Article

The Use of End-of-Line SUDS for Residential Development

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ABSTRACT

As new housing developments continue to increase, traditional methods of managing surface water are not sustainable, as watercourses cannot cope with the increased surface water run-off partnered with the impact of climate change. Sustainable Urban Drainage Systems (SUDS) act as an alternative method to directly channelling surface water flows through the traditional pipe and sewer system. SUDS utilise a series of management techniques to recreate the natural drainage routes by aiming to intercept at source. It has been identified that optimum methods of managing surface water are rarely achieved due to the number and different priorities of stakeholders involved in the approval process. The aim of this study was to identify the driving factor influencing the end of line (EoL) SUDS features being implemented within residential developments across central Scotland with focus on stakeholders' influences. Mixed method approach was adopted via an electronic questionnaire to collect qualitative and quantitative data in tandem. Case study approach was also taken to identify common SUDS features within twelve existing residential developments and redesign an existing site based on the principles of the SUDS philosophy. The data collected confirmed that end-of-line SUDS such as basins and swales are most frequently implemented within residential developments and there are many organisations involved in the design and approval process. The data highlighted that end-of-line SUDS are specified as this is a cost-effective solution that usually avoids encountering unnecessary problems throughout the approval process with the local and water authorities. The re-design of a representative case study showed that by implementing the principles set out in the SUDS management train, managing the volume and quality of surface run-off will be easier as this will be captured at source initially. However, there is a lower construction cost associated with installing an end-of-line detention basin within residential developments compared to a cellular storage system, and this could be a critical factor for developers when designing SUDS features as they often look to keep construction costs as low as possible.

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INTRODUCTION

As the impact of climate change in terms of increased, and more intensive precipitation becomes more severe with the population growing and developments increasing [1], it is clear that flooding risk becomes a major issue for residential areas [2,3] and must be managed as part of the planning process [4]. While the 2017 Climate Change Risk Assessment predicts the annual damage associated with flooding to residential properties could rise by 22%–78% in 2050 and 47%–160% in 2080 [5], in Scotland at present, it is understood that approximately 284,000 homes, businesses and services are at risk from potential flooding from surface water and watercourses. It is also envisaged that an additional 110,000 properties will be at risk due to the impacts of climate change by the year 2080 [6], considering the steady increase in building new residential developments since 2017, only slowed down by the Covid-19 lockdown in the past few years [7]. As the number and extent of new housing developments continues to increase year on year [8], traditional methods of managing surface water are proving insufficient and not sustainable [9,10], with many watercourses not coping with the increased surface water run-off and pollutants [8] from new developments partnered with the impact of climate change. Various researchers have concluded that design rainfall intensities can increase by 20%–80% due to climate change [8]. To better manage surface water, it is crucial that the full suite of integrated drainage measures is utilised to target flooding to reduce the impact as much as possible, whilst improving the efficiency of critical infrastructure and the environment [1,11].

Sustainable Urban Drainage Systems (SUDS) were introduced to combat the effects of flooding and promote a more sustainable development. SUDS are designed with a view to maximise the benefits for our development by managing surface water correctly to better resiliency against flooding [2,12]. The benefits achieved by utilising SUDS correctly can be split into four main categories: [12–14].

- Water Quantity—to control the water and reduce flood risk
- Water Quality—to reduce pollution and contamination
- Amenity—to achieve a sustainable development for humans
- Biodiversity—to achieve a sustainable development for nature

The SUDS management train [15] was derived to recreate the natural drainage effect [16] by utilising a variety of SUDS elements in sequence to manage the volume and quality of run-off [10]. The SUDS management train principles are as follows [16,17].

