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Optimum designs for Sustainable Drainage Systems (SUDS) in cities of varying size and climate

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1. Introduction

Urban drainage systems are crucial kinds of infrastructure that collect, treat and redistribute wastewater to prevent flooding and ensure the effective functioning of other urban facilities. Rapid urbanisation increases the extent and density of impermeable surfaces, straightens watercourse channels and increases the concentration of toxic contaminants in receiving water bodies (Arora, 2013). Meanwhile, climate change alters precipitation regimes, causing more severe and frequent storms (Charlesworth, 2003). These effects combine to modify the urban hydrological cycle by increasing peak flows and decreasing lag times, resulting in severe urban floods – Figure 1.

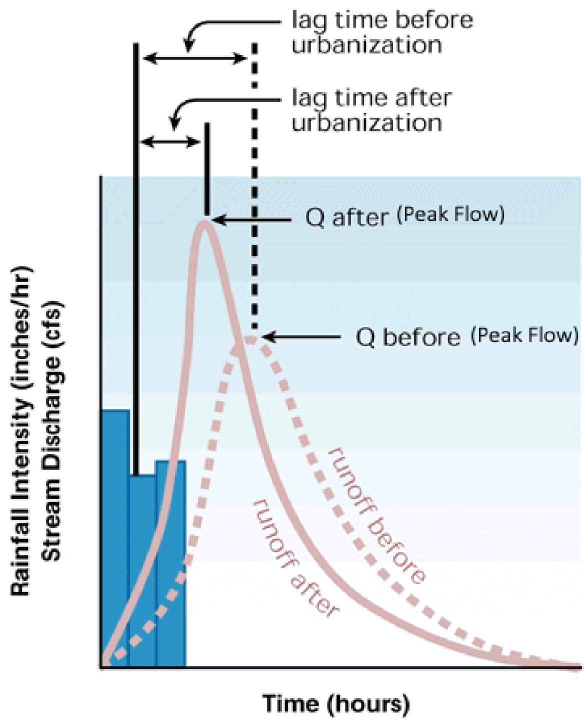

Figure 1:Difference in storm hydrograph between primary land use and after urbanisation. (Boulomytis, 2017)

For example, we can consider the 2007 flooding that took place in the UK, when 13 people died, and 48,000 homes were flooded. This resulted in a total cost of £4 billion (ABI, 2007). These kinds of devastating events reveal that ageing conventional sewage infrastructure in urban areas is exceeding its capacity. With climate change's effects on the weather, population growth and urban expansion, flooding will become more frequent and severe (Huong, 2013). Therefore, the implementation of alternative, more sustainable and flexible wastewater management techniques is one of the top priorities for cities.

One of the response strategies for urban flood management is Sustainable Drainage Systems (SUDS), consisting of certain above-ground technologies and spatial planning techniques (Wahl, 2009). It mimics the natural hydrological process of evapotranspiration infiltration and retention to handle potential flood events (Peras-Momparler, 2015). By adopting SUDS, it is possible to achieve water self-sufficiency in urban areas through absorption, filtration and transportation of water to storage aquifers via technologies such as green roofs, permeable pavements or continuous green spaces. Such principles are characteristics of the 'sponge city' and are particularly popular in China (Jia, 2016), where both CMIP5 and CMIP6 models have robust projections for a significant precipitation increase by the end of the 21st century – 2.2% -25%, depending on the climatic scenario (Chen, 2013; Li, 2021).

Moreover, SUDS addresses the United Nations' (UN) sustainable development targets, particularly 11.5 (creating resilient urban areas), and 13.1 (mitigation and adaptation to natural disasters, e.g. flooding) (UN, 2015). Moreover, it facilitates targets set by the EU's Water Framework Directive (WFD) to improve the ecological status of urban water bodies. Therefore, the sustainability benefits of SUDS are commonly accepted, explaining trending implementation via activation of natural hydrological cycle processes within the urban environment (Fryd, 2012). Nevertheless, the uptake of the SUDS management approach is relatively low (Oluwayemi, 2021) due to their multi-sector nature, lack of clear cost-benefit analysis and scarcity of quantitative evidence regarding their effectiveness (Piacentini, 2020).

