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Life cycle assessment (LCA) and life cycle costing (LCC) of road drainage systems for sustainability evaluation: Quantifying the contribution of different life cycle phases

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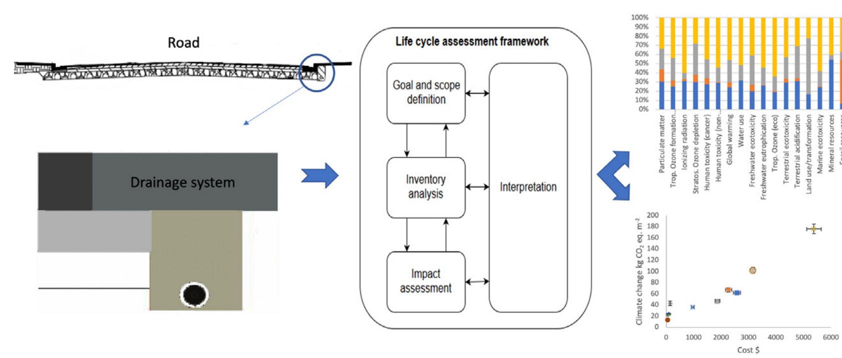
HIGHLIGHTS

- Life cycle costs and environmental impacts of road drainage systems were evaluated.
- Civil works, maintenance and end-of-life phases were included in system boundary.
- Costs and environmental impacts were normalised to size and flow capacity of systems.
- Transportation and civil works phases had a large contribution in LCI and LCIA stages.
- Drainage systems with higher demand for materials showed larger environmental impacts.

GRAPHICAL ABSTRACT



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ABSTRACT

Previous Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) studies on urban drainage systems only included construction materials in the system inventories. The present study aims to suggest an LCA and LCC method that for the first time, considers the inventories from four main phases in the life cycle impact assessment, including extraction of aggregates and production of construction blocks, transportation, construction, civil work and finally maintenance and end-of-life. LCA and LCC were carried out for 10 drainage systems including filter drains, infiltration trenches, soakaways, permeable pavement, infiltration basin, wetland, retention ponds, swales, filter strip, kerb and gully. Results showed that normalisation of environmental impacts and costs to drainage system size (length or area) was more appropriate for drainage systems with higher flow rate capacities (e.g., kerb and gully). However, drainage systems with low flow rate capacities that were designed to store runoff, required normalisation of environmental impacts and costs to storage capacity. The environmental impacts associated with urban drainage systems that needed considerable amounts of virgin aggregates (e.g., filter drains) were higher than those with limited construction material (e.g., swales). Transportation of materials and construction civil works had a larger contribution in life cycle inventories and associated environmental impacts in drainage systems with higher demand for materials. The lowest environmental impacts and life cycle costing were from swales, wetland and retention pond. Uncertainty assessment revealed that drainage systems with extensive application of materials and civil work had more negative impacts on human health, ecosystems and resources.

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1. Introduction

Climate change is believed to trigger changes in precipitation patterns around the world and cause increases in the volume of runoff on roads (IPCC, 2014; Gariano and Guzzetti, 2016). As world population has increased along with urbanisation, the permeable surfaces on natural land have been replaced by impermeable surfaces such as pavements and building roofs (Ercolani et al., 2018; McGrane, 2016). Increases in impermeable surfaces, alongside increased rainfall intensities and volumes in some parts of the world, have caused problems such as flooding for cities (Miller and Hutchins, 2017; Du et al., 2015). Road designers are constantly searching for best practice solutions for managing the runoff produced by extreme precipitation events to protect people, roads and urban infrastructure from flooding (Pregnolato et al., 2017). In recent years innovative methods have been introduced to manage and remediate urban runoff including green drainage systems which try to minimise the environmental impacts (Esmail and Suleiman, 2020; Fathollahi et al., 2021a).

Sustainable Urban Drainage Systems (SuDS) are one of the approaches that simulate natural drainage by techniques such as collection, storage and remediation of contaminated urban surface runoff, before staged and gradual release to the natural catchments (Davis and Naumann, 2017; Shuttleworth et al., 2017). The notable benefits of SuDS, are reducing the risk of flooding, ground water pollution and drought, providing habitats for wildlife and improving water quality (Viavattene and Ellis, 2013; Shuttleworth et al., 2017; Fathollahi et al., 2021b). The main SuDS drainage techniques are swales, wetlands, permeable pavements, filter strips, retention ponds and filter drains (Gavrić et al., 2019; Hubert et al., 2013). SuDS devices are expected to become more important due to the increase in urban population growth and the effects of climate change on runoff volume, requiring planners and designers to increase drainage capacity (Wheater and Evans, 2009; Sohn et al., 2019). The SuDS approach in managing the runoff is fundamentally different from traditional underground drainage methods that usually consist of cementitious blocks and plastic pipes. This primary difference between SuDS and traditional drainage methods leads to a difference in demand for material, construction blocks, civil works and construction procedures as well as the end-of-life disposal procedures (Ezema, 2019; Akadiri et al., 2012). These different approaches result in a considerable alteration in the life cycle environmental impacts and life cycle costing of the drainage components. Considering the importance of drainage systems in coping with the problems caused by climate change, it is necessary to understand the life cycle environmental impacts and costs of the new and traditional drainage techniques and their disposal. Some work on the environmental impact of SuDS disposal has been done, based on the deconstruction of an 11-year-old field permeable pavement field site, including chemical safety values and the likelihood of environmental harm (Mbanaso et al., 2018), but this is not typical of types of SuDS systems or SuDS sites.

Life Cycle Assessment (LCA) has increasingly become a popular and effective method to estimate the environmental impacts of different stages of construction and disposal of urban infrastructure such as drainage systems due to its broader look at the system components and associated environmental impacts (Pajula et al., 2017; Burnley et al., 2019). The standardised ISO 14044 LCA method, evaluates the environmental performance of the whole life of construction systems from aggregate and material extraction, transportation, construction and civil works, to the project end-of-life, demolition and disposal (Khasreen et al., 2009; Ajayi et al., 2015). This standard LCA method has been excessively used to evaluate the environmental performance of construction projects and urban infrastructure (Serrano and Álvarez, 2016; Karlsson et al., 2017; Saxe et al., 2020; Buyle et al., 2013; De Lassio et al., 2016). Although there are some limited studies on the LCA of urban runoff and stormwater drainage systems (Brudler et al., 2016; Wang et al., 2013; Phillips et al., 2018; Hengen et al., 2016), the number of studies is limited and the aims and objectives do not consider the whole life of the project, focusing on the LCA of construction materials. The particular problem with this approach is that the amount of civil works, transportation and end-of-life disposal of the drainage systems are neglected. Furthermore, urban drainage systems are complex and are designed for various functions such as conveyance and storage which are important to account for during study of the LCA, to choose the most suitable functional unit and normalisation approach. This approach of selecting the proper functional unit for the drainage systems, will allow the LCA study to compare the whole life environmental impacts of different systems without inaccuracies introduced by use of inappropriate functional units or normalisation methods. A survey of the existing literature revealed that many studies have considered the area of the projects as the system functional unit instead of the goal and design purpose of the project (Flynn and Traver, 2013; De Sousa et al., 2012; Spatari et al., 2011). Studies in the literature lack consideration of direct aquatic emissions and consideration of the life cycle inventories from civil works, maintenance and end-of-life disposal of the drainage system. Finally, even in the limited number of LCA studies in the literature, the life cycle costing (LCC) analysis of the drainage systems is missing. LCC assessment is a valuable technique that helps the urban infrastructure decision makers to select the most appropriate alternative according to the LCA of the environmental impacts (Wang et al., 2018; Ilg et al., 2017).

