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Article

Decision-Making and Sustainable Drainage: Design and Scale

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Abstract: Sustainable Drainage (SuDS) improves water quality, reduces runoff water quantity, increases amenity and biodiversity benefits, and can also mitigate and adapt to climate change. However, an optimal solution has to be designed to be fit for purpose. Most research concentrates on individual devices, but the focus of this paper is on a full management train, showing the scale-related decision-making process in its design with reference to the city of Coventry, a local government authority in central England. It illustrates this with a large scale site-specific model which identifies the SuDS devices suitable for the area and also at the smaller scale, in order to achieve greenfield runoff rates. A method to create a series of maps using geographical information is shown, to indicate feasible locations for SuDS devices across the local government authority area. Applying the larger scale maps, a management train was designed for a smaller-scale regeneration site using MicroDrainage[®] software to control runoff at greenfield rates. The generated maps were constructed to provide initial guidance to local government on suitable SuDS at individual sites in a planning area. At all scales, the decision about which device to select was complex and influenced by a range of factors, with slightly different problems encountered. There was overall agreement between large and small scale models.

Keywords: management train; modelling; Sustainable Drainage (SuDS); design; climate change; Green Infrastructure (GI)

1. Introduction

Sustainable Drainage (SuDS) is a multiple-benefit and flexible means of addressing many of the environmental impacts associated with urbanization and industrialization. It does this by mimicking nature, infiltrating where ground conditions allow, detaining excess stormwater and conveying it slowly to the receiving watercourse. In doing so, the storm peak is attenuated and issues with flooding are reduced, or eliminated depending on conditions. The multiple benefits of the SuDS approach are exemplified by the SuDS “triangle” [1] of water quantity reduction as already discussed, but at the same time water quality is improved, and amenity and biodiversity are provided [2]; most recently this has been represented by the SuDS “square” [3]. There are other benefits such as [4]’s “SuDS Rocket” whereby a suitable single SuDS device, or preferably an efficiently designed full SuDS management train, can mitigate and adapt to climate change. One example of this is the ability of any Green Infrastructure (GI) associated with SuDS such as green roofs or swales to sequester and store carbon (see [5]). The approach is being encouraged through policy and legislation, for example in England, the National Planning Policy Framework and its associated technical guidance [6] prioritise their use. However, it is applicable globally, e.g., [7,8]. SuDS are said to be multiple benefit and flexible in

application [2], and thus local authorities will have to understand how this is achieved. Designing SuDS into the environment, whether urban new build, retrofit or in rural areas is a complex process; it needs to be fit for purpose in order to take full advantage of these multiple benefits. SuDS design therefore begins with a consideration of its overall role, whether source control, infiltration, detention/retention, filtration or conveyance, an overview of which is given in Table 1. However, research to date has typically focussed on the role of individual SuDS devices such as a green roof, or an area of porous paving [9,10], with little attention paid to the effects of combining devices into an overall management train. This paper demonstrates a novel support system for SuDS selection, based on the design of a full management train capable of mitigating large scale flood events, and compares its performance against conventional pipe based systems.

Table 1. Overview of Sustainable Drainage (SuDS) device groupings ([3,11]).

| SuDS Device Grouping | Function | Example Devices |
|-------------------------|--|--|
| Source Control | Slow down, store and treat runoff at locations close to where rain has fallen. Water can be released gradually or utilised for non-potable purposes. | Green Roof Rainwater harvesting Permeable paving Sub-surface storage Trees Rain garden Disconnected downpipe |
| Infiltration | Runoff storage and infiltration into the ground to recharge groundwater | Soakaway Infiltration basin Infiltration trench |
| Detention and retention | Basins with temporary or permanent storage of runoff. Removal of pollutants to improve water quality | Detention basin Retention basin Pond Wetland |
| Filtration | Slow down flow and treat runoff to remove pollutants | Sand filter Filter strip Filter trench Bioretention device |
| Conveyance | Channels that convey runoff. Can also store and infiltrate water into the ground | Swale Rill |

All the devices in Table 1 can play a pivotal role in tackling the impacts of climate change, whether via Ecosystem Services provision through GI [12], or the flooding reduction benefits of devices such as porous paving [7,13]. However, underlying these factors are site-specific features of the drainage catchment which impact on the potential to infiltrate on site, detain water and also to be able to convey it to the next SuDS device, the receiving watercourse or groundwater reservoir. Soil type and ground conditions, for instance whether it is a brownfield site, also drive decision-making. Examples are given in Table 2 where they are classified into physical factors which are fixed over relatively long timescales, and anthropogenic drivers that may vary over a shorter term. Physical (or environmental) factors include geology, soil, topography and the presence of water above and below ground level. Anthropogenic (human-induced) factors are related to definitions of groundwater protection near extraction boreholes, plus known and potential sites of groundwater contamination risk, and existing land cover. All of these factors have scale-related importance in terms of efficient design, whereby knowledge of their extent and potential impacts is essential.

