suggesting that soil type influences the urban surfaces'
224 infiltration and runoff behaviour.

225 The loss of rainfall from road surfaces can be investigated through a number of field measurement
226 techniques, making either direct or indirect measurements of infiltration, storage and evaporation.

227 Depending on the hydrological process and type of surface studied, different units are used within
228 the literature to report empirical results, making direct comparisons between studies challenging.

229 Ragab et al. (2003b) used soil moisture sensors installed underneath in-situ impervious surfaces
230 (three car parks and one road) to show that between 6-9% of annual rainfall infiltrated through the

231 impervious surface, with evaporation accounting for between 21-24% of rainfall, with greater
232 evaporation in summer than winter. Irrigation experiments by Hollis and Ovenden (1988a)

233 compared the infiltration losses recorded at kerb joins and on road surfaces, where infiltration
234 losses reported are variable between sites and over time. For road surface experiments infiltration

235 rates range between 0.0119-0.0590 l/min/m², whilst for kerb experiments infiltration rates range
236 between 0.325-7 l/min/m (Figure 1). A seasonal pattern of increased infiltration rates in winter

237 months is attributed to freeze-thaw action opening pore spaces within the road surface. In some
238 cases large volumes of water are applied before runoff occurred (from 0.5mm equivalent rainfall

239 depth to greater than 16.7mm equivalent rainfall depth), indicating that initial losses of rainfall are
240 considerable, highly variable and difficult to generalise between the studied roads. A similar

241 irrigation experiment by Zondervan (1978) estimated infiltration rates of between 7-27 mm/hr on
242 road surfaces, with infiltration attributed to cracks and joins in the surface, as solid road samples

243 were taken and subjected to laboratory experiments with infiltration losses of 0.5 mm/hr recorded;
244 supporting the findings of Ridgeway (1976) who also identified that cracks, joins and fractures in

245 road surfacing could explain high rates of infiltration. Using a double ring infiltrometer to directly

246 measure infiltration through road surfaces in residential and commercial areas in Austin, USA,
247 Wiles and Sharp (2008) report that up to 20% of the annual water balance of the area could be
248 accounted for by infiltration through impervious road surfaces, though highly variable over space,
249 with up to a third of experiments recording no infiltration. An analysis comparing the fracture and
250 joint apertures against the infiltration rate offered no correlation, suggesting that the sub-surface
251 structure of surfaces and soil conditions influences infiltration, rather than the size of fracture or
252 joint in the surface.

253

254 [Insert Figure 1]

255

256 The age and traffic loading on road surfaces influences infiltration potential. For example,
257 Fernandez-Barrera et al. (2008) using a “Laboratorió de Caminos de Santander” (LCS)
258 permeameter found an eleven year old impervious asphalt and a heavily trafficked pervious asphalt
259 to have a similar infiltration potential to that of a clay-soil grass surface (Table 4). Roads are often
260 resurfaced in patches either to repair areas of poor condition (i.e. pot holes or cracks) or to cover
261 areas that have been excavated for infrastructure trenches (e.g. water, electricity, broadband
262 infrastructure etc.). Depending on the quality of the join between patching and extant surfacing,
263 preferential pathways for infiltration can form with up to 8.78 l/hr/m² recorded around patches by
264 Taylor (2004).

265

266 Table 4: Infiltration rates through common urban surface types recorded by two techniques (data
 267 taken from Fernandez-Barrera et al. (2008) and Gilbert and Clausen (2006). High LCS
 268 Permeameter results indicate low infiltration rates.

