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Are stormwater pollution impacts significant in life cycle assessment? A new methodology for quantifying embedded urban stormwater impacts

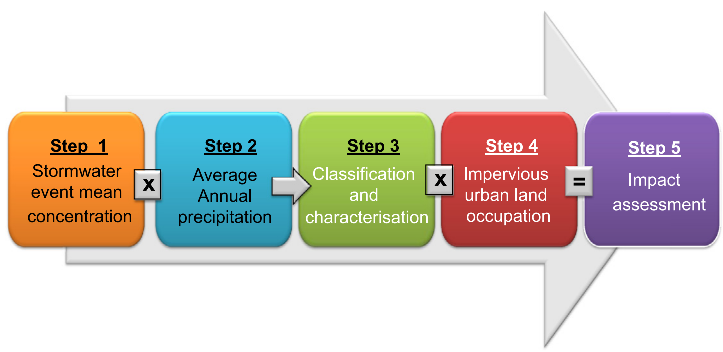
Robert Phillips [a], Harish Kumar Jeswani [b], Adisa Azapagic [b,*], Defne Apul [a]

[a] Department of Civil Engineering, The University of Toledo, 2801 W. Bancroft St., Toledo 43606, OH, USA
[b] Sustainable Industrial Systems, School of Chemical Engineering and Analytical Science, The University of Manchester, Manchester M13 9PL, UK

HIGHLIGHTS

- A new framework to incorporate stormwater impacts into LCA is proposed.
- It captures the effects of stormwater pollution mobilised from impervious urban areas.
- Contribution of stormwater pollution to LCA impacts is substantial for certain systems.
- The method can be incorporated into existing life cycle inventory databases.

GRAPHICAL ABSTRACT



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ABSTRACT

Current life cycle assessment (LCA) models do not explicitly incorporate the impacts from urban stormwater pollution. To address this issue, a framework to estimate the impacts from urban stormwater pollution over the lifetime of a system has been developed, laying the groundwork for subsequent improvements in life cycle databases and LCA modelling. The proposed framework incorporates urban stormwater event mean concentration (EMC) data into existing LCA impact categories to account for the environmental impacts associated with urban land occupation across the whole life cycle of a system. It consists of five steps: (1) compilation of inventory of urban stormwater pollutants; (2) collection of precipitation data; (3) classification and characterisation within existing midpoint impact categories; (4) collation of inventory data for impermeable urban land occupation; and (5) impact assessment. The framework is generic and can be applied to any system using any LCA impact method. Its application is demonstrated by two illustrative case studies: electricity generation and production of construction materials. The results show that pollutants in urban stormwater have an influence on human toxicity, freshwater and marine ecotoxicity, marine eutrophication, freshwater eutrophication and terrestrial ecotoxicity. Among these, urban stormwater pollution has the highest relative contribution to the eutrophication potentials. The results also suggest that stormwater pollution from urban areas can have a substantial effect on the life cycle impacts of some systems (construction materials), while for some systems the effect is small (e.g. electricity generation). However, it is not possible to determine *a priori* which systems are affected so that the impacts from stormwater pollution should be considered routinely in future LCA studies. The paper also proposes ways to incorporate stormwater pollution burdens into the life cycle databases.

1. Introduction

In 2007, the global urban population exceeded the rural population and projections for the end of the century estimate that 60–90% of the

* Corresponding author.
E-mail address: adisa.azapagic@manchester.ac.uk. (A. Azapagic).

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global population is expected to be living in urban areas (United Nations, 2015; Jiang and O'Neill, 2015). During urbanisation, vegetated soils are replaced with impermeable surfaces, altering the natural hydrological cycle and impacting both the quantity and quality of stormwater runoff. Impermeable surfaces decrease infiltration rates, resulting in an increase in overland runoff flow, which is often polluted with pathogens (Arnone and Walling, 2007), suspended solids (Zanders, 2005), heavy metals (Gunawardena et al., 2015; Wicke et al., 2012), nutrients (Kim et al., 2007) and polycyclic aromatic hydrocarbons (Brown and Peake, 2006).

Stormwater pollution effects of urbanisation are well known, yet life cycle assessment (LCA) models have not adequately captured these effects. LCA research on this topic developed in two disparate directions. In one direction, LCA has been used as an extension of the low-impact development (LID) efforts that promote the retention of rainwater utilising green infrastructure (GI). This water-management method is an alternative to the traditional grey infrastructure, which uses underground stormwater pipes to convey rainwater off-site. Researchers interested in understanding the environmental implications of GI technologies developed LCA models for bio-infiltration/retention (Flynn and Traver, 2013; O'Sullivan et al., 2015), rainwater harvesting (Devkota et al., 2015; Morales-Pinzón and Rieradevall, 2015; Wang and Zimmerman, 2015), and green roofs (Cubi et al., 2015; Kosareo and Ries, 2007; Saiz et al., 2006). In these studies, the GI reduces the stormwater runoff volume and quantity. The effects are captured in the LCA results as part of the foreground data. However, any other systems included in the GI system boundary also likely have impervious surfaces within its land use inventory. Stormwater pollution effects resulting from impervious surfaces from any one of these foreground and background processes are not captured in these studies.