This literature review evaluates the most popular types of SUDS and outlines how they were implemented in various cities. Moreover, it will explain the necessity for, and assess existing knowledge about the economic and technical transition from conventional drainage systems to SUDS using existing case studies and theoretical research.

2. *Issues with Conventional Drainage Systems*

It is critical to understand the challenges of conventional drainage systems when recommending SUDS for policymakers, relevant stakeholders and engineers. Traditional drainage systems were designed primarily to manage water volume by collecting and transporting excess runoff to nearby water bodies via a sewer network as fast as possible (Chocat, 2004). Such systems were built at the early stages of urban growth (Torgersen, 2014), so their designs do not consider urbanisation and climate change effects. Climate change alters seasonal precipitation patterns and causes hydraulic deterioration of drainage systems through sedimentation and blockage of pipes (Yazdanfar, 2015). Meanwhile, urbanisation increases the concertation and variety of contaminating particles in the wastewater. Respectively, the limited capacity of conventional drainage for the storage and removal of stormwater leads to frequent combined sewer overflows (CSOs) (Hellström, 2000). Thus, the outdatedness of conventional drainage poses a critical risk relating to urban flooding, watercourse pollution and urban degradation (Eckart, 2012). Importantly, these systems consist of concrete pipes and underground basins, so expansion and restoration are expensive, timely and problematic. Therefore, updating conventional drainage is strategically ineffective; this infrastructure simply does not meet its sustainability criteria (Sieker, 2008) and is inflexible at times of critical hydrological circumstances (Chocat, 2004).
Urban drainage systems can only meet sustainability aims if both factors of urbanisation and climate change are implemented in the system's design framework. A simulation study in Helsingborg, Sweden by Semedeni-Davies (2007) quantitively proved this by using the Regional Climate Model. The study projected that due to urbanisation alone, sewer overflow volumes might double, but if climate change is considered concurrently, overflow volumes can rise by up to 450%. Additionally, a 10-fold increase in NH_4 release is a critical

environmental hazard, posing a risk of contamination in aquifers and biodiversity loss. Thus, by implementing both factors into the design framework, an adequate expandable drainage system that can adapt to future city and climate changes can be created.
Hyong (2013) noted that considering the combined effect of influences would lead to increased planning uncertainties, as interactions between these drivers are complex and location-specific. However, the recently launched CMIP6 has developed emission scenarios driven by distinctive socio-economic assumptions, where urbanisation is one of the variables that can influence climate change (Gidden, 2019). By downscaling these novel models, policymakers and engineers can look into the effects of climate change on finer temporal and spatial scales (such as within a city) to choose the most effective and sustainable urban drainage design.

3. Conceptual framing of SUDS and associated technologies (252)

The SUDS management approach is much more advanced than its conventional counterparts. Instead of removing water from cities, it treats it as a 'liquid asset' (Semadeni-Davies, 2008) by promoting the infiltration and confinement of water within its urban environment. To graphically represent these conceptual differences (Charlesworth, 2010) created a Venn diagram - Figure 2 (a & b), where discrepancies can be observed between water quality, quantity, and environmental services (amenities and wildlife maintained by SUDS). Furthermore, the author presents Figure 2c as a 'rocket' of climate change mitigation effects.