	Surface type	Description of experiment	LCS Permeameter average results (s)
Barrera et al., (2008)	Reinforced Grass (concrete cells)	Clay soil	1223.86
	Reinforced Grass (plastic cells)	Sandy Soil	150.94
	Impervious Asphalt	New surface course (1 years)	>1800
		Old surface course (11 years)	1233.34
	Impervious Asphalt	High traffic intensity	1052.01
	Impervious Asphalt	Light traffic intensity	21.21
	Concrete block impervious pavement	Mortar in joints	21.77
	Concrete block pervious pavement	No fill between joints	4.55
	Metallic plate		>1800
	Gilbert & Clausen (2006)	Surface	Description of infiltration test
Asphalt		Single ring (2002)	0
		Single ring (2003)	0
		Flowing (2003)	0
Paver		Single ring (2002)	11.8±9.5
		Single ring (2003)	10.5±5.9
		Flowing (2003)	11.4
Crushed stone		Single ring (2002)	11.3±3.1
		Single ring (2003)	9.7±7.8
		Flowing (2003)	6

269

270 Surfaces within domestic curtilages (e.g. driveways) or public open spaces (e.g. paths) are often
 271 constructed of similar materials to road surfaces, or of non-continuous surfaces such as gravel,
 272 concrete slabs or bricks. However, they may not have direct connections to the surface water
 273 drainage system and instead may discharge to nearby permeable surfaces. Understanding the
 274 hydrology of these surfaces is important, as changes in surface types within domestic areas has
 275 been cited as a mechanism leading to increased surface water flood risk, as vegetated gardens are
 276 replaced by car parking areas (Perry and Nawaz, 2008). Grass surfaces can be reinforced to allow

277 movement of vehicles with limited impacts on infiltration capacity (Fernandez-Barrera et al.,
278 2008), whilst concrete paving and crushed stone surfacing have been shown to allow
279 comparatively greater infiltration than that of asphalt (Gilbert and Clausen (2006); Table 4). The
280 significance of changes in domestic surface cover is therefore likely dependant on the materials of
281 construction and connectivity to the surface water drainage system.

282 In summary, roads exhibit a complicated hydrological behaviour that varies both over space and
283 time. Whilst small samples of new road surface materials studied in laboratory conditions are
284 shown to be highly impermeable, actual in situ roads that have been in place for a number of years
285 are shown to allow considerable infiltration. It is likely that the hydrological properties of road
286 surfaces change over different timescales. Over the short (minutes to months) timescale evidence
287 suggests that between rainfall event variability can be explained in part by variations in the
288 connectivity of pore spaces within road structures, caused by temperature related expansion and
289 contraction; with the hydrological properties of the underlying soil also contributing to variability.
290 Over longer timescales (years to decades) the hydrological properties of a road surface may
291 change, as wearing and weathering processes degrade the impervious nature of the uppermost
292 wearing course. The gradual or rapid subsidence of underlying soils may also encourage the
293 degradation of road surfaces, by encouraging cracking and fracturing.

294

295 **Hydrological behaviour of urban green spaces and soils**

296 Urban areas contain vegetated surfaces (e.g. gardens, parks and road side verges) which need
297 characterising in hydrological models and in storm water management planning (Law et al., 2009).
298 This is difficult given that few studies have investigated the variability of soil hydrological
299 properties in urban ecosystems through empirical measurements (Ossola et al., 2015).

300 Understanding the hydrological characteristics and infiltration capacity of urban green spaces and
301 soils is significant for the sustainable management of storm water, as urban green spaces are often
302 cited as potential areas for storm water disconnection (Dietz and Clausen, 2008).

303 Typically urban green spaces are perceived as pervious surfaces or modelled with similar
304 characteristics to more natural vegetated areas (Gregory et al., 2006). However, urbanisation can
305 impact on the physical properties of underlying soils in a manner that impacts on the hydrological
306 characteristics of urban green spaces through two linked systems of direct and indirect impacts
307 (Pouyat et al., 2010). First, direct impacts include those in the immediate timescale of urban
308 development such as the loss of vegetation, removal of top soils, importation of foreign soils and
309 aggregates and static (buildings) and dynamic (cars and vehicles) compaction of soils (Cogger,
310 2005); meaning that urban soils can become highly degraded in terms of water retention capacity
311 and infiltration potential (Pitt et al., 2008). Second, indirect impacts of urbanisation on soils
312 involve changes in the biotic and abiotic environment that can affect undisturbed soils in proximity
313 to urban developments, which include a changed urban climate (urban heat island effect) (Muller
314 et al., 2014), increased soil hydrophobicity and the deposition of pollutants (i.e. heavy metals, N
315 and S) (White and McDonnell, 1988). Urban development usually follows a pattern of parcelization
316 based upon land ownership, which creates discreet parcels with separate soil disturbances and
317 management regimes, so that soils develop differential properties over time, resulting in a complex
318 mosaic of soil disturbance at small spatial scales (Scharenbroch et al., 2005).

