Citation for published version:
Redfern, T, Macdonald, N, Kjeldsen, T, Miller, J & Reynard, N 2016, 'Current understanding of hydrological processes on common urban surfaces', Progress in Physical Geography, vol. 40, no. 5, pp. 699-713. https://doi.org/10.1177/0309133316652819

DOI:
10.1177/0309133316652819

Publication date:
2016

Document Version
Peer reviewed version

Link to publication

Current understanding of hydrological processes on common urban surfaces.

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

Abstract

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

Introduction

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

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

Modern storm water management practices have developed away from the historical focus on removing surface water as quickly and efficiently as possible, reflecting the need to address the larger scale impacts of urbanisation on the hydrological cycle (Charlesworth et al., 2003). To reduce runoff volumes and improve urban runoff water quality, contemporary storm water management technologies aim to reduce and disconnect impervious surfaces from the storm water drainage system (Walsh et al., 2005), use pervious areas and engineered surface features to increase infiltration and therefore groundwater recharge (Hamel et al., 2013) and construct artificial areas of storage within urban catchments (Woods-Ballard et al., 2007). The legacy of extant urban developments combined with climate change and increasing imperviousness within urban areas (urban creep) means retrofitting the existing built environment with modern storm water management techniques has become a priority (MacDonald, 2011), both for local flood risk management and for the mitigation of hydrological impacts in urbanised catchments. Understanding the runoff generation processes and infiltration potential of diverse urban land surfaces is therefore a priority for the design and implementation of storm-water management policies and technologies (Salvadore et al., 2015).

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

The ability of hydrological models to accurately replicate the impacts of urbanisation on the hydrological system is reliant upon the accurate representation, mathematical description and parameterisation of rainfall-runoff processes on urban surfaces (Packman, 1980). However, no universally accepted characterisation of urban surfaces for inclusion in hydrological models exists (Shields and Tague, 2012) leading to a large number of hydrological models, with a high degree of variability in the representation of hydrological processes in urban areas (Salvadore et al., 2015). Commonly roads, roofs and other constructed surfaces are grouped together as *impervious surfaces*, with estimates of their extent determined from aerial photographs, maps (Miller et al., 2014) or remote sensing (see review by Slonecker et al. (2001)). Impervious surfaces are often assumed to prevent precipitation from directly infiltrating into the soil, converting high proportions of rainfall into direct runoff (Jacobson, 2011). Representing the hydrological behaviour of impervious surfaces is often based on estimates e.g. percentage runoff = 70%, (Packman, 1980; Kjeldsen, 2009), theoretical assumptions e.g. infiltration= 0% (Wiles and Sharp, 2008), or the application of previously calibrated techniques linking the degree of imperviousness to hydrological behaviour (Holman-Dodds et al., 2003). Other techniques include estimating the hydrological characteristics of impervious surfaces as a function of proximity to the stream network (Franczyk and Chang, 2009), or as a function of land use (Baker and Miller, 2013). This list is by no means exhaustive and many other methods have been applied within the literature (Salvadore et al., 2015). The outputs of hydrological models are therefore sensitive to the determination of the extent of imperviousness, degree of connectivity to the surface water drainage system (Roy and Shuster, 2009) and the definition of hydrological processes on urban surfaces (Yao et al., 2016; Beighley et al., 2009). However, there is currently no thorough understanding of hydrological processes occurring on extant urban surface types; as little research has assessed the veracity of the underlying assumptions regarding the imperviousness of impervious surfaces, or provided detailed assessments of the hydrological properties of other types of urban surface (Evans and Eadon, 2007). The aim of this study is to review empirical measurements of hydrological processes upon common urban surface types, through three objectives:

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

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

Review Methodology

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

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

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

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

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

The hydrological behaviour of roofs

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

Table 1: Annual rainfall, runoff and evaporation estimates for six roofs studied by Ragab et al. (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	61.5
		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 (30^0 slope)**	**Metal sheeting (30^0 slope)**	**Polycarbonate plastic (30^0 slope)**	**Flat gravel**			
	Annual average percentage runoff (%)	0.84 ± 0.01	0.92 ±0.00	0.91 ± 0.01	0.62 ± 0.04			

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

	For all storms		**Storms >5mm**	
Month	**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