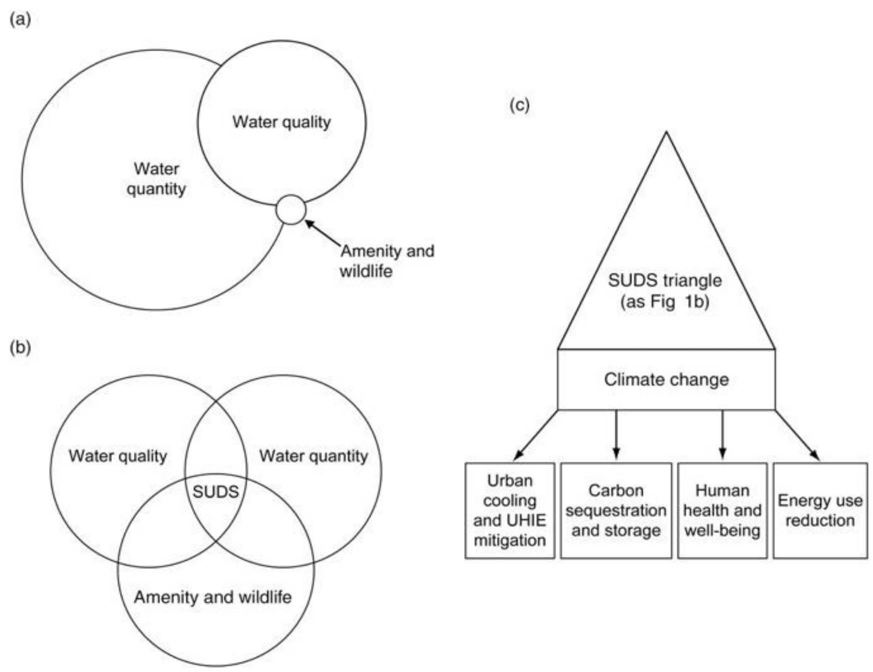

Figure 2: Conceptual diagram of SUDS, (Charlesworth, 2010)

Efficient incorporation of these concepts into the urban environment requires the selection of appropriate technologies. However, in most cases, a series of interlinked SUD devices are integrated within conventional systems to address both the quality and quantity of water, providing a resilient flood management strategy (Ashley, 2007). SUD technologies are split into 'hard devices' and 'vegetated devices', as documented in Table 1.

Table 1: Types of SUDS, (Charlesworth, 2010)

Vegetated devices	Hard devices
Green roofs and walls	Porous paving (PPS)
Rain gardens	Concrete built street rain garden
Constructed wetlands	Rainwater harvesting
Filter strips	Proprietary devices
Swales	Other: using existing urban green infrastructure – front gardens, school playing fields, traffic islands, grass verges, parks
Vegetated PPS	
Individual householder's rain garden	
Street trees	

In consolidated urban areas, the integration of large-scale vegetated landscape components such as wetlands, rain gardens or filter strips is problematic, as it changes the urban layout. Furthermore, the ambiguous evaluation of the economic benefits of SUDS and their sustainability (Ashley, 2018) in addition to high competition for land within metropolitan areas (Peng, 2014) means that these methods are rarely adopted. Consequently, methods that can be implemented in an urban environment without significant landscape modifications, such as green roofs and porous paving, are much more applicable for densely built-up spaces.

3.1 Pervious paving

Pervious pavements enhance stormwater infiltration and remove contaminants, so water can either be harvested and reused productively within cities or be allowed to recharge the groundwater (Jayasuriya, 2005). These structures have two classifications: porous, where a thick porous material features a strong infiltration capacity; and permeable, constructed as a grid of impermeable concrete blocks and infiltration voids. Via field testing, it is possible to quantify the effectiveness of these structures. Jayasuriya (2007) designed a study comparing the performance of traditional asphalt with that of pervious pavement (C&M Ecotrihex). The results are represented in a hydrograph (Figure 3). When we observe the pervious pavement, peak discharge has dropped by 52% in comparison to the asphalt, while lag time has been extended by an hour. Furthermore, water filtration performance is favourable, reducing SS, Oil and TP contaminants by 80, 88, and 50%, respectively. Similar findings were published by Fletcher (2003), indicating the reliability of these findings.