In common with conventional drainage, SuDS planning has to take account of the temporal and spatial characteristics of the design storm. Thus in England, the SuDS National Standards [14] indicate that runoff from a 1 in 100-years rainfall event must not exceed greenfield runoff rates, with a critical storm duration of 6 h. Using a UK drainage industry standard flood modelling product [15], the software MicroDrainage® [11], modelled the storm attenuation potential of various SuDS management

trains using a small part of the Canley Regeneration Zone (CRZ) in Coventry, West Midlands: Prior Deram Park. The resulting hydrographs showed that peak flow and time to peak were both reduced in comparison with a pipe-based system, rainfall response increased and total volume of runoff decreased by 20% [16]. Investigated how these reductions were achieved by deconstructing the management train hydrograph at different storm intensities. It was found that a management train of green roofs, tanked porous paving, swales and dry detention ponds reduced peak flow by 88%.

Table 2. Examples of site specific physical and anthropogenic factors driving SuDS design. Columns show the device groupings (see Table 1). Rows show characteristics. Cells marked as ‘x’ indicate the factors that influence implementation of the SuDS devices.

| Implementation Guidelines | Source Control | Infiltration | Detention | Filtration | Conveyance |
|-----------------------------------|----------------|---|-----------|--|------------|
| Factors | First Priority | Infiltrate Where Detention is not Possible, Detain Where Infiltration is not Possible | | These Should Be Used Wherever Possible | |
| <i>Physical</i> | | | | | |
| Bedrock & surface geology | | x | x | | |
| Water bodies | x | x | x | x | x |
| Fluvial flood zones | | x | | x | |
| Soil drainage type | | x | x | | |
| Topography | | x | x | | |
| Water Table | | x | x | | |
| <i>Anthropogenic *</i> | | | | | |
| Waste & landfill sites | | x | | | |
| Current & former industrial sites | | x | | | |
| Surface & ground water quality | | x | x | | |
| Land cover | x | x | x | x | x |
| Planning constraints | x | | | | x |

* Land ownership, sewer and historical flood locations add a further layer of complication to the decision-making process but are not discussed further in the examples here.

The aims of this paper are:

- To show how the decision-making process in terms of designing a SuDS management train is scale-related with reference to the city of Coventry, a local government authority in central England.
- To illustrate this with the application of a large scale site-specific model that identifies the individual SuDS devices suitable for the area using geographical information.
- To model at the smaller scale to achieve greenfield runoff taking climate change into account.

2. Methodology

The case study presented here is based in Coventry, in the West Midlands, UK, specifically the Canley Regeneration Zone (CRZ), situated about 6 km southwest of Coventry city centre, and covering just over 123 ha, some of which is brownfield (for further site details, see [11,16]). Outline planning permission has been granted for 700 new dwellings in total, new community services and open space improvements [17].

Based on the information contained in Table 2, the spatial distribution of each factor driving SuDS device choice across the CRZ was determined using data from a number of sources, including the British Geological Survey, Coventry City Council, Ordnance Survey, National Soil Resources Institute and the Environment Agency [18]. A set of decision criteria, or rules, were created for each of the factors (see Figure 1 and Table 3), for example, different rock types were assessed in relation to their capacity for infiltration or detention of runoff. Table 3 summarises the decision-making process in the design of SuDS across Coventry and signposts the outputs in this paper. Figure 1 illustrates the relationship between each set of data and factors in the production of the maps. The decision-making process was an iterative one of constant refinement. This was done through the modelling, but also

the rules were agreed and coded so they could be applied spatially in collaboration with stakeholders such as the Local Authority, Water Companies, planners and environmental regulators such as the Environment Agency, all of whom had local knowledge, at several workshops. Details of these are beyond the scope of this paper, whose focus is on the physical design and issues of scale, but comments and feedback from these sessions were used to ensure that relevant factors were included and suitable emphasis applied. The spatial relationships were then analysed using a geographical information system (GIS), in order to determine appropriate locations for the different types of SuDS for new developments and regeneration sites, the output for which was a set of maps. By using a GIS approach, the maps were scalable; they could be viewed at different resolutions from full city scale to that of individual development and regeneration sites.