319 Studies have shown that urban soils are more compacted than natural soils, with a larger proportion
320 of large stones, poorer structure and less porosity with a reduced ability to hold water or allow root
321 growth (Jim, 1998). The impact of large stone fragments on soil infiltration is complex, with the
322 potential to increase or decrease infiltration depending on whether the stones are within the soil

323 column or on the surface. Surface rock cover can increase soil strength, reducing the compaction
324 as a result of loading with the potential to resist changes in soil structure (Brakensiek and Rawls,
325 1994). The compaction of urban soils can reduce infiltration potential, altering the proportion of
326 rainfall that is converted to runoff (Yang and Zhang, 2011). Pitt et al. (2002) found that the
327 modelled response of a residential development with a natural soil surface under-predicted runoff,
328 and that urban soils had runoff behaviour similar to impervious cover. Similarly Legg et al. (1996)
329 found that newly established residential lawns showed runoff coefficients of between 60-70%,
330 whilst older more established lawns had coefficients of between 5-30%. The infiltration
331 performance of an urban, compacted clay soil is shown to be similar to a saturated natural clay
332 soil; whilst compaction reduced infiltration rates of dry sandy soils by around 90%, irrespective of
333 antecedent conditions (Pitt et al., 2008).

334 Different vegetation cover can influence the hydrological properties of urban green spaces.
335 Increased complexity of vegetation type, the properties of the litter layer, age and management
336 regimes are all found to influence physical soil properties and infiltration capacity in urban park
337 areas in Melbourne, Australia (Ossola et al., 2015). Woltemade (2010) identified that lawn surface
338 condition and percentage cover of woody vegetation influenced the degree of infiltration and
339 runoff of 108 residential lawns. However, the age of the residential development was found to
340 significantly impact the hydrological characteristics with post-2000 development having mean
341 infiltration rates 69% less than those developments constructed pre-2000, a similar conclusion to
342 Legg et al. (1996). Experimental results from (Bartens et al., 2008) suggest that tree growth and
343 root development can restore natural soil hydrological characteristics to urban soils, as roots offer
344 preferential pathways for infiltration, which overtime can penetrate through heavily compacted
345 soil layers.

346

347 **Discussion and summary**

348 This study identifies that the hydrological behaviour of urban surfaces is complex, with more
349 infiltration than often assumed. Roads and roofs have different hydrological properties, with roofs
350 potentially converting more rainfall into runoff (Table 2). Roads can degrade in condition, altering
351 their water balance over time, reducing runoff and increasing urban infiltration. The hydrological
352 behaviour of an urban area is therefore likely to not only be a function of total or connected
353 impervious cover, but related to the relative proportions of surface types, their ages and condition.
354 Future research should focus on linking the layout, age and condition of urban areas to hydrological
355 response to aid the characterisation of urban areas for inclusion in hydrological models.

356 Contemporary drainage design models are typically applied at scales within urban settings where
357 it is possible to collect highly detailed surface geospatial data. Thus, these models allow for the
358 inclusion of detailed surface characterisations with a number of hydrological processes calculable.
359 Whilst it is possible to estimate model parameters taking into account surface condition, the
360 definition of suitable model parameters is difficult (unless supported by experimental data)
361 potentially leading to poor calibration and uncertainty in model outputs (Kellagher, 2000; Evans
362 and Eadon, 2007). This study indicates that hydrological behaviour of urban areas at small scales
363 is likely sensitive to the condition and type of urban surface being drained. Developing new and
364 improved techniques to map and characterise the hydrology of different surface types and
365 conditions will aid in their inclusion within drainage design practice. The interception of runoff on
366 impervious surfaces by features such as cracks and fractures may disconnect impervious surfaces
367 from the storm water drainage system, directing runoff to infiltration, meaning caution should be
368 exerted when applying the results of small scale experimental studies in defining the hydrological

369 characteristics of urban surface cover at larger scales, as this could overestimate runoff potential
370 and underestimate urban infiltration.