- Prevention—design of the site to reduce run-off

- Source Control—intercept the run-off at first impact
- Site Control—manage the run-off for a development at end of line
- Regional Control—manage the run-off for a large catchment area

SUDS techniques have been designed to ensure they can be implemented effectively within any site constraints to comply with the SUDS design principles and management train [13]. Techniques such as rainwater harvesting, green roofs, infiltration systems, filter drains, swales, porous paving, storage tanks, detention basins, ponds and wetlands have been identified as most viable and representative of the SUDS way of managing the water and protecting the environment [12,18] from developments where it is created (at source, Table 1) or at the development site (site control measures, Table 1) or managing the water across a wider area (regional control, Table 1).

Table 1. SUDS features and their adoptability. Adapted from [19,20].

SUDS Type	**Location of Use**		
	At Source	**Site Control**	**Regional Control**
Detention Basin	-	X	X
Pond/Wetland		X	X
Swale	X	X	X
Soakaway	X	X	-
Permeable Paving	X	X	
Green Roofs	X	-	
Rainwater Harvesting	X		
Filter Drains	X	X	

Note: Green hatch denotes high adoptability. Orange hatch denotes occasionally adopted. Red hatch denotes unlikely to be adopted.

Although the SUDS philosophy discourages the use of end-of-line (EOL) solutions where the drainage water is directly discharged into a wetland, swale, pond or soakaway, the residential housing developers often opt for these despite potentially larger costs, faster runoff flows, higher levels of pollution, and larger space requirements. This type of design does not provide a balancing of different options and associated risks where the risk of an area flooding is not balanced with the costs of flood protection measures.

In order to establish the appropriate balance between the risks and the costs, life cycle costing can be used. This involves establishing and analysing all relevant cash flow relating to the SUDS solution which will provide a comprehensive cost associated with the system. Additionally, this will give an insight into the long-term costs associated with the design, construction, and maintenance of the SUDS system [21]. Life cycle costing is not often used during the initial design proposals for drainage for residential developments as traditional drainage components are adopted [22] by the sewerage undertakers (Water Authority or Local Authority) as an asset in accordance with the current legislation which shows a responsibility conflict between the capital outlay and long-term investment [21,22]. The developers are looking to reduce construction costs with little concern for the long-term maintenance costs to the adopter. On the other hand, the adopter is not concerned with the initial outlay from the developer and is focused on the long-term impact of the system. Developers, adopters, and other stakeholders are often not working in tandem towards the same goal [22] of maximising the benefits of SUDS within the residential developments which results in the most cost-effective SUDS solution being utilised [8] even though this may not be the most effective or sustainable method in accordance with the SUDS principles. It is important that SUDS are considered early in the master planning of any developments prior to detailed design being carried out. Early discussions can be very effective as the various stakeholders involved in SUDS design will be engaged in communications and all parties can work towards the same goal [9,23] rather than focusing on their own organisation's priorities during decision-making and approval [8].

The Scottish Government has set out a new policy framework for surface water management and blue-green infrastructure to ensure creation of Water-Resilient Places by implementation of new technologies and co-ordination with other fields into drainage design [12]. These will ensure surface water flooding impacts are reduced as it has been identified that the optimum method of managing surface water is rarely achieved due to the number of stakeholders that influence the decision-making and the range of legislation and policies in place [7,8,24–28].

The implementation of SUDS design requires correspondence between the developer, design team [14,29] and external stakeholders that include the following:

- Various Local Authority Departments
- Planning, Flooding, Highways, Ecology, Open-Space
- Environmental Regulators
- Water and Sewerage Undertakers
- Scottish Environmental Protection Agency (SEPA)
- Developers, Consultants, Engineers
- Members of Public, Local Community Groups & Resident Organisations

Design and elements of the SUDS is dependent on the willingness of the external stakeholders to buy into what the developer is trying to achieve [30]. Ultimately, approval and adoption of the system is what drives the design. However, obtaining approval from the stakeholders is often difficult due to their unwillingness to change [22] as there is often limited practical evidence to prove the effectiveness of SUDS schemes [9,31].