The present study aims to propose a comprehensive LCA and LCC methodology, to address all the missing aspects of the existing LCA studies in the literature on the urban drainage systems, to guide future application of LCA on urban drainage infrastructures. To achieve this goal, the life cycle environmental inventories to water and soil from 10 different SuDS and traditional urban drainage techniques (e.g., wetland, swale, kerb and gully and permeable pavement) were evaluated using a proposed comprehensive LCA and LCC method for 4 different stages of projects across the whole life. Monte Carlo simulation was used to carry out the uncertainties related to the environmental impacts associated with all drainage systems. Ultimately, two alternative normalisation approaches are investigated and proposed for future application of LCA and LCC on urban drainage systems, to achieve the most accurate environmental impacts and costing according to the system goal and scope. The present manuscript was structured according to ISO 14040 (2006b). Primarily, the goal and scope (phase 1 of LCA) of the study was defined in Section 2.1. Life cycle inventory (phase 2 of LCA analysis was carried (Section 2.2). The third phase of LCA (life cycle impact assessment) is described in Section 2.3. The results of the LCA are interpreted (phase 4 of LCA) in results and discussion section (Sections 3.1, 3.2 and 3.3). Finally, the uncertainty of the inventory of drainage systems were assessed (Section 2.5) and discussed in Section 3.4.

2. Materials and methods

2.1. Goals and scope definition

The goal of this study was to compare the environmental impact and life cycle costing of 10 different common drainage systems. The utility of urban drainage systems in this study in terms of management train suitability, water quantity, water quality and environmental benefit are shown in Table 1 (CIRIA, 2006). The main selected urban runoff management systems in this study were filter drain, infiltration trench, soakaways, permeable pavement, infiltration basin, wetland, retention pond, swale, filter strip and kerb and gully which are suggested by Design Manual for Roads and Bridges (DMRB, 2020; CIRIA, 2001; CIRIA, 2006). In this study the LCA methodology described in ISO 14040 (2006b) and ISO 14044 (2006a) standards was used to design the LCA and LCC phases, list of inventories and impacts which are illustrated in Fig. 1a. LCA and LCC were carried out for 10 different drainage systems and the results were compared to identify their environmental impacts during life time and their representative life cycle costs.

Table 1
Drainage systems (proposed by CIRIA, 2007) under investigation in the present study and their utilities for management, environmental benefits, water quality and water quantity.

Drainage system	Unit	Management suitability						Water quantity				Water quality								Environmental benefit		
		Prevention	Conveyance	Pretreatment	Source control	Site control	Regional control	Conveyance	Detention	Infiltration	Water harvesting	Sedimenta on	Filtration	Adsorption	Biodegradation	Volatisation	Precipitation	Uptake plants	Nitrification	Aesthetics	Amenity	Ecology
Filter drain	m^3 stored volume		x		x	x		x	x				x	x	x	x						
Filter strip	m^2 area			x	x			x	x	x		x	x	x	x					x	x	x
Infiltration basin	m^3 detention volume					x	x		x	x			x	x	x	x				x	x	x
Infiltration trench	m^3 stored volume		x		x	x		x	x	x			x	x	x	x						
Kerb & gully	m length		x	x				x				x										
Permeable pavement	m^3 permeable surface	x			x	x			x	x	x	x	x	x	x	x				x	x	x
Retention pond	m^3 treatment volume					x	x		x	x	x	x	x	x	x	x	x	x	x	x	x	x
Soakaway	m^3 stored volume				x					x			x	x	x							
Swale	M^2 swale area		x		x	x		x	x	x		x	x	x	x			x		x	x	x
Wetland	m^3 treatment volume		x			x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x

2.2. Inventory analysis

The life cycle inventory (LCI) consists of all material, fuels and energy inputs that are necessary for the construction and maintenance of drainage systems. The inventories were assigned to emissions to water, air and soil, consisting of those produced in the transport, construction, maintenance stages as well as the end-of-life phase. A scheme of the present study system boundaries is presented in Fig. 1b.

The life span of the runoff management systems to calculate the LCA and LCC was assigned as 60 years before reconstruction was to become necessary (Trigaux et al., 2017). The end-of-life for materials such as pipes, aggregates, culverts from all systems was assumed to be sent to landfill and vegetation parts of the drainage systems such as Infiltration basin, wetland, retention pond and swale were projected to be kept in the area at the project end-of-life. LCA and LCC were carried out for all 10 runoff management systems representative for 1 km of roadway and the construction date was assumed as 2019 to 2020 with average traffic of 20,000 vehicles per day (Department for Transport, 2018). The design specifications and details for all 10 systems were extracted from the following UK standards and are presented in Section SI.1 of the supplementary material:

- Filter drain: Design of highway drainage systems, formerly HD 33/16, TA 80/99 (DMRB CG 501, 2020).
- Infiltration trench: Infiltration Drainage Manual of Good Practice. Construction Industries Research and Information Association (CIRIA R156, 1996).
- Soakaways: Design of soakaways, formerly HA 118/06, (DMRB CD 530, 2020b).
- Permeable pavement: Reservoir pavements for drainage attenuation, formerly HD 221/18 (DMRB CD 531, 2020c).
- Infiltration basin, wetland, retention pond and swale: 1. Vegetated drainage systems for highway runoff, formerly HA 103/06 (DMRB CD 532, 2020a) and 2. Design of highway drainage systems, formerly HD 33/16, TA 80/99 (DMRB CG 501, 2020).
- Filter strip: Hydraulic design of road edge surface water channels and outlets, formerly HA 37/17, HA 78/96, HA 113/05, HA 119/06 (DMRB CD 521, 2020d).
- Kerb and gully: Spacing of road gullies, formerly HA 102/17 (DMRB CD 526, 2020e).