371 Design models used in engineering hydrology are typically concerned with estimating runoff,
372 focussing on the sizing of storm water management assets at small scales, and so are not concerned
373 with larger scale, longer term processes such as infiltration to groundwater recharge. However,
374 understanding the infiltration of soil water into drainage assets is of increasing importance, as this
375 can increase the receding limb of hydrographs reducing capacity, particularly in older systems
376 where cracking can occur in piped surface water drainage systems (Berthier et al., 2004). The data
377 examined within this study indicates that a significant proportion of an urban areas' water balance
378 can infiltrate through road surfaces (20% recorded by Wiles & Sharpe, 2008), which may
379 contribute to pipe infiltration. Variable hydrograph behaviour in urban drainage systems therefore
380 is likely sensitive to a combination of rainfall, soil moisture and groundwater conditions,
381 depending on the physical characteristics of the urban surface. This study has found that the
382 hydrological properties of urban surfaces can change over long and short time-scales. Detailed
383 representation of such processes could be challenging in design practice, which is often focused
384 on event based rainfall-runoff modelling and time static parameterisation of urban surfaces (Rauch
385 et al., 2002).

386 At larger, whole-catchment scales, where typically the large-scale impacts of urbanisation on
387 hydrology are investigated, the detailed definition of impervious surface cover is less practical, but
388 potentially of equal importance given the number of hydrological processes that build to larger-
389 scale, long term hydrological behaviour (Salvadore et al., 2015). Evidence of infiltration through
390 impervious surface types demonstrates that impervious covers should not be assumed to be 100%
391 impermeable to the infiltration of precipitation. Establishing how small scale hydrological

392 processes (as reviewed within this study) translate into large scale hydrological behaviour is
393 therefore a priority, in particular the trade-off between spatial-temporal resolution of data and
394 process representation against gain in terms of predictive accuracy, i.e. model complexity vs.
395 predictive ability. This study highlights the importance of the accurate definition of surface types
396 and condition within urban areas, for representing urban land cover within hydrological models. It
397 is likely that without detailed ground-truthing of impervious cover from aerial photographs and
398 remote sensing, runoff production potential within urban settings could be overestimated if
399 surfaces are assumed to be wholly impervious. Finding improved ways of defining surface cover
400 at small scales within urban areas should therefore be a priority.

401 Green spaces such as gardens or parkland are often considered to be permeable and therefore allow
402 the infiltration of water (Law et al., 2009) which includes runoff from impervious surfaces on to
403 green surfaces or *vice versa*, with some modelling techniques able to include surface interactions
404 (Shaw et al., 2010). However this study has found that urban green spaces and soils can be heavily
405 degraded in their water holding capacity and infiltration potential. There is currently little guidance
406 available on how best to represent urban pervious land cover with degraded soil properties within
407 hydrological models (Law et al., 2009). Therefore understanding of how urban green surfaces
408 contribute to urban rainfall-runoff behaviour should be improved to include a better representation
409 of the impacts of urbanisation on soil hydrological characteristics.

410 Increasing infiltration within urban areas is often cited as a mechanism by which the impacts of
411 urbanisation on low flows and groundwater could be mitigated (Hamel et al., 2013), with a number
412 of permeable pavement technologies available to increase infiltration (Scholz and Grabowiecki,
413 2007), whilst such technologies are also advocated as a means of reducing flood risk at local scales
414 within urban settings (DCLG, 2014). However, this review has found evidence for significant

415 infiltration on common urban road surfaces, particularly on aged surfaces where features such as
416 cracks and joins offer preferential pathways for infiltration. Therefore future research should aim
417 to determine how effective the retro-fitting of permeable surfacing technologies is, given a more
418 accurate description of existing urban hydrological processes on extant urban surfaces presented
419 in this review.

420 The importance of understanding and managing the hydrological behaviour of urban surfaces will
421 increase as projected changes in extreme precipitation events (Murphy et al., 2009), combined
422 with further urban development and expanding urban surface cover will likely present greater
423 challenges to flood and water management over coming decades (Stocker et al., 2014).