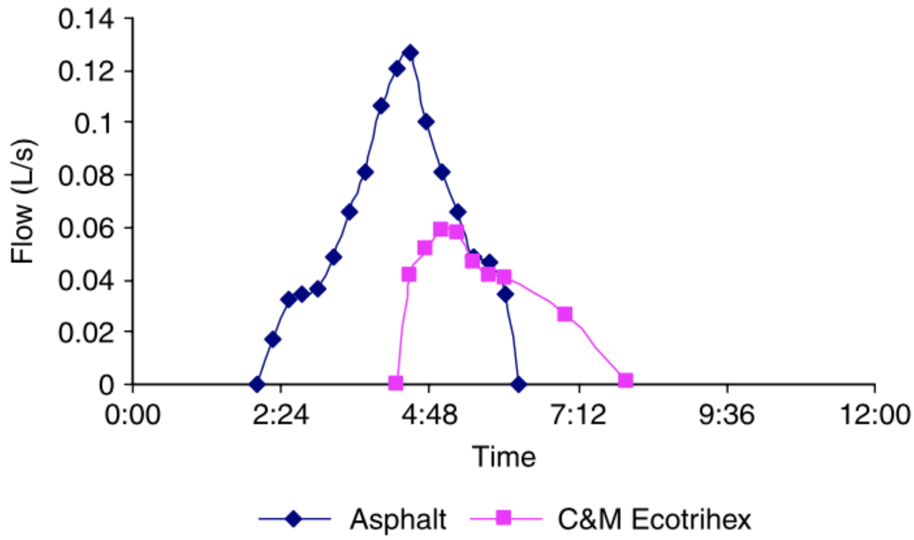

Figure 3: Stormwater hydrograph of asphalt and pervious pavement (Jayasuriya, 2007)

Multiple studies recommending pervious paving for Australian cities, especially Melbourne, have been published (Shackel, 2004; Sartipi, 2019). Due to an extensive period of below-average rainfall (11 years), the Central Region Sustainable Water Strategy (CRSWS) set a goal of reducing water consumption by 25-30% per capita in Australia (Our Water Our Future, 2006). Therefore, the incorporation of SUDS, such as pervious pavements, can facilitate water harvesting and recycling while mitigating urban water scarcity. To enhance the efficiency and sustainability of these strategies, the spatial variation of stormwater quality must be taken into account. Therefore, by exploiting the findings of Newton (2001), who reported a high correlation regarding land type and water quality, and Booth (2003), who examined the long term filtering capacity of various types and brands of pervious pavements, cost-effective strategies can be designed.

Despite the reported effectiveness of pervious pavements, these structures alone do not lead to a sufficient, sustainable level of urban drainage. To achieve a complete SUDS, a variation of vegetated and hard technologies much be implemented within an interconnected network that will gradually replace conventional systems. The first step may be taken by investing in updating car parks, pedestrian paths, sporting grounds and public areas.

3.1 Green Roofs

Roofs account for 40-50% of impermeable surfaces in cities within the developed world (Stovin, 2009), so are substantial sources of urban runoff. Green roofs are types of SUDS that enhance urban drainage sustainability without using additional land. Figure 5 visualises the structure of typical green roofs. Their cycle is driven by precipitation and evapotranspiration, as in natural settings. Consequently, this approach can reduce the volume of roof runoff and reduce the stress on surface drainage systems.

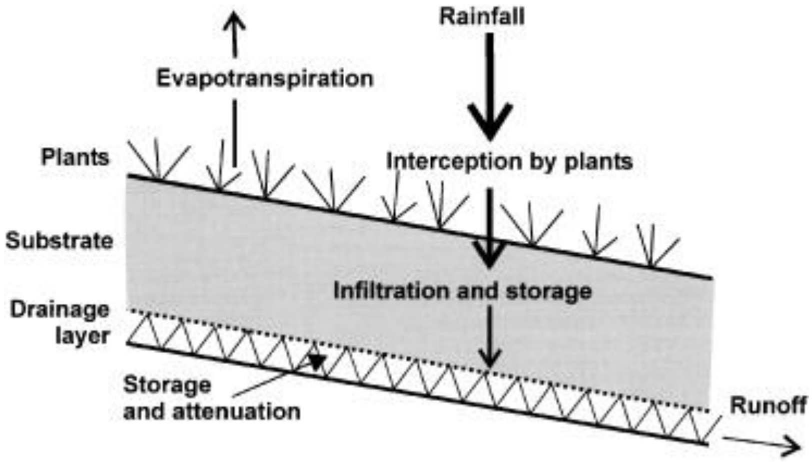

Figure 3: Green roof hydrological processes (Stovin, 2009)