The maintenance routine including removal of litter, debris and sediment, e.g., grass cutting for the vegetated basin and cleaning of surfaces by mechanical means or all runoff management systems, was based on Asset delivery asset maintenance requirements (DMRB GM 701, 2020f). The determined maintenance routines for all drainage systems in this study are presented in Tables SI.1 to SI.6 in supplementary material. The necessary equipment and materials for construction of all systems were extracted from the UK Design Manual for Roads and Bridges (DMRB) documents mentioned earlier and are presented in Table SI.7.

SimaPro 9.0 software package developed by Pre Consultants and the ecoinvent 3.5 (2018) database were used to study life cycle inventory of each material used in the drainage system assets. Materials were assumed to be transported to the construction site from a fixed distance of 10 km (Gibbons et al., 2019) to calculate the emission inventories accordingly. As the ecoinvent 3.5 database does not consider the emissions from construction machinery, the LCI process was modified in this study by using OFFROAD2011 (California Air Resources Board, 2010) emission model to help establish a process that regionalizes LCI for all construction machineries in this study. The fuel consumption efficiency of the equipment used for the construction of the systems and total amount of CO, CO_2, SO_2, NO_X, N_2O, VOCs, HCs, PM_{10}, $PM_{2.5}$ and NH_3 emitted per litre of fuel,

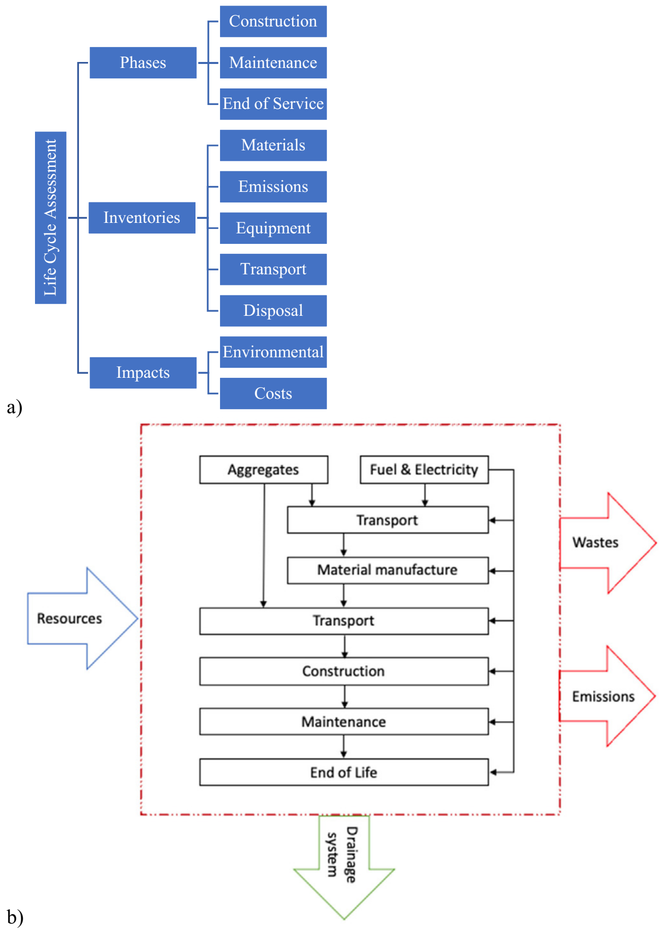


Fig. 1. a) Life cycle assessment stages in the present study: phases, list of inventory classifications and impacts. b) a scheme of the LCA system boundaries.

were also obtained by using OFFROAD2011 software. PlanSwift software version 10.2 (2018) was used to estimate the productivity rates and operation durations for construction of all systems components as well as the maintenance and cleaning procedures.

To calculate the amount of runoff entering the drainage systems, the representative surface area of 1 km length of the pavement was calculated. The surface of the pavement was assumed to be the only source of dust and pollution and 95% impervious. The precipitation duration, depth and volume for the pavement was calculated using the precipitation data for Coventry between 2000 and 2019 (Hollis et al., 2019). Water quality data such as total heavy metals concentrations including Chromium, Manganese (Mn), Iron (Fe), Cobalt (Co), Nickel (Ni), Copper (Cu), Mercury (Hg), Zinc (Zn), Lead (Pb), Cadmium (Cd), Hydrocarbons such as Benzo(*k*)Fluoranthene, Hexachlorobenzene, Benzene, Benzo (g, h,i) Perylene, 1,2-Dichloroethane and Phosphorus (total as P), Nitrite (total as N), Total Dissolved Solids (TDS), Total Suspended Solids (TSS), 5 days Biochemical Oxygen Demand (BOD) were obtained from water quality archive of the UK environment agency (Environment Agency, 2019).

The efficiencies of mentioned pollutants removal by infiltration basin, wetland, retention pond and swale were obtained from National Pollutant Removal Performance database (Center for Watershed Protection, 2007) while it was assumed that the water pollutants were not removed by the drainage components. However, a study by Fathollahi et al. (2020) has shown that high concentrations of heavy metals are removed from contaminated runoff by urban drainage components. BOD, TDS and TSS were assumed to be removed by aerobic degradation, soil deposition and settlement, respectively.

Table 2
Midpoint and Endpoint impacts relations proposed by ReCiPe LCIA model.

Midpoint impact	Endpoint impacts
Particulate matter	Damage to human health
Tropical ozone formation	Damage to human health
Ionizing radiation	Damage to human health
Stratosphere ozone depletion	Damage to human health
Human toxicity (cancer)	Damage to human health
Human toxicity (non-cancer)	Damage to human health
Global warming	Damage to human health, Damage to ecosystems
Water use	Damage to human health, Damage to ecosystems
Freshwater ecotoxicity	Damage to ecosystems
Freshwater eutrophication	Damage to ecosystems
Tropospheric ozone formation	Damage to ecosystems
Terrestrial ecotoxicity	Damage to ecosystems
Terrestrial acidification	Damage to ecosystems
Land use or transformation	Damage to ecosystems
Marine ecotoxicity	Damage to ecosystems
Mineral resources depletion	Damage to resource availability
Fossil resources depletion	Damage to resource availability

2.3. Life cycle impact assessment

The ReCiPe model version 1.10 was used to evaluate the impacts of inventories for all drainage systems. ReCiPe is a method for inventory impact assessment in an LCA study that translates emissions and material extraction into environmental scores. The ReCiPe LCIA method consists of 18 midpoint indicators and 3 endpoint indicators to derive characterisation factors as shown in Table 2. At the midpoint level, ReCiPe model quantifies the indicators such as climate change, ozone depletion etc. that are produced during the material extraction, transportation and construction stages by the means of reference substances such as kg PO_4^{3+} eq. that are presented in Table 3. At the endpoint level, the indicators are measured to estimate the direct relative impact of different inventories on human health, ecosystem and resources. The emissions from equipment estimated by the OFFROAD2011 model were matched with indicators in the ReCiPe model for hydrocarbons, TDS and TSS. The impact scores in ReCiPe model were calculated by multiplying the amount of released compound by its corresponding factor. The impact score defines the negative effect of the specific substance on human health and the ecosystem. For instance, the impact score of 1 kg of released H_2S may be equivalent to 5kgPO_4^{3+}.