Table 3. Data collection and analysis overview.

| Stage | Activity | Output |
|-------|---|-----------------------|
| 1 | Define SuDS groupings | Table 1 |
| 2 | Identify influencing factors | Table 2 and Figure 1 |
| 3 | Allocate influencing factors to SuDS groupings | Table 2 |
| 4 | Define rules for influencing factors | Figures 1 and 2 |
| 5 | Determine spatial distribution of influencing factors | Figure 1 |
| 6 | Agree rules for influencing factors | Stakeholder workshops |
| 7 | Apply rules to each SuDS grouping | Figure 1 |
| 8 | Present outputs in map form | Figures 3 and 4 |
| 9 | Determine site specific SuDS Management Train options | Figure 5 |

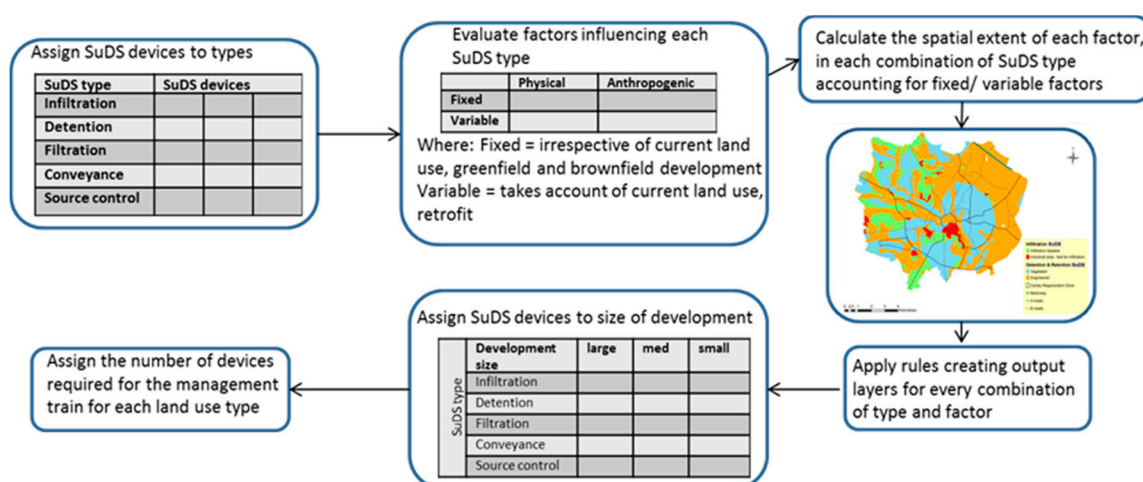


Figure 1. Implementation of the framework used to determine the suitability of SuDS devices.

Overlying the map creation process shown in Figure 1 are a number of individual processes which were fed into the overall model. Figure 2 shows an example of how the theoretical framework was implemented to determine the suitability of SuDS according to the driving factors and SuDS device types. The GIS software ArcGIS [19] was utilised to collate and analyse spatial data. Figure 2 illustrates the ArcGIS process followed in order to identify where the most appropriate areas might be with respect to water quality and water quantity based on the fixed and variable factors influencing conveyance SuDS.