Studies based in cities of various climatic zones show consistent results of significant stormwater attenuation. For instance, Kolb (2004) revealed that annual runoff could be reduced by 45-70% in Germany, based on experiments in Veitshöchheim, as 14% of roofs in Germany can support the installation of green roofs (Herman, 2003), it is possible to significantly reduce runoff within cities on a national scale. Furthermore, Moran (2004) investigated the effectiveness of two green roofs in North Carolina and reported excellent performance of 60% rainfall retention and 85% reduction in peak flowrate. Also, the performance of plant species was evaluated, and the author concluded that the plants delosperma bignum and sedum reflexum were the most effective within the studied region. The methodology included in this study is a vital contribution towards optimally designed green roofs, as due to different aerodynamics and temperatures at higher elevations, plant species may perform differently at height.

While annual performance is promising, seasonal effects must be taken into account. In Portland, green roofs must be irrigated during the summer, due to a 65-100% reduction of stored water through evapotranspiration (Liptan, 2003). This results in significant expenditure increases for cities in climatic regions with significant seasonal temperature fluctuations. This may discourage policymakers and stakeholders from adopting this strategy. Thus, for cities in climatic regions with uneven temperature or precipitation distribution rates throughout the year, green roofs might not be the most viable option.

Furthermore, there is a lack of research regarding green roof performance in a maritime climate, such as that observed in the UK. This leads to uncertainty regarding the suitability of this technology. In UK cities, rainfall is more intense and frequent, while evapotranspiration rates are much lower than in climates examined in published literature, implying a lack of appropriate data. Stovin (2009) addressed this research gap by installing and monitoring an experimental green roof in Sheffield. The research concluded that average volume retention was 34%, with a 57% decrease during peak flow. Based on these results, it can be inferred that green roofs can reduce annual runoff by 300mm in most UK regions, which is consistent with European data (Mentens, 2003). Nevertheless, it is crucial to undertake more research; only via robust results from multiple studies will it be feasible to prove the effectiveness of SUDS to policymakers and stakeholders.

Thus, there is considerable international evidence on the effectiveness of green roofs as a component of SUDS due to their effective runoff volume retention and improvement of water quality via filtration devices. While limitations of necessary irrigation for cities in hotter climates are present, biodiversity improvements (e.g., the habitat of Black Redstart in London [Gedge, 2003]), carbon sequestration (Getter, 2008), air pollution reduction (Banting, 2005) and the mitigation of the urban heat island effect (Sailor, 2008) could outweigh the costs of irrigation. Most importantly, green roofs improve the existing space within cities and enhance the quality of the environment without changing the layout of urban areas; this approach is highly applicable for cities of varying sizes and densities.

4. *Planning frameworks*

The effectiveness of SUDS depends on the physical, environmental, and social characteristics of their locations, implying the necessity for the development of a multicriteria decision-making framework for the generation of the most sustainable and efficient SUDS strategies. GIS-based techniques have been widely used for the site selection of SUDS devices. However, the holistic approach of considering social, environmental, and economic selection criteria simultaneously has rarely been adopted. In most cases, priority areas are selected according to hydrological and hydraulic aspects only, as is the case with Martin-Mikle (2015) and Dagenais (2017). These methodologies are limited, as while they investigate areas with the highest need for water management, they do not consider economic feasibility local opinion.

In contrast, Garcia-Cuerva (2018) examined a spatial distribution regarding the impact of SUDS implementation in the watershed in North Carolina, revealing the most beneficial locations. Nevertheless, the recommendation was based on the socio-economic qualities of areas, implying prioritisation of the most vulnerable population groups instead of areas with the highest flood risk. While this approach is considered effective in urban flood risk management (Sayers, 2018), socio-demographic characteristics are dynamic; the most vulnerable location is subject to frequent change. Thus, locating SUDS devices in places with the highest flood risk could be a more sustainable approach in SUDS design.