The LCIA was carried out according to midpoint and endpoint levels of ReCiPe model for various stages of construction and maintenance to evaluate the contribution of each individual stage in environmental and human health impacts (Goedkoop et al., 2008). The four main phases of the LCIA in the present study were: 1. Extraction of virgin materials, fuels and construction of building blocks, 2. transport of materials and equipment, 3. construction of drainage systems (civil works) and 4. using, maintenance and end-of-life.

Table 3
Impact categories and their unit of measurements in the LCA model.

Impact category	Unit
Climate change potential	kg CO_2 eq. m^{-1} or kg CO_2 eq. m^{-2}
Ozone depletion potential	kg CFC11-eq. m^{-1} or CFC11-eq. m^{-2}
Acidification potential of soil and water	kg SO2 eq. m^{-1} or kg SO2 eq. m^{-2}
Eutrophication potential	kg PO4 eq. m^{-1} or kg PO4 eq. m^{-2}
Photochemical oxidant formation	kg C_2H_2 eq. m^{-1} or kg C_2H_2 eq. m^{-2}
Depletion of abiotic resources-elements	kg Sb eq. m^{-1} or kg Sb eq. m^{-2}
Depletion of abiotic resources-fossil fuels	MJ m^{-1} or MJ m^{-2}

2.4. Life cycle cost analysis

The life cycle costing (LCC) is a method consisting of estimating the total cost of constructing the project, taking into account the whole life cycle of the construction as well as the direct and external costs. In the present study, the costs for materials, transport, construction and maintenance of the drainage systems were estimated using the PlanSwift database by matching the required activities related to the project construction and maintenance. Landfilling fees were applied to the end-of-life of the drainage systems except vegetation in infiltration basins, wetlands, retention ponds and swales which were assumed to stay in place. The costs for end-of-life landfilling and life time maintenance were converted to the present time amount using a 5% discount (Zhang, 2017). The life cycle costing analysis was carried out using following procedure:

1. Determine the project life.
2. Estimate the construction cost.
3. Estimating the annual maintenance and operation cost.
4. Estimate the Equivalent Annual Cost.

2.5. Uncertainty assessment

The uncertainty of the inventory of drainage systems were assessed by the Monte-Carlo routine with 1500 runs using SimaPro software. The uncertainty range of the present study was evaluated for different stages of the project including extraction of virgin materials and fuels,

transport of materials and equipment, construction of drainage systems, use and maintenance of the drainage systems which were carried out using the SimaPro data pedigree algorithm (Risch et al., 2015) which adds datum uncertainties to the representative source features and considers the location of the project, adequacy and size of the sample. The factors that were taken into account in the present uncertainty assessment, are the quantity of materials used in construction of drainage systems and the mean transportation distance, amount of equipment used, the duration of construction period and total amount of used fuel and energy used.

2.6. Functional unit

The functional unit is a key element in LCA studies that helps to measure the function of a system to be studied and provides a mean to which to relate the inputs and outputs of the LCA study (Khasreen et al., 2009). A properly designed functional unit provides outputs that can be compared to other systems outputs with the same functional unit. To do so, systems under study should have the same common function. In order to be able to compare results from different drainage systems in the present study, it was assumed that all 10 drainage systems were constructed to convey the stormwater related to the same 1 km section of the pavement and no water from other pavement sections or urban wastewater was added or managed by the systems. Moreover, some of the 10 drainage systems investigated in this study are solely designed to convey the stormwater such as kerb and gully, whereas, some systems design goal is to store the stormwater (e.g., retention pond). To eliminate this difference in drainage systems, the LCIA and LCC analysis was carried out using normalised impacts and costs based on: 1. size (length) and 2. volume (flow capacity) of the drainage system.

3. Results and discussion

3.1. Life cycle impact assessment normalised by size

Table 4 presents the normalised cost and normalised climate change potential, ozone layer depletion potential, acidification potential of soil and water, eutrophication potential, Photochemical oxidant formation, depletion of abiotic resources-elements and depletion of abiotic

Table 4
Normalised environmental impacts and cost for drainage systems. Results are normalised to length or surface area depending on the drainage system. Environmental impacts and costs are associated to the phases A1, A2, A3 and A4 of the projects (Section SI.4 of the supplementary material).

Cost or impact	Filter drain	Infiltration trench	Soakaways	Permeable pavement	Infiltration basin	Wetland	Retention pond	Swale	Filter strip	Kerb and gully
Cost ($\$\cdot m^{-1}$ or $\$\cdot m^{-2}$)	2.58E+03	2.27E+03	1.86E+03	5.38E+03	9.68E+02	6.30E+01	8.70E+01	5.10E+01	1.45E+02	3.16E+03
Climate change potential (kg CO_2 eq. m^{-1} or kg CO_2 eq. m^{-2})	6.20E+01	6.70E+01	4.70E+01	1.76E+02	3.60E+01	2.20E+01	2.40E+01	1.30E+01	4.30E+01	1.02E+02
Ozone layer depletion potential (kg CFC11-eq. m^{-1} or kg CFC11-eq. m^{-2})	3.50E+01	2.90E+01	1.60E+01	4.20E+01	1.20E+01	8.00E+00	9.00E+00	5.00E+00	7.00E+00	3.10E+01
Acidification potential of soil and water (kg SO_2 eq. m^{-1} or m^{-2})	6.30E+04	6.69E+04	4.69E+04	6.04E+04	1.53E+04	9.06E+03	1.08E+04	8.85E+03	1.47E+04	9.50E+04
Eutrophication potential (kg PO_4 eq. m^{-1} or kg SO_2 eq. m^{-2})	1.08E+05	8.52E+04	9.32E+04	1.21E+05	2.01E+04	1.65E+04	3.53E+04	1.29E+04	1.45E+04	1.90E+05
Photochemical ozone creation potential (kg C_2H_2 eq. m^{-1} or kg C_2H_2 eq. m^{-2})	1.12E+05	1.65E+05	6.53E+04	2.03E+05	4.43E+04	4.47E+04	5.11E+04	3.57E+04	4.25E+04	1.68E+05
Depletion of abiotic resources-elements (kg Sb eq. m^{-1} or kg Sb eq. m^{-2})	2.00E+02	2.05E+02	2.05E+02	3.45E+02	8.30E+01	4.50E+01	3.80E+01	2.80E+01	4.60E+01	3.35E+02
Depletion of abiotic resources-fossil fuels ($MJ\cdot m^{-1}$ or $MJ\cdot m^{-2}$)	2.98E+09	3.43E+09	1.43E+09	4.91E+09	3.04E+08	1.11E+08	2.33E+08	3.20E+08	7.03E+08	4.81E+09