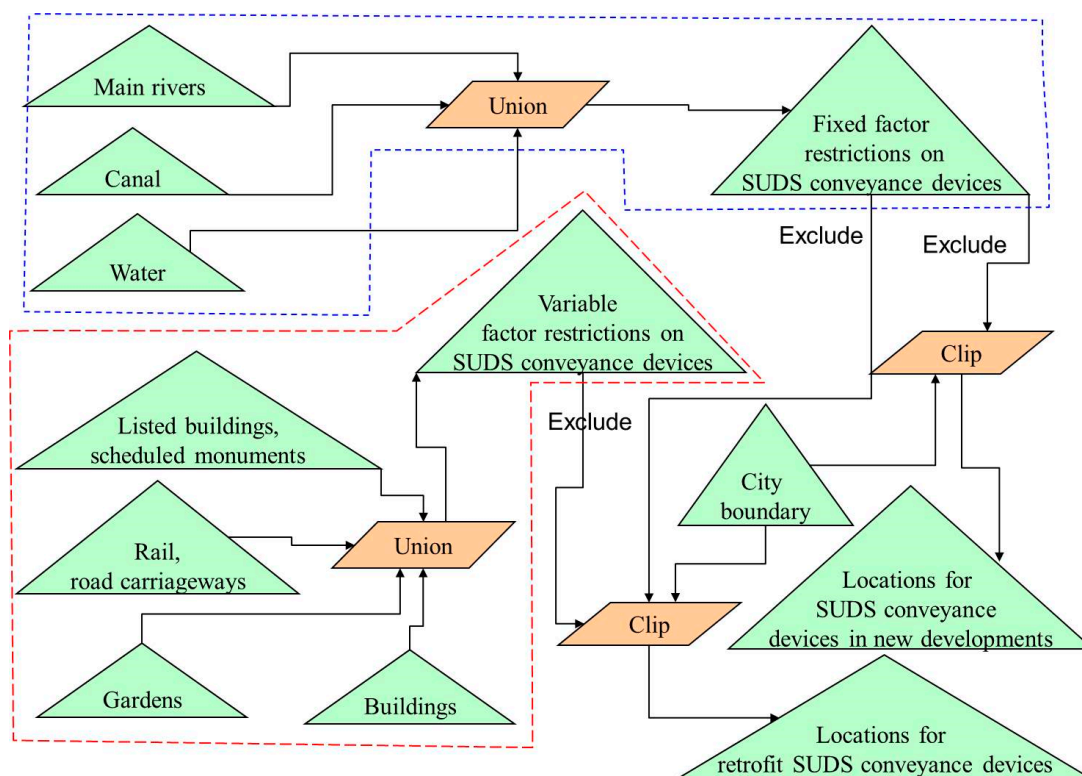


Figure 2. The steps in ArcGIS to identify factors influencing conveyance SuDS: those enclosed in the dotted line are fixed, those enclosed in the dashed line are variable. Datasets are depicted as triangles, processes as rectangles.

Figure 2 illustrates the ArcGIS process followed in order to identify where the most suitable areas might be with respect to the locations of SuDS conveyance devices based on their fixed and variable factors. Fixed factors are here defined as those which vary over long timescales such as lithology, soil type and topography, whereas variable factors vary over short timescales and include changing land use. Figure 3 contains fixed factors inside a blue box, in which the 3 datasets that identify locations of water bodies are combined (Union) into one dataset that is the spatial representation of all fixed factors limiting or restricting where conveyance SuDS can be located. The red box contains planning constraints and land cover datasets, again combined into one dataset which represents the variable factors limiting or restricting the location of conveyance SuDS. Restricted places are excluded (Clipped) from the full extent of the planning area, so that SuDS conveyance devices should therefore be possible everywhere else.

Once the suitable SuDS devices had been mapped, both a SuDS management train and also a piped system for comparison were designed using MicroDrainage[®] but at a reduced scale with the desktop modelling exercise located at a smaller parcel in the CRZ, Prior Deram Park where permission had been granted for the construction of 250 houses. A strategic flood risk assessment of the CRZ [20] identified SuDS generically as necessary to address flooding issues, without specifying suitable SuDS, advising only of the need to “take account of groundwater and geological conditions”. The example SuDS train was designed to limit runoff to less than $10 \text{ L}\cdot\text{s}^{-1}$ for the whole 5 ha site; this was to comply with the previous draft SuDS National Standards since the current version [14] has yet to stipulate a runoff rate. To ensure the site was defined as accurately as possible, a 1 m^2 resolution digital elevation model was used to determine the destination of runoff. Large-scale map information indicated that infiltration was not possible, therefore the design concentrated on provision of detention via ponds, which also provided a treatment stage. Runoff was directed into the nearby Canley Brook. The response of the site to the 1 in 100 years 30-min winter critical storm ($73.13 \text{ mm}\cdot\text{h}^{-1}$) was then simulated.