The second direction of research developed many methods, tools, and studies to incorporate land use in LCA. For example, Lindeijer (2000a) explored a methodology for incorporating land use in LCA using biodiversity and life support functions as indicators, later reviewing existing land-use impact assessment approaches and identifying next steps to integrate them into LCA (Lindeijer, 2000b). Concerns with the scope and scientific justification of accounting for land use in LCA were documented by de Haes (2006). Some of these concerns were later addressed in a study by Canals et al. (2007a) which proposed biotic production, carbon sequestration, freshwater regulation, water purification and erosion-regulation potentials as primary land use indicators. Several other indicators for assessing land-use impacts on ecosystem services have also been recently suggested (Koellner et al., 2013a, 2013b). These include terrestrial biodiversity, groundwater recharge, mechanical and physiochemical water purification and climate-regulation potentials. These indicators have been further developed in the LANCA® (LANd use indicator value CAlculation) tool (Bos et al., 2016) but none of the indicators recommended thus far has included the increase in stormwater runoff and contaminant transport resulting from impervious surfaces.

A couple of studies have illustrated the connection between land use and stormwater in the entire life cycle of a system, but did not consider an increase in pollution from stormwater. For instance, Saad et al. (2013) acknowledged that surface sealing (or imperviousness) due to urbanisation can impact the water cycle through reduction in groundwater recharge. Another study (Berger and Finkbeiner, 2010) discussed that rainwater coupled with land-use change alters evapotranspiration and runoff, but considered this issue only with respect to a change in the availability of water for aquatic ecosystems. Again, the pollutants associated with the change in water flows, including those from indirect land use (i.e. background systems), were not modelled in this study.

In this study, we address this gap by modelling explicitly and systematically the effects of stormwater pollution mobilised from urbanised areas used in the whole system considered. We hypothesise that current LCA approaches may be excluding an important, urbanisation related pollutant source, thereby underestimating the life cycle impacts of a system. To test this hypothesis, we developed a framework for estimating midpoint life cycle impacts associated with pollution from stormwater and expressed per unit area of urban land occupation. The framework is generic and can be applied to model the foreground and background stormwater pollution effects of any system, using any of the life cycle impact assessment methods. Thus, the framework captures the *embedded stormwater pollution* of a given system. To illustrate the application of the framework and get a sense for whether the proposed expanded analysis is justified, we present two examples (electricity generation technologies and construction materials) for which we quantified the contribution of urban stormwater impacts to the total impacts. We also comment on how this method can be incorporated into existing life cycle inventory databases such as ecoinvent.

2. Methods

2.1. Overview of the framework

The framework is designed to model urban stormwater pollution throughout the life cycle of a system in five steps (Fig. 1). In Steps 1 and 2, the stormwater mean concentrations and average annual precipitation are determined, respectively, and used to estimate the annual emissions per square meter of land. These emissions are then classified and characterised in Step 3, dependent upon the chosen impact assessment method. The characterisation is deliberately performed at this stage of the analysis to assess the various impact categories on a unit area basis – the embedded urban stormwater pollution intensity. In Step 4, the impervious urban land occupation inventory is developed and in Step 5, the total impact for the system is assessed.

The impacts specific to stormwater pollution from urban land occupation can then be added to the other LCA impacts, yielding a more comprehensive assessment of the environmental impacts throughout the life cycle of a system. The following sections detail each of the five steps of the framework and identify possible data sources.

2.2. Step 1: Event mean concentration (EMC)

The first step is to quantify the pollutant concentrations in stormwater flows (Fig. 1). Primary pollutants in urban stormwater include (Pitt et al., 2004):

- nutrients: total Kjeldahl nitrogen (TKN), total phosphorous (TP), NO_3, and PO_4;
- heavy metals (antimony, arsenic, beryllium, cadmium, chromium, copper, lead, mercury, nickel, and zinc);
- oil and grease;
- bacteria; and
- sum parameters: total suspended solids (TSS), total dissolved solids (TDS), chemical oxygen demand (COD), and biological oxygen demand (BOD).

Since the proposed framework is applied to the entire life cycle of a system, it would not be practical to estimate the site-specific concentrations of all these pollutants from all impervious areas in the life cycle due to the spatial variation of supply chains. For this reason, we propose to use urban stormwater pollutant concentrations generic for a given region, for example, a country. The spatial resolution of a country may be used for both the stormwater pollutants (Step 1) and the land-use inventory (Step 4).

Stormwater pollutant concentrations are not uniform throughout a storm event or for different sizes of catchments. In smaller catchment areas, pollutant concentrations are highest within the 30 min of a storm event (aka "first flush"), whereas in larger catchments (>162 ha) pollutant concentrations are highest during peak flow (Pitt et al., 2004). A practical approach to characterising pollutant