The aim of this study is to investigate the driving factors influencing an end-of-line SUDS solution often being implemented within residential developments across central Scotland with focus on stakeholders' engagement/participation. To achieve this aim, the following objectives will be pursued:

- Identification of stakeholders and common SUDS design solutions for residential developments across central Scotland by reviewing the industry databases and expert experience.
- Determination of a design approach to utilise SUDS source control within residential developments based on existing design standards.
- Selection of a representative case study to re-design an existing site adopting source control SUDS.
- Cost comparison between the original and re-designed solution for the case study site to determine the effect of cost as the main driving factor for an end-of-line SUDS solution being utilised.

MATERIALS AND METHODS

Mixed method research was selected for this study as the benefits outweighs the limitations of adopting either qualitative or quantitative research [32]. A questionnaire survey of relevant stakeholders was followed by case study analysis and re-design of SUDS system for a representative construction project. The case study design analysis and re-design included estimates of costs involved in implementation of different SUDS. The flow chart on Figure 1 shows the methodological approach followed in this study.

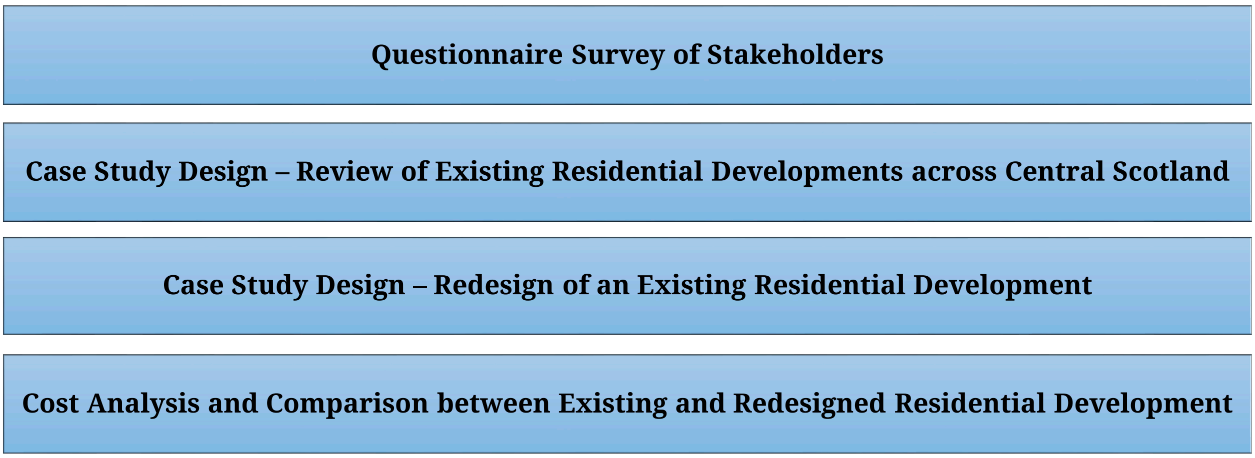


Figure 1. Flowchart of research methodology.

Questionnaire Survey Design

To identify the stakeholders and common SUDS design solutions for residential developments across central Scotland a critical literature review of industry standards and company databases were carried out. Expert experience and opinions were collected based on communication with Senior Engineer's in a multi-discipline Consultancy, Senior Architects, Water Authority Engineers, and Local Authority Engineers. The former included identification of stakeholders in the SUDS planning and design process based on the planning process for residential developments [17] and the industry guidance for SUDS design and construction [14]. The critical review showed that the relevant stakeholders comprised:

- Housing Developers (construction)
- Local Authorities (planning and transportation departments)
- Water Authority
- Designers (consulting engineers and architects)
- Homeowners

To ensure robustness and representativeness in the survey of the stakeholder experiences and opinions, it was decided to issue a questionnaire survey to seven individuals of each stakeholder (35 questionnaire surveys issued), covering a number of geographical locations across Central Scotland where many residential developments have been identified. The questionnaire survey was issued in an electronic format and enabled collection of qualitative and quantitative data in tandem [33]. The questionnaire survey was designed to collect quantitative data to provide hard evidence and measure the knowledge of participants [34] in the area of SUDS planning and design. Qualitative data was also collected from the participants to gauge their deeper understanding and experience by allowing each participant to provide personal comments. This approach allowed a fuller view of the study topic, while providing a link between the two research methods [35].