3. Results

The hierarchy of recommended SuDS approaches for new build in Coventry developed from the mapping exercise described in the methodology is shown in Table 4. Placing source controls as the initial stage agrees with SuDS management train principles in which excess rainfall should be dealt with as close as possible to the point at which it falls [3]. Source controls can be designed to deal with runoff from the first 15 mm of rainfall, and will principally address water quality issues; they are feasible in over 99% of Coventry. However, source controls will not manage large volumes of runoff which increase flood risk, for which one of the remaining approaches in the hierarchy should be selected. Infiltration SuDS, which reduce both the rate and volume of runoff, should be implemented as the second priority where potential land contamination is not a risk (14.5% of Coventry). Infiltration effectively removes runoff from a drainage system, rather than retaining it within the system [21]. Where infiltration is feasible, but land contamination is a concern, field investigations should be performed to ascertain suitability before proceeding, which applies to 2.5% of Coventry. In areas where infiltration is not feasible, above ground vegetated detention and retention SuDS should be prioritised (32% of Coventry). In the remaining 50% of the city, engineered detention and retention SuDS (e.g., re-landscaping, lined basins or hard infrastructure) will be needed. Here also, above ground SuDS should be prioritised, although these will require greater design, and possibly construction, effort than other suggested applications. A spatial representation of these is depicted in Figure 3 and indicates the complexity of the decision-making process at the large scale.

The different performance characteristics of individual SuDS techniques in terms of the SuDS triangle or Rocket must be taken into account when considering their suitability for addressing particular requirements at the detailed design stage. These requirements can therefore be based on, for example, flood resilience, or reduction of the Urban Heat Island Effect (UHIE) [4]. It is important to note that Figure 3 offers outline guidance, whereas evidence-based investigations at each site, undertaken for detailed planning, may generate alternative SuDS solutions which should take precedence over these recommendations.

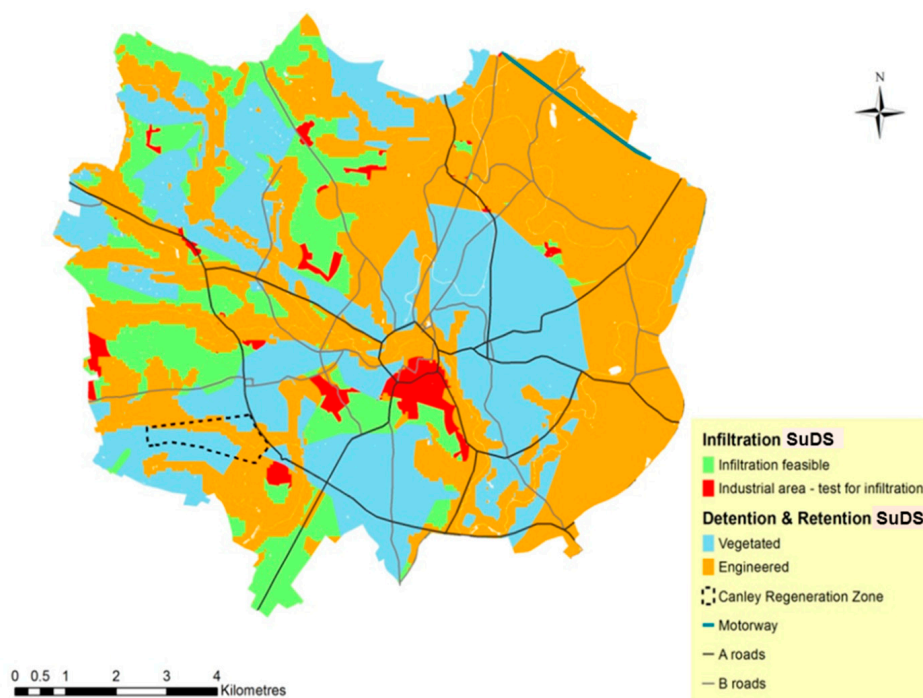


Figure 3. Locations of recommended SuDS approaches in new developments in Coventry.

Table 4. Hierarchy of recommended SuDS approaches for new developments in Coventry.

| Priority | SuDS Approach | Suitable Area of City |
|----------|---|-----------------------|
| 1 | Source controls | 99% |
| 2 | Infiltration SuDS | 14.5% |
| 3 | Infiltration SuDS in former industrial land, if tests show no potential for contamination | 2.5% |
| 4 | Vegetated detention SuDS | 32% |
| 5 | Engineered detention and retention SuDS | 50% |

Applying the methodology at the smaller scale, the recommendations given in Figure 3 were applied to the CRZ. All groups of SuDS devices were possible in Canley apart from infiltration, where only small areas to the southeast and southwest of the zone were possible (Figure 4a). Source control, filtration and conveyance were possible across the whole site, therefore no maps are presented for these. Figure 4b shows the potential for detention and retention SuDS for the site, illustrating where “softer” vegetated SuDS could be used, and also where the more engineered applications need to be installed due to ground conditions or proximity to the local watercourse, the Canley Brook.

