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Review Article

Hydrological balance of paved surfaces in moist mid-latitude climate – A review

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ABSTRACT

Growing urbanisation and an increase of paved surfaces lead to drastic changes of the urban hydrological cycle. Pavements are often perceived and modelled as runoff generator that prevents any kind of infiltration and inhibits evaporation. This review takes a closer look at different paving materials and examines their water transport processes and the resulting hydrological balance by collecting and evaluating literature data and descriptions. Hydrological balance and water retention capacities are collected for numerous materials, ranging from asphalt to infiltration-active grass pavers, for moist mid-latitude climate. The assessment demonstrates that evaporation and infiltration from paved surfaces play an important role and often exceed the expected values. This results in a new classification of sealing degrees for rough estimations of the annual hydrological balance of different paving materials. Additionally, common modelling concepts and possible sources for detailed land cover data are introduced and reflected. The review concludes that paving materials are much more active and complex systems than often assumed.

1. Introduction

Rapid urbanisation is a process attracting worldwide attention in many different scientific research areas. As of 2014, 54% of the global population was living in cities, with 59 countries exceeding 80% urbanisation and some countries like Belgium reaching up to 98% (UN, 2014). This trend is expected to continue with two thirds of the world population becoming urban by 2050 (UN, 2014). Linked to urbanisation is a significant alteration of our environment which creates many challenges, such as flooding (Haase, 2009; Pistocchi, Calzolari, Malucelli, & Ungaro, 2015; Qin, Li, & Fu, 2013), air pollution (Rodríguez, Dupont-Courtade, & Oueslati, 2016) and altered, heterogeneous microclimates (Chatzidimitriou & Yannas, 2015).

Of these alterations, soil sealing is often seen as the main driver for the challenges attributed to urbanisation, with many studies from numerous fields focusing on the hydrological impact of paved areas (e.g. Bhaduri, Minner, Tatalovich, & Harbor, 2001; EC, 2012; Scalenghe & Marsan, 2009). Depending on the discipline, pavements may be seen in many different ways, e.g. as necessity for urban life, runoff generator and pollution source, storage for heat and water, or a product to be optimized. Table 1 gives an overview of communities researching and designing pavements. While some of these have been dealing with pavements for a long time (e.g. road construction and urban planning), the subject might be relatively new to others (urban water ecology and climatology). Based on different priorities (e.g. safety, function, ecological impact, drainage), they make use of a wide range of measurement scales and methods. From a soil science perspective, soil sealing is considered to irreversibly destroy natural soil functions (Morel, Chenu, & Lorenz, 2015) and to reduce the soils ecological functionality (Lehmann & Stahr, 2007). Similarly, urban hydrologists perceive soil sealing as the cause for drastically altered hydrological balances, which is most visible in storm water and flood generation after heavy rainfalls (Hibbs & Sharp, 2012; Salvadore, Bronder, & Batelaan, 2015). These impacts illustrate why paved surfaces are seen as the key urban water interface, determining transformation and transport processes of water, matter, and energy between the soil and atmosphere in urban areas (Gessner et al., 2014).

With a focus on addressing safety issues such as flood prevention and increased water pollution, pavements are often seen as an impermeable runoff generator (Fletcher, Andrieu, & Hamel, 2013; Jacobson, 2011) and pollutant source (Göbel, Dierkes, & Coldewey, 2007). Accordingly, over the last few decades models have been developed for water transport at the surface, their input to streams and sewer networks, and the effectiveness of storm water remediation measures such as localised recharge areas. To our best knowledge, this quick development of numerous models is often based on few measured data. Soil sealing with any material is often defined as the prevention of any infiltration and evaporation, resulting in very little or no losses in

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Table 1
Disciplines dealing with water transport processes of paved surfaces.

Field	Paving seen as	Elements & Keywords	Priority
Urban Planning[1]	Necessity for urban life and functions	Land-use, Urban life, Habitat quality, Streetscape	Design, Function, Safety, Public health
Road Construction[2]	Product to be optimized	Material properties, Freeze-Thaw-Cycles, Deterioration	Safety, Durability, Cost efficiency
Urban Water Management[3]	Runoff generator, Pollution source	Urban water cycle, Water supply, Drainage, Storm water management, Sanitation, Rainwater harvesting	Water quality & quantity, Decision tools, Management
Urban Hydrology[4]	Runoff generator, Pollution source	Catchment hydrology, Pollution of surface & groundwater, Flooding	Water regime, Flood protection, Hydrological cycle
Urban Climatology[5]	Heat & Water storage	Urban heat island, Albedo, Evapotranspiration, Radiation, Heat stress	Cooling (Urban heat island mitigation)
Soil Science[6]	Soil sealing, Loss of function	Water & solute transport, Ecosystem functions	Urban ecosystem services

[1] Fukahori and Kubota (2003), Jung, Lee, Kim, and Lee (2017), Kaparias, Bell, Biagioli, Bellezza, and Mount (2015).
[2] Corazza, Mascio, and Moretti (2016), Kardos and Durham (2015), Kelly, Delaney, Chai, and Mohamed (2016).
[3] Gogate, Kalbar, and Raval (2017), Willuweit and O'Sullivan (2013).
[4] Chen, Theller, Gitau, Engel, and Harbor (2017); Jacobson (2011).
[5] Qin (2015).
[6] Morel et al. (2015); Scalenghe and Marsan (2009).

the rainfall-runoff relationship (Fletcher et al., 2013; Mansell & Wang, 2010). However, it is well known in construction and building material science that asphalt and concrete mixtures do take up moisture, which leads to damage to the material and shortening of the service life (Kakar, Hamzah, & Valentin, 2015; Liu & Hansen, 2016b; López-Montero & Miró, 2016; Penttala, 2006; Xu, Guo, & Tan, 2016). Further evidence for the permeability of pavements is provided by studies assessing the overall hydrological balance of paved surfaces in Europe. Under moist mid-latitude (Cfb) climate (updated Köppen-Geiger classification after Kottek, Grieser, Beck, Rudolf, & Rubel, 2006), studies (see section 4) have shown that infiltration and evaporation take place for all types of pavement, including asphalt.