resources-fossil fuels for 10 drainage systems under investigation in this study. This table includes the environmental impacts of systems normalised to the length or area of the project. The normalised cost is for the whole life of the drainage systems from the extraction of aggregates and materials to tipping at the landfill.

According to Table 4 the highest cost and environmental impacts were associated with filter drain, infiltration trench, soakaways, permeable pavement and kerb and gully. The highest climate change indicator was observed for permeable pavement (176 kg CO_2 eq. m^{-2}). Kerb and gully (102 kg CO_2 eq. m^{-2}), infiltration trench (67 kg CO_2 eq. m^{-2}), filter drain (62 kg CO_2 eq. m^{-2}) and soakaways (47 kg CO_2 eq. m^{-2}) showed second to fifth highest climate change indicators based on normalised length and area. The median life cycle costs for mentioned drainage systems were estimated as 5375, 3156, 2575, 2267 and 1863 $\$\cdot m^{-1}$ or $\$\cdot m^{-2}$, respectively. The observed high normalised costs and climate change indicators was due to the fact that these drainage systems demand the highest amount of aggregates, materials and building blocks which need to be extracted and manufactured and finally transported to the construction site. However, the lowest normalised climate change indicators were associated with swales (13 kg CO_2 eq. m^{-2}), wetland (22 kg CO_2 eq. m^{-2}) and retention pond (43 kg CO_2 eq. m^{-2}), respectively. Swale, wetland and retention ponds showed the lowest median life costs of 51, 63 and 87 $\$\cdot m^{-2}$, respectively. The lower normalised costs and climate change effects of these drainage systems were associated with lower necessary material requirements and building blocks necessary for the construction, that resulted in lower inventories in both stages of virgin aggregates extraction and transportation. The negative effects of land transportation on climate change have been reported by various studies (Axsen et al., 2020; Giannakis et al., 2020; Stanley et al., 2011). Jullien et al., 2012 reported that the production of raw aggregates for construction purposes can impact climate change in terms of fossil fuel consumption and explosives which supports the high climate change effect of drainage systems with high demand for aggregates.

Ozone layer depletion causes an increase in the UV radiation from sun on the surface of earth which can cause negative effects on human health such as skin cancer and immune system deficiencies (Slaper and de Gruijl, 2004; Lucas et al., 2015; Brenna et al., 2019). The ozone layer depletion potential figure shows the same trend as climate change effect where permeable pavement had the highest contribution with 42 kg CFC11-eq. m^{-2}. It is very important to take into account that permeable pavement is the only drainage method in the present study that serves as an actual pavement and not solely as a drainage component. However, to be able to compare the inventories from different drainage components, the traffic bearing function of permeable pavement was not considered. Following permeable pavement, filter drain (35 kg CFC11-eq. m^{-2}), kerb and gully (31 kg CFC11-eq. m^{-2}) and infiltration trench (29 kg CFC11-eq. m^{-2}) showed the highest impact on the ozone layer respectively. Swale, wetland and retention pond showed the lowest negative effects on the ozone layer with values of 5, 8 and 9 kg CFC11-eq. m^{-2}, respectively. This trend was similar to the climate change results that can also be attributed to more vehicles that are required for the transportation of materials to the construction sites, resulting in higher ozone layer depletion for projects with a high demand for materials. This result is in consistent with results from a study by Uherek et al. (2010).

The results from normalised acidification potential of soil and water (Table 4) showed that the maximum value was associated with the kerb and gully system (94,953 kg SO_2 eq. m^{-1}). This observation was due to the considerable amount of cementitious material used in construction of blocks for kerb and gully drainage systems. In the production process of cementitious and concrete block substances, such as NO_x, NH_3, NH_4^+, COD, NO_3^-, and PO_4^{3-} are produced and emitted to the air and soil. This process is known to cause acidification of the environment (Kim and Chae, 2016; Kurda et al., 2018). However, the acidification potential was considerably lower (12 times) for the systems with limited application of concrete materials during the construction such as infiltration basin (15,318 kg SO_2 eq. m^{-1}) and filter strip (14,682 kg SO_2 eq. m^{-1}).

Eutrophication occurs when the water bodies are extremely rich in nutrients and cause a rapid algal growth (Yang et al., 2008). The major substances with an impact on eutrophication are NO_x, NH_3, N_2, and NO_3, NH_4^+, COD, NO_3^-, HNO_3, N_2, PO_4^{3-}, and NO_2 (Kim and Chae, 2016). The results presented in Table 4 revealed that in a trend similar to the acidification potential, the eutrophication potential was higher in projects that consume considerable amounts of raw aggregates during the construction process (e.g., filter drain and soakaway). The highest eutrophication risk was introduced by kerb and gully (189,740 kg PO_4 eq. m^{-1}) which was a result of using cementitious and concrete blocks during the construction phase. However, the lowest eutrophication risk to the environment was associated with drainage systems with limited raw aggregate and cementitious materials needed during the life cycle of the project, such as swales (12,941 kg PO_4 eq. m^{-1}) and wetland (16,548 kg PO_4 eq. m^{-1}).

Depletion of abiotic resources; elements and fossil fuels rates for all drainage systems are presented in Table 4. According to the results, permeable pavement, kerb and gully, filter drain, infiltration trench and soakaways showed the highest consumption of elements and fossil fuels during the life time of the project. This observation was due to 4 stages during the life cycle of the drainage systems:

1. Extraction of virgin aggregates and manufacturing construction blocks,
2. Transportation of aggregates and blocks,
3. Repetition of stage 1 and 2 during the maintenance,
4. Transport of end-of-life construction blocks and aggregates to the landfill.