A more detailed desktop assessment was carried out by [16], utilising detention ponds for storage, swales for conveyance, and permeable paving and green roofs as source controls while modelling combinations of techniques to judge the effectiveness of different SuDS management trains. Infiltration was not regarded as a suitable option at this site due to soil type and prior use of part of the site as a landfill as reflected in Figure 3. The results of the desktop modelling exercise are shown in Figure 5 and it should be emphasised that this is just one possible suggestion.

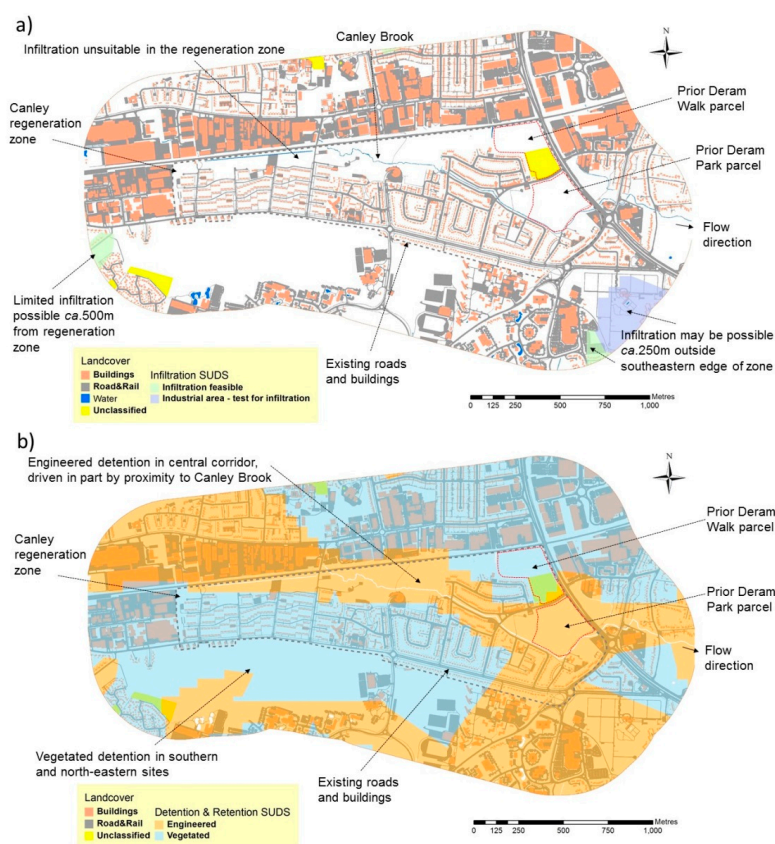


Figure 4. SuDS guidance for Canley Regeneration Zone (CRZ): (a) Infiltration and (b) detention and retention. Some details derived from Ordnance Survey © Crown Copyright and Database Right 2010. Ordnance Survey (Digimap Licence).

A combination of swales and pipes was used to convey water through the site, with tanked porous paving and a green roof to every house. Pipes were only used when either space was unavailable for a swale, or water needed to travel below either a road or the driveway of a house. Finally four ponds were installed across the site to retain water during a large event; all runoff was conveyed into one of the ponds prior to being released into the nearby Canley Brook at three separate outlet points. An orifice plate was added at the outlet of each pond to ensure compliance with greenfield runoff rates; this would be a weir plate of some kind to slow the water's exit from the pond. Comparing this design against a fully impermeable construction serviced by a piped drainage system, the SuDS management train would easily deal with a 1 in 100 years storm. As a cautious approach, 30% was added to rainfall to account for climate change, such an addition is recommended by the UK EA [22], and applies across all of England. It is based on the introduction of the National Planning Policy Framework in 2012 [23] which was brought in to reduce vulnerability to climate change and to increase resilience. The recommendations use 1961–1990 rainfall as a baseline and add between 20% and 40% at the upper end as a precautionary measure for the total changes anticipated for 2050–2080, thus the present study added 30% as an intermediary. In fact, the system could have coped with up to a 1 in 275 years storm; however, in a 1 in 100 years flood, the piped system would result in the equivalent of 40 of the 250 houses being flooded, amounting to 858 m³ of excess water.