Acknowledging the range of experiences and expertise in the identified stakeholders, we considered distributing two separate questionnaires [36]: one to industry professionals and authorities who are more likely to have greater expertise in SUDS, and one to home-owners who are unlikely to have any or deep understanding of SUDS. However, we recognised that sufficient data could be obtained with one questionnaire by prompting the participant to questions specific to their background. By avoiding separate questionnaires, we mitigated the potential for misinterpretation and representativeness of the collected data.

The questionnaire survey was designed to collect specific information on the participants background, experience, and knowledge through the initial closed-answer questions. These questions were designed to explore any links between different stakeholders against topics introduced later in the questionnaire. The first part of the questionnaire also comprised an open-ended question to gauge each participant's perceptions and experiences of most common SUDS within residential developments.

The participants from the industry, and the authorities were further asked how often different types of SUDS measures are designed/constructed or adopted within their respective organisations.

They were also asked to provide the justification for this selection in an open-ended question, which not only showed which SUDS measured are most commonly used but also allowed the authors an insight into each stakeholder's ethos in terms of design/construction and adoption of SUDS measures.

The homeowners, on the other hand, were asked about their level of awareness with regards to SUDS philosophy, the maintenance requirements of SUDS within private property boundary, and their willingness to maintain the SUDS within their property boundary. These questions were designed to gauge the existing knowledge of SUDS related issues within the homeowners but also to provide back-up to counteract opinions gained from housing developers on the reasons why certain SUDS are more commonly implemented than others.

The data obtained from the questionnaire was analysed using common statistical methods before being presented as descriptive statistics in graphs and numerical tables [35]. These were intended to highlight the links between respondents' answers needed for achieving the aim and objectives of this study, and support or disprove the information discussed within the Introduction. Thematic analysis [33,35] was used to convert the open-ended text responses into quantitative data, to create data that can be easily analysed to ascertain if there is a consensus between or within each stakeholder type.

The purpose of the questionnaire was to obtain information from individuals who are responsible for SUDS and professionals associated with SUDS design in residential developments. The questionnaire was issued to the Local Authority, Water Authority, Housing Developers, Consultant Engineers, and homeowners. The response rate was well balanced through each stakeholder type with a minimum of 5 out 7 responses received from each with a return rate percentage of 80% as shown in Table 2.

Table 2. Questionnaire distribution and return rate.

Distribution	Number Issued	Number Returned	Return Rate
Local Authority	7	5	14.2%
Water Authority	7	5	14.2%
Housing Developer	7	5	14.2%
Designers	7	7	20.0%
Homeowner	7	6	17.1%
Overall Total	35	28	80.0%

Case Study Design

To determine the most common SUDS measure constructed in the residential property developments in Central Scotland, a review of existing residential sites was carried out. The review included sources such as the national ePlanning portal as well as company databases and personal communication with relevant industry professionals including Senior Engineers in a multi-disciplinary Consultancy, Senior Architects, Water Authority Engineers, and Local Authority Engineers.

The findings of this review were then compared to the responses from the questionnaire survey to ascertain the most common SUDS design approach and to identify a representative case study where such SUDS approach has been adopted. Case study research was deemed suitable for this study as it allowed identification of an existing SUDS method which is often used in real life and take action to support the view that alternative methods could be more beneficial [37] to the development and SUDS philosophy. The viability of this method of research for this particular study is supported by [38] who concluded that a case study is an empirical enquiry that uses various sources of evidence to analyse one instance within a