Knowledge about these processes could be used to actively design and utilize pavements for specific purposes. For example, water may be applied to streets in order to increase evaporation and thereby cool cities that struggle with the urban heat island effect (Daniel, Lemonsu, & Viguié, 2018; Hendel, Gutierrez, Colombert, Diab, & Royon, 2016). For storm water mitigation, specifically designed pervious paving materials are used to increase infiltration and reduce runoff volumes (Booth & Leavitt, 1999; Brattebo & Booth, 2003; Haselbach, Valavala, & Montes, 2006; Solpuker, Sheets, Kim, & Schwartz, 2014).

Due to increased contaminant loads, water quality of urban runoff has been the subject of hundreds of studies (Göbel, Dierkes et al., 2007). Kayhanian, Suverkropp, Ruby, and Tsay (2007) analysed storm water runoff from highways and observed an increase of mean concentration of most contaminants with traffic density. While few data is available for sidewalks and bicycle paths, the available studies indicate considerably smaller concentration of most contaminants for these surfaces (Göbel, Dierkes et al., 2007). Additionally, a large fraction of contaminants is bound to particulate matter (Kayhanian et al., 2007) which can be partly retained by the material filling joints between paving stones (Nehls, Jozefaciuk, Sokolowska, Hajnos, & Wessolek, 2008).

An examination of recent reviews about urban hydrology from the last 15 years, whether focusing on runoff (e.g. Fletcher et al., 2013), catchment modelling (e.g. Salvadore et al., 2015), groundwater recharge (e.g. Lerner, 2002) or the overall impact of urbanisation (Gessner et al., 2014; Jacobson, 2011; Shuster, Bonta, Thurston, Warnemuende, & Smith, 2005), reveals that they all reach the same conclusion: urban water cycle as well as its basic physical processes are not yet well understood and require additional research.

This review takes a step back from the commonly used catchment scale and takes a closer look at the element ultimately causing these alterations in urban hydrology: the pavement as the urban soil-atmosphere interface. It considers the hydrological balance and water transport processes of both, classic paving materials (e.g. sett stones, concrete plates, and asphalt) and newer materials designed for increased infiltration (e.g. grass pavers and pervious asphalt). While it is an important aspect, water quality and treatment of urban runoff are not subject of this review, as there are numerous studies covering water quality of road, roof and parking lot runoff (e.g. Göbel, Dierkes et al., 2007; Huber, Welker, & Helmreich, 2016; Revitt, Lundy, Coulon, & Fairley, 2014; Werkenthin, Kluge, & Wessolek, 2014). The focus of this review are processes and impacts of existing paving materials, rather than the design of special on-site water treatment, retention or infiltration facilities. It aims to provide information needed to improve current and future models, as well as reveal possibilities to better govern the urban hydrological balance with all its benefits.

2. Paved surfaces

Surfaces, such as streets and sidewalks, can be paved using a wide range of materials. Paving can consist of a single continuous cover (e.g. asphalt or concrete) or an assembly of individual pavers (made of e.g. stone, concrete, or brick). In the latter case, the paved surface will also feature numerous joints of varying width between the pavers. These joints are filled with seam material and may facilitate growth of vegetation. Furthermore, the joints allow water to infiltrate into the underlying soil. Paving with a uniform cover is denoted as *Low Permeability Pavement* (LPP) and paving consisting of pavers and joints as *Classic Permeable Pavement* (CPP). CPPs differ from *Designed Permeable Pavement* (DPP), which refers to (super) porous concrete or asphalt, and other new materials specifically designed as storm water remediation methods allowing more infiltration (Andersen, Foster, & Pratt, 1999; Bonicelli, Giustozzi, & Crispino, 2015; Carbone, Mancuso, & Piro, 2014; Haselbach et al., 2006; Yong, McCarthy, & Deletic, 2013). In this article, pavement is always defined as surface consisting of paving material and (if present) joints between individual pavers. Examples of various common pavements are shown in Fig. 1.

Surfaces with all types of paving are considered sealed soils. The definition of soil sealing often includes a complete absence of infiltration (Salvadore et al., 2015; Scalenghe & Marsan, 2009), or generally refers to any sealing material used for street, parking lots and pavement (Fletcher et al., 2013; Hibbs & Sharp, 2012; Jacobson, 2011) including bricks, concrete and asphalt (Mansell & Rollet, 2009; Yao, Wei, & Chen, 2016). While CPPs are examples of pervious materials in some studies (Mansell & Rollet, 2009; Nehls, Jozefaciuk, Sokolowska, Hajnos, & Wessolek, 2006; Nehls et al., 2008), they are often grouped together with LPPs. The term *pervious paving* mostly refers to DPPs.

3. Water transport processes

The studies introduced in the previous section are commonly cited to point out that infiltration and evaporation are processes that should not be neglected when assessing urban 'impermeable' surfaces (Dupont,