However, for drainage systems such as swale, wetland and retention pond, due to less application of virgin aggregates and lower demand for transportation, depletion of fossil fuels and elements were observed to be much lower. According to the assumptions of the present study at the end-of-life of the swale, wetland and retention pond drainage systems, the materials were presumed to stay in place and not require transport to the landfill. This resulted in a lower potential for depletion of abiotic resources such as fossil fuels.

3.2. Life cycle impact assessment normalised by flow or storage capacity

In Section 3.1 the costs and environmental impacts of the drainage systems were normalised to the size, which was effective for understanding the impacts of the systems in terms of the roadway length. However, it is important to evaluate the cost and environmental efficiency of drainage systems according to the water quantity aspect. Table 5 presents the normalised cost and environmental impacts such as climate change potential, ozone layer depletion potential, acidification potential of soil and water, eutrophication potential, Photochemical oxidant formation, depletion of abiotic resources-elements and depletion of abiotic resources-fossil fuels for 10 drainage systems normalised to length and flow capacity or storage volume. According to the results, the life cycle cost (48 $\$\cdot m^{-1}$. $(m^3\cdot s^{-1})^{-1}$) and environmental impacts (climate change: 67 kg CO_2 eq. m^{-1}) of drainage systems constructed by cementitious materials with high flow capacity such as kerb and gully, were lower than when cost and environmental impacts were normalised by size (102 kg CO_2 eq. m^{-2} and 3156 $\$\cdot m^{-2}$). However, for drainage systems with lower flow capacity or storage volume, the normalised to storage capacity life cycle cost and environmental impacts showed higher values. For instance, the infiltration trench that showed low cost and environmental impacts during the normalisation to size, revealed relatively high cost and impacts when normalised to the storage capacity. This result is due to the relatively lower flow capacity of

Table 5
Normalised environmental impacts and cost for drainage systems. Results are normalised to length and flow rate or length and storage volume. Environmental impacts and costs are associated to the phases A1, A2, A3 and A4 of the projects (-Section SI.4 of the supplementary material).

Cost or impact	Filter drain	Infiltration trench	Soakaways	Permeable pavement	Infiltration basin	Wetland	Retention pond	Swale	Filter strip	Kerb and gully
Cost ($\$\cdot m^{-1}.(m^3\cdot s^{-1})^{-1}$ or $\$\cdot m^3$)	9.38E+02	3.27E+03	1.21E+03	1.89E+03	1.58E+03	1.03E+02	7.26E+02	6.10E+01	4.73E+03	2.78E+02
Climate change potential (kg CO_2 eq. m^{-1} or kg CO_2 eq. m^{-2})	5.60E+01	1.45E+02	8.70E+01	1.16E+02	9.10E+01	2.30E+01	7.20E+01	1.30E+01	2.06E+02	6.70E+01
Ozone layer depletion potential (kg CFC11-eq. m^{-1} or kg CFC11-eq. m^{-2})	2.46E+01	4.47E+01	3.62E+01	3.29E+01	2.14E+01	1.05E+01	2.19E+01	6.30E+00	6.72E+01	2.39E+01
Acidification potential of soil and water (kg SO_2 eq. m^{-1} or kg SO_2 eq. m^{-2})	5.09E+04	9.43E+04	7.16E+04	7.16E+04	6.30E+04	2.96E+04	2.61E+04	1.68E+04	8.43E+04	1.04E+04
Eutrophication potential (kg PO_4 eq. m^{-1} or kg PO_4 eq. m^{-2})	2.10E+05	3.06E+05	2.52E+05	2.95E+05	1.64E+05	1.48E+05	2.13E+05	1.34E+05	3.72E+05	1.15E+05
Photochemical ozone creation potential (kg C_2H_2 eq. m^{-1} or kg C_2H_2 eq. m^{-2})	2.42E+05	4.42E+05	2.64E+05	3.42E+05	4.23E+05	2.03E+05	9.85E+04	9.64E+04	5.28E+05	7.57E+04
Depletion of abiotic resources-elements (kg Sb eq. m^{-1} or kg Sb eq. m^{-2})	3.23E+02	6.87E+02	3.99E+02	6.28E+02	3.89E+02	1.83E+02	2.42E+02	1.93E+02	3.93E+02	1.40E+02
Depletion of abiotic resources-fossil fuels ($MJ\cdot m^{-1}$ or $MJ\cdot m^{-2}$)	8.09E+08	9.09E+08	6.62E+09	7.13E+09	6.72E+09	3.28E+08	2.08E+08	5.70E+08	1.03E+10	6.78E+08

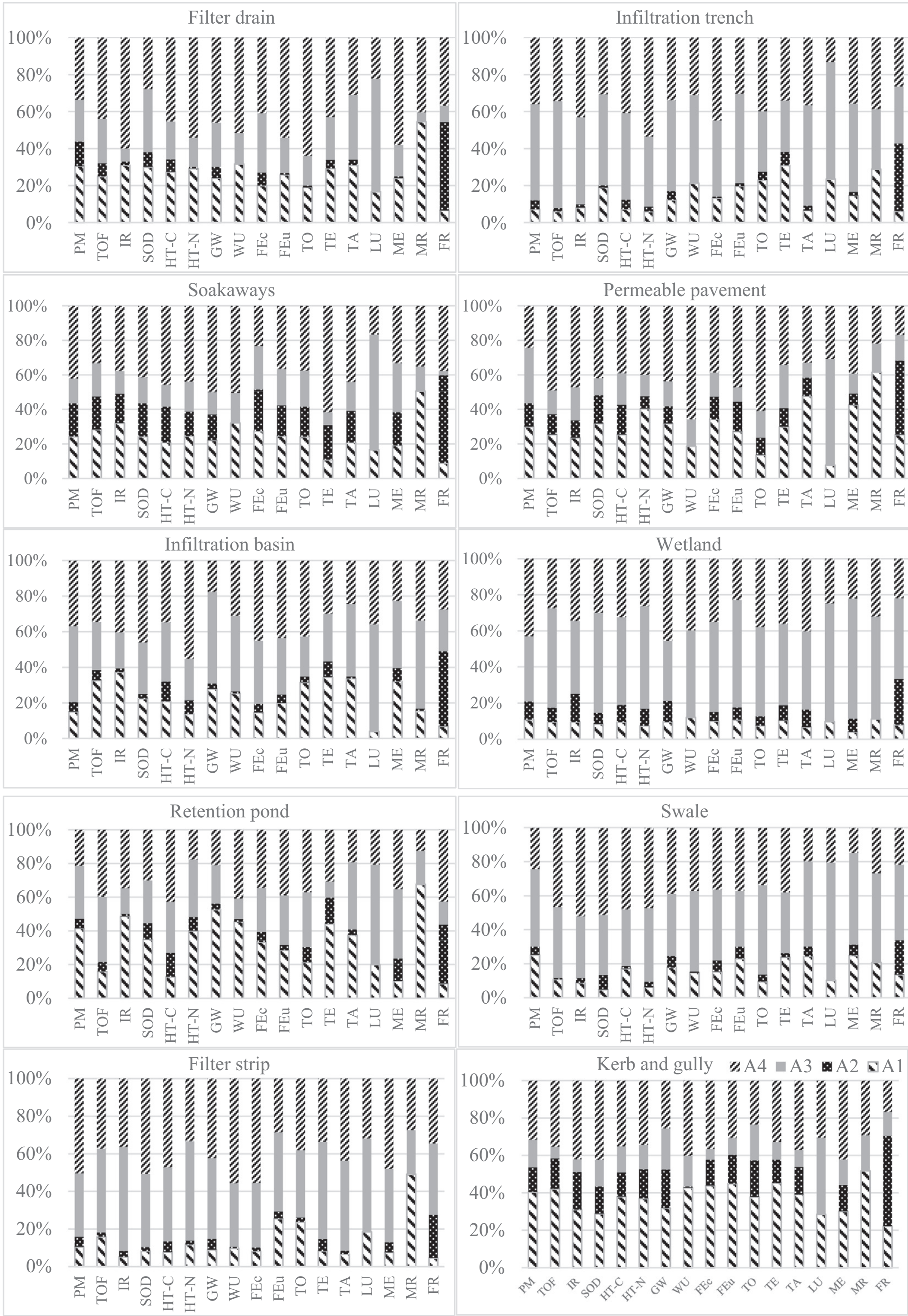
storage volume of these drainage systems to kerb and gully which is designed to convey high volumes of flow per second. Moreover, the observed result can be attributed to the application of more underdrain PVC pipes in drainage systems with lower flow capacity and as a result higher environmental impacts in comparison with a drainage system using cementitious piping blocks. This observation is consistent with previous studies (Hajibabaei et al., 2018; Vahidi et al., 2015; Du et al., 2013). The results of this section as well as Section 3.1 revealed the importance of selection of appropriate normalisation methods (to the size or flow rate) according to the type of project under investigation.