424

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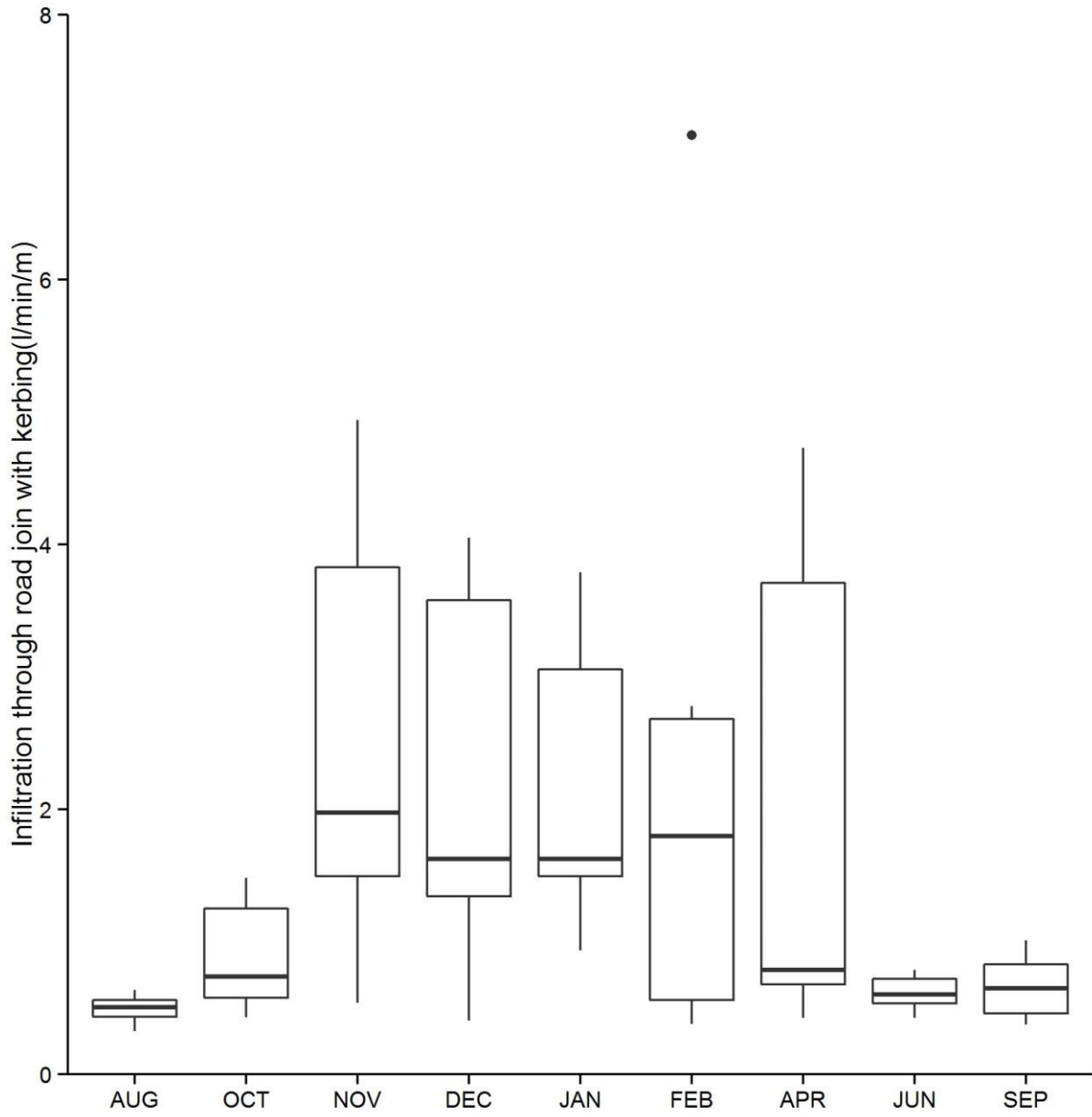
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641

642

643 FIGURE 1



644