The selection of SUDS devices is made through modelling their performance in various environmental conditions. Despite advances in computational techniques, most models only select technologies according to the volume of runoff reduction and, in rare cases, water quality improvements, disregarding the associated environmental services in performance evaluation. Elliott (2007) presented an overview of 10 models for the evaluation of SUDS devices. All models investigated the most popular SUDS devices, such as wetlands, swales, pervious pavements, and green roofs. Moreover, every model had strong capabilities when modelling precipitation regimes and runoff routing, but only two models (SWMM and MOUSE), could model the hydraulics of existing drainage networks. Consequently, a comparative analysis of conventional and SUDS management approaches could only be conducted on 2 out of 10 models, leading to difficulty when justifying results to policymakers.

Overall, decision-making tools for assessing SUDS suitability and quantification of potential benefits is an emerging field of research and to date, the reliability of existing models is low. Future models will need to incorporate the simulation capacities of existing conventional drainage to create the most effective planning framework. Moreover, model ensembles could be generated, which is a much more reliable planning technique than a single-model output. Most importantly, future climate change and urbanisation dynamics must be incorporated into decision-making tools. Without the ability to adapt to future conditions, drainage systems will not be regarded as sustainable.

5. SUDS: barriers and their limitations

The shortage of evidence regarding the superiority of SUDS due to their sustainability and long-term cost-effectiveness over conventional drainage systems is the most severe obstacle in the way of adopting these strategies. Inclusion of the monetary value of ecosystem services created by multiple SUDS devices, such as green roofs and swales, could increase the return rate on investment. As a result, investments could be justified via a positive benefit-cost ratio, leading to improved perception of SUDS by policymakers, stakeholders, and the local population. Vincent (2017) proved this theory by conducting a cost-benefit analysis of the sewage network within the Montevideo Municipality in Uruguay, where he examined flood reduction capacities of conventional systems and SUDS. When environmental services were not included in the valuation, green roofs were less cost-effective than rain barrels. However, by considering them in conjunction with flood reduction capacities and sustainability prospects, green roofs had effectiveness that was comparable to conventional devices.

Despite multiple strengths and benefits, Bergman (2011) evaluated two infiltration trenches in Copenhagen, Denmark, revealing that the clogging effects of sand significantly reduce the lifespan of infrastructure. As maintenance of infiltration trenches is problematic, due to the difficulty of accessing these underground structures, the author suggests addressing the problem at the design stage or adopting alternative SUDS methods. Moreover, thermal water pollution, occurring when colder stormwater is released in wetlands, ponds, and reservoirs, causes degradation of water quality. Changes in water temperatures also alter the proportion of O2, which leads to the 'thermal shock' of aquatic biota (Huertos, 2020), altering the species mix and limiting the development of biodiversity. Nevertheless, limitations can be addressed by conducting more lab-based and on-site experiments, generating data, and using it to design more effective and sustainable management techniques concordant with local urban characteristics and climates

6. *Conclusions*

Despite several limitations and implementation-related obstacles, SUDS are gaining increased acknowledgement due to their multidimensional benefits for urban environments and sustainability prospects. Despite progress in the technological development of devices and decision-making tools, modelling their functionalities and environmental responses remains uncharted. The most critical limitation is an underestimation of the benefits of SUDS, excluding climate change mitigation and environmental aspects from conclusions. Thus, an integrated and transdisciplinary approach, where scientific findings, engineering innovations and policymaking expertise are examined holistically, must be designed to ensure an efficient and effective transition from conventional to sustainable urban drainage systems. Unquestionably, due to climate change and accelerated urbanisation, more cities will suffer from low-capacity drainage systems. Therefore, adaptability and resilience are vital in SUDS design, which can be achieved via a mix of high- and low-tech solutions.

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