3.3. LCIA at midpoint level of ReCiPe model

The impact assessment was carried out for 4 life cycle stages of extraction of virgin materials and fuels, manufacturing blocks (A1), transport of materials and equipment (A2), construction of drainage systems (A3), using maintenance and end-of-life of the drainage systems (A4) to understand which LCA stage contributed the most total environmental impacts presented in Sections 3.1 and 3.2. The results of LCIA using 18 midpoint ReCiPe models for 10 different drainage systems are presented in Fig. 2. According to this figure, drainage systems with considerable amount of aggregates and materials needed for the construction such as permeable pavement and kerb and gully, showed that the extraction of aggregates and preparation of construction blocks have a high contribution in overall environmental impacts of the project (30–60%). The environmental impacts of the stage 2 of LCA (transportation) were relatively large in comparison with drainage systems that had lower material requirements (6–12 times higher). A breakdown of the environmental impacts for permeable pavement revealed that between 17 and 67% of whole impacts on the environment by the whole life of the project was imposed by the A4 stage of the LCA. This observation is due to the fact that permeable pavement had a considerable amount of material in its structure which resulted in a large percentage of environmental impacts due to transportation to the landfill as well as maintenance and cleaning procedure during its 60 years life time. The same trend was observed for kerb and gully systems, that 30 to 50% of the impacts were associated with A1 stage of the LCA and 20–42% was from stage A4. Moreover, more than 50% of fossil fuel consumption was associated with transportation, which was in line with the results from Section 3.1. and the fact that drainage systems with larger consumption of materials, showed higher costs and environmental impacts in comparison with drainage systems with less materials needed.

The LCIA figures for swale and wetland revealed that stage A3 of LCA was associated with the majority of environmental impacts (60 to 70%). This was a result of limited materials needed for the construction and as a result less transportation and inventories. Moreover, according to the assumption that swales and wetland drainage systems stay in place at the end-of-life, this reduced the inventories from end-of-life transportation and landfilling. The breakdown of impact assessments revealed that the A3 stage had the largest percentage of land use for swale and wetland drainage systems. This is due to the fact that swales and wetlands occupy larger areas of land in the construction stage of LCA to manage the same volume of stormwater in comparison with systems such as kerb and gully and filter drains. This result can be attributed to the different design goals of swales and wetlands in comparison with kerb and gully or filter drains. Wetlands are designed to store the stormwater, however, kerb and gully system goal is to convey the runoff. This fact emphasizes the importance of normalising the cost and environmental impacts by size or flow rate according to the conveyance or storage goal of the project (discussed in Sections 3.1 and 3.2).

According to Fig. 2, the highest percentages of environmental impacts from stage A1 (preparation of material) were associated with permeable pavement (up to 61%), kerb and gully (up to 52%) and retention pond (up to 67%). Stage A2 (transportation) of LCA had the largest impacts on the environment in soakaways (up to 51%) and permeable



PM: Particulate matter
TOF: Trop. Ozone formation
IR: Ionizing radiation
SOD: Stratos. Ozone depletion
HT-C: Human toxicity (cancer)
HT-N: Human toxicity (non-cancer)
GW: Global warming
WU: Water use
FEu: Freshwater eutrophication
TO: Trop. Ozone (eco)
TE: Terrestrial ecotoxicity
TA: Terrestrial acidification
LU: Land use/transformation
ME: Marine ecotoxicity
MR: Mineral resources
FR: Fossil resources.

Fig. 2. Midpoint LCIA scores from ReCiPe model for phases A1, A2, A3 and A4 of drainage system construction. Results are presented in Tables SI.10 to SI.19.