Figure 5. SuDS management train designed for Prior Deram Park, CRZ, Coventry. Site design details are in colour. Some context details derived from Ordnance Survey © Crown Copyright and Database Right 2012. Ordnance Survey (Digimap Licence). Adapted from [14].

4. Discussion

The recommendations of the city-wide feasibility maps were compared with the more detailed assessment as is shown in Figure 5. The results of this comparison are presented in Table 5, which shows broad agreement between the two. Thus, many of the source controls that were suggested at the broad scale, such as pervious paving systems, green roofs, trees and subsurface storage were included in the detailed assessment, with detention ponds and swales also common to both approaches.

The feasibility maps define a menu of possible SuDS choices, and not all feasibility map options can or should be used at an individual site. Detailed designs need to consider how individual SuDS features can best be combined into a management train taking account of the specific characteristics and needs of the site. Figure 5 is an *indication* of how SuDS can be designed to manage flood risk at the

scale of a redevelopment site. While the focus of Figure 5 is to address flood risk, some of the designed SuDS features also deal with water quality issues, as well as providing amenity and biodiversity benefits and the means to adapt to and mitigate the impacts brought about by climate change. The feasibility maps indicated additional options that could have been included in the site design, such as rain gardens and rainwater harvesting for runoff attenuation, but like filter strips, these were not available options in MicroDrainage®. Bioretention devices were suggested by the feasibility maps, and could have been included in the more detailed design to manage runoff from the estate roads.

Table 5. Comparison of SuDS feasibility map proposals for CRZ with Figure 5 for Prior Deram Park.

| Device Grouping | Detailed Assessment for Prior Deram Park (Figure 5) | Broad-Scale Feasibility Map Options for CRZ |
|-----------------------|---|--|
| | Options in bold show agreement between the two methods across different scales | Proposals that could be considered for this site |
| Source Control | Permeable paving; green roofs; sub-surface storage; trees | Green roof; rainwater harvesting; permeable paving; sub-surface storage; trees; rain garden; disconnected downpipe; soakaway; infiltration trench; bioretention device |
| Infiltration | none | none |
| Detention & retention | Detention ponds , Orifice plate | Engineered: detention basin; retention basin; pond; sub-surface storage; rainwater harvesting; bioretention device; swale |
| Conveyance | Swales | Swale, rill |
| Filtration | | Filter strip; filter trench; bioretention device; detention basin; retention basin; pond; swale; permeable paving |

The SuDS design produced a plan that would easily deal with a 1 in 100 years storm (including +30% rainfall to account for climate change, [22]), compared to a conventional piped-based system which would be unable to cope, producing flooding extending to one fifth of the planned new build housing. SuDS management trains can provide betterment over conventional drainage solutions, but need to be designed so that the component devices link effectively. Whereas conventional drainage focuses on water quantity, SuDS management trains can be designed to include provision for water quality and amenity, as well as mitigate and adapt to a changing climate and therefore have multiple benefits; such a design at Prior Deram Park included temporary storage for excess surface water which also had a role as a community park. Inclusion of GI in designs such as this also has the potential to provide a means of addressing some of the changes in climate by, for example, carbon sequestration and storage and reduction of the UHIE. The maps provided guidance at the large scale, but could be subject to issues associated with coarseness of scale. In this study, closer examination at the smaller design scale supported findings from the larger scale maps.

5. Conclusions

This paper has considered the design of Sustainable Drainage systems at different scales and has illustrated the factors and decision-making required for this process to be successfully carried out. However the use of SuDS in England requires local government to understand these techniques. This study presents a method which can identify feasible locations for SuDS devices at the city scale early in the decision-making process. However, the process to build the maps requires a substantial amount of information and an understanding of its meaning. Whilst it is recognised that the larger-scale maps are suitable for the early stages of discussion, more technical tests and modelling results are required for a detailed planning application, and other design approaches will be more appropriate

for these later stages. The maps provide information which is readily understandable and which will support the initial discussions which take place between planning officers and developers. Consequently, they may contribute to the reduction of potential barriers limiting the uptake of more sustainable forms of stormwater management.

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