The hydrological behaviour of roads

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

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

Table 3: Water balance components for common urban surface types from direct measurements 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)
Mansell & Rollet (2006)	Flat Concrete Slab	69	1	30	
	Inclined Concrete Slab	93	2	5	
	Brick Work	9	2	37	52
	Hot Rolled Asphalt	56	0	44	
	Dense Bitumen Macadam	36	0	64	
Ramier et al. (2004)	Asphalt Concrete (deteriorated) (15% porosity)	16	58	26	
	Asphalt Concrete (5% porosity)	74	3	23	
	Asphalt Concrete (5% porosity)	73	2	25	

The permeability of asphaltic mixtures is controlled by the size and interconnectivity of pore spaces (Dawson et al., 2009). Vivar and Haddock (2007) identified that increasing porosity (a function of aggregate mix) influences the permeability of new road surfaces in laboratory experiments, where porosities over 7% show rapid increases in permeability. The deterioration of condition of surface materials can increase the permeability of a road surface, reducing the proportion of rainfall converted to runoff. By applying a specially developed urban lysimeter, Ramier et al. (2004) measured components of the water balance on three samples of asphalt concrete, of the three samples tested, one surface was more porous than the other two (15% porosity rather than 5%) arising from a deteriorated condition. On the sample with increased porosity (deteriorated condition), infiltration is reported to account for 58% of rainfall, runoff 16%, with the remaining 26% lost to evaporation. The less porous (good condition) samples evidenced infiltration rates of 2-3%, with runoff at 73-74% and evaporation at ~24% of rainfall (Table 3). In summary, small samples of road surfaces and newly constructed materials can convert a large proportion of rainfall into runoff, whilst infiltration is limited, but where surface condition has deteriorated infiltration can occur.

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

The loss of rainfall from road surfaces can be investigated through a number of field measurement techniques, making either direct or indirect measurements of infiltration, storage and evaporation. Depending on the hydrological process and type of surface studied, different units are used within the literature to report empirical results, making direct comparisons between studies challenging. Ragab et al. (2003b) used soil moisture sensors installed underneath in-situ impervious surfaces (three car parks and one road) to show that between 6-9% of annual rainfall infiltrated through the impervious surface, with evaporation accounting for between 21-24% of rainfall, with greater evaporation in summer than winter. Irrigation experiments by Hollis and Ovenden (1988a) compared the infiltration losses recorded at kerb joins and on road surfaces, where infiltration losses reported are variable between sites and over time. For road surface experiments infiltration rates range between 0.0119-0.0590 l/min/m^2, whilst for kerb experiments infiltration rates range between 0.325-7 l/min/m (Figure 1). A seasonal pattern of increased infiltration rates in winter months is attributed to freeze-thaw action opening pore spaces within the road surface. In some cases large volumes of water are applied before runoff occurred (from 0.5mm equivalent rainfall depth to greater than 16.7mm equivalent rainfall depth), indicating that initial losses of rainfall are considerable, highly variable and difficult to generalise between the studied roads. A similar irrigation experiment by Zondervan (1978) estimated infiltration rates of between 7-27 mm/hr on road surfaces, with infiltration attributed to cracks and joins in the surface, as solid road samples were taken and subjected to laboratory experiments with infiltration losses of 0.5 mm/hr recorded; supporting the findings of Ridgeway (1976) who also identified that cracks, joins and fractures in road surfacing could explain high rates of infiltration. Using a double ring infiltrometer to directly measure infiltration through road surfaces in residential and commercial areas in Austin, USA, Wiles and Sharp (2008) report that up to 20% of the annual water balance of the area could be accounted for by infiltration through impervious road surfaces, though highly variable over space, with up to a third of experiments recording no infiltration. An analysis comparing the fracture and joint apertures against the infiltration rate offered no correlation, suggesting that the sub-surface structure of surfaces and soil conditions influences infiltration, rather than the size of fracture or joint in the surface.

[Insert Figure 1]

The age and traffic loading on road surfaces influences infiltration potential. For example, Fernandez-Barrera et al. (2008) using a "Laboratorió de Caminos de Santander" (LCS) permeameter found an eleven year old impervious asphalt and a heavily trafficked pervious asphalt to have a similar infiltration potential to that of a clay-soil grass surface (Table 4). Roads are often resurfaced in patches either to repair areas of poor condition (i.e. pot holes or cracks) or to cover areas that have been excavated for infrastructure trenches (e.g. water, electricity, broadband infrastructure etc.). Depending on the quality of the join between patching and extant surfacing, preferential pathways for infiltration can form with up to 8.78 $l/hr/m^2$ recorded around patches by Taylor (2004).