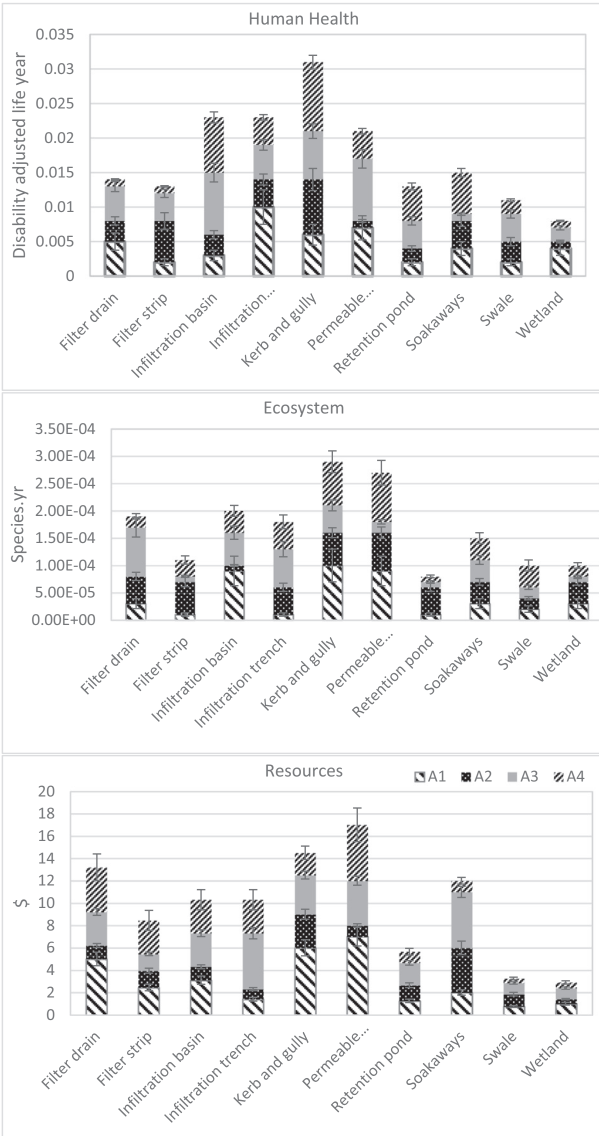


Fig. 3. Uncertainty analysis of endpoint indicators of ReCiPe model for drainage systems (phase A1, A2, A3 and A4 of construction) using the Monte-Carlo routine with 1500 runs with 95% confidence interval (Tables SI.20 to SI.22).

pavement (up to 43%). Swale (up to 60%) and wetland (up to 65%) showed the highest impact percentage in stage A3 of the whole life cycle of the project. Finally, the highest percentages of impacts from stage A4 (construction) were from retention pond (up to 43%) and filter strip (up to 56%).

3.4. Uncertainty assessment

The results of uncertainty analysis on the endpoint levels of ReCiPe models, including human health, ecosystem and resources are presented in Fig. 3. Uncertainty analysis was carried out using a 95% confidence interval of 1500 Monte Carlo simulation runs for all four stages (A1 to A4) of 10 drainage systems in this study. Human health scores are reported in Disability Adjusted Life Year (DALY) which represents the total number of years lost to illness, disability or premature death within the population. According to the uncertainty figure related to the human health, kerb and gully (0.031 DALY), infiltration basin (0.023 DALY), infiltration trench (0.023 DALY) and permeable pavement (0.021 DALY) had the highest contribution in the endpoint scores in human health. However, wetland (0.008 DALY), swale (0.011 DALY), retention pond (0.013 DALY) and filter strip (0.013 DALY) had the lowest endpoint scores associated with human health. The same trend can be observed in endpoint scores related to receiving ecosystems (Fig. 3) which is reported in a species·yr unit that represents loss of species during a year. The lower negative effects on the human health and ecosystem by wetland, swale and retention pond in comparison with other drainage systems were a result of their limited contribution in environmental impacts discussed in Section 3.1 such as global warming, ozone depletion and eutrophication. However, drainage systems with higher effects on the mentioned environmental impacts in ReCiPe model showed larger endpoint scores. According to Fig. 3, drainage systems with a higher demand for virgin aggregates and construction blocks such as permeable pavement, kerb and gully, filter drain and soakaways showed the highest uncertainty scores in the endpoint level of ReCiPe model. More than 40% of the observed uncertainty was associated with stage A1 of the LCIA. Between 25 and 30% of the uncertainty scores for permeable pavement and kerb and gully was in stage A3, that was related to the large civil works during the construction period. This is due to the costs related to the extraction of aggregates, manufacturing blocks and fuel (transportation). However, the uncertainties associated with swale and wetland systems were quite low (Ecoinvent database) which was due to the limited material and civil works needed during the drainage construction.

3.5. Application of LCA and LCC results in SuDS

LCA and LCC when applied to drainage systems, in particular SuDS, add further detail to the benefits of using the most appropriate, site-based drainage option. This extra evaluation of the net environmental impact now covers the lifetime of the asset, including water quality and quantity aspects for the first time. It is hoped that the information from LCA and LCC will drive decisions that promote the use of best available technologies and avoid decisions that are based purely on costs, which is often a default option due to a lack of characterisation or performance evidence.

As described above, it is necessary to discriminate between some of the inherent and in-use characteristics of different drainage options, so that heavy environmental impact in some areas of the assessment, particular construction and material costs, does not exclude options from selection. As demonstrated in Table SI.23, mutually exclusive uses of drainage options exist and should be recognised and incorporated into the selection process for drainage, along with LCA and LCC analysis.

Performance data and decades of empirical evidence on SuDS are now established to an extent necessary for their widespread international field deployment. The outputs of the work in this paper can be usefully added to the body of evidence that is starting to address the scepticism of decision makers, over choosing default drainage solutions such as traditional pipe and gully drainage.

4. Conclusions

The present study is the first comprehensive life cycle assessment of 10 of the most common drainage systems. Life cycle costing and uncertainty analysis were carried out for these drainage systems. The results of this study highlight the important factors influencing the environmental impacts and life cycle cost of the drainage systems to help urban designers choose the best available practice according to the drainage requirements of the project.

Previous LCA studies of the drainage systems assessed materials and construction blocks in the process of life cycle inventories and neglect the civil works, maintenance and landfilling environmental impacts and the life cycle costing. Results of the present study showed that the environmental impacts associated with urban drainage systems that needed considerable amounts of virgin aggregates and construction blocks (e.g., kerb and gully) were higher than those with limited construction material. Transportation of materials and construction civil works had a large contribution in life cycle inventories and associated environmental impacts of the drainage systems. Moreover, uncertainty assessment revealed that drainage systems with extensive application of materials and civil work had more severe negative impacts on human health, ecosystem and resources. The lowest environmental impacts and life cycle costing were from swale, wetland and retention pond. Kerb and gully, permeable pavement and filter drain showed the highest environmental impacts. It should be noted that permeable pavement was the only system in the present study which serves as the pavement surface as well as draining the runoff. Normalisation of costs and environmental impacts to size was more proper to study the drainage systems with high flow rates that are designed to convey the runoff. However, for drainage systems with lower flow capacity that are designed to store the runoff, it is more appropriate to normalise the costs and environmental impacts to the storage capacity.

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CRediT authorship contribution statement

Alireza Fathollahi: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Writing – original draft, Writing – review & editing. **Stephen J. Coupe:** Conceptualization, Methodology, Validation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2021.145937.

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