Table 4: Infiltration rates through common urban surface types recorded by two techniques (data taken from Fernandez-Barrera et al. (2008) and Gilbert and Clausen (2006). High LCS 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
	Impervious Asphalt	Old surface course (11 years)	1233.34
	Porous Asphalt	High traffic intensity	1052.01
	Porous 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**	**Infiltration rate (cm/h)**
	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

Surfaces within domestic curtilages (e.g. driveways) or public open spaces (e.g. paths) are often constructed of similar materials to road surfaces, or of non-continuous surfaces such as gravel, concrete slabs or bricks. However, they may not have direct connections to the surface water drainage system and instead may discharge to nearby permeable surfaces. Understanding the hydrology of these surfaces is important, as changes in surface types within domestic areas has been cited as a mechanism leading to increased surface water flood risk, as vegetated gardens are replaced by car parking areas (Perry and Nawaz, 2008). Grass surfaces can be reinforced to allow movement of vehicles with limited impacts on infiltration capacity (Fernandez-Barrera et al., 2008), whilst concrete paving and crushed stone surfacing have been shown to allow comparatively greater infiltration than that of asphalt (Gilbert and Clausen (2006); Table 4). The significance of changes in domestic surface cover is therefore likely dependant on the materials of construction and connectivity to the surface water drainage system.

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

Hydrological behaviour of urban green spaces and soils

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

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

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

Studies have shown that urban soils are more compacted than natural soils, with a larger proportion of large stones, poorer structure and less porosity with a reduced ability to hold water or allow root growth (Jim, 1998). The impact of large stone fragments on soil infiltration is complex, with the potential to increase or decrease infiltration depending on whether the stones are within the soil column or on the surface. Surface rock cover can increase soil strength, reducing the compaction as a result of loading with the potential to resist changes in soil structure (Brakensiek and Rawls, 1994). The compaction of urban soils can reduce infiltration potential, altering the proportion of rainfall that is converted to runoff (Yang and Zhang, 2011). Pitt et al. (2002) found that the modelled response of a residential development with a natural soil surface under-predicted runoff, and that urban soils had runoff behaviour similar to impervious cover. Similarly Legg et al. (1996) found that newly established residential lawns showed runoff coefficients of between 60-70%, whilst older more established lawns had coefficients of between 5-30%. The infiltration performance of an urban, compacted clay soil is shown to be similar to a saturated natural clay soil; whilst compaction reduced infiltration rates of dry sandy soils by around 90%, irrespective of antecedent conditions (Pitt et al., 2008).

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

Discussion and summary

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

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

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

At larger, whole-catchment scales, where typically the large-scale impacts of urbanisation on hydrology are investigated, the detailed definition of impervious surface cover is less practical, but potentially of equal importance given the number of hydrological processes that build to larger-scale, long term hydrological behaviour (Salvadore et al., 2015). Evidence of infiltration through impervious surface types demonstrates that impervious covers should not be assumed to be 100% impermeable to the infiltration of precipitation. Establishing how small scale hydrological processes (as reviewed within this study) translate into large scale hydrological behaviour is therefore a priority, in particular the trade-off between spatial-temporal resolution of data and process representation against gain in terms of predictive accuracy, i.e. model complexity vs. predictive ability. This study highlights the importance of the accurate definition of surface types and condition within urban areas, for representing urban land cover within hydrological models. It is likely that without detailed ground-truthing of impervious cover from aerial photographs and remote sensing, runoff production potential within urban settings could be overestimated if surfaces are assumed to be wholly impervious. Finding improved ways of defining surface cover at small scales within urban areas should therefore be a priority.

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

Increasing infiltration within urban areas is often cited as a mechanism by which the impacts of urbanisation on low flows and groundwater could be mitigated (Hamel et al., 2013), with a number of permeable pavement technologies available to increase infiltration (Scholz and Grabowiecki, 2007), whist such technologies are also advocated as a means of reducing flood risk at local scales within urban settings (DCLG, 2014). However, this review has found evidence for significant infiltration on common urban road surfaces, particularly on aged surfaces where features such as cracks and joins offer preferential pathways for infiltration. Therefore future research should aim to determine how effective the retro-fitting of permeable surfacing technologies is, given a more accurate description of existing urban hydrological processes on extant urban surfaces presented in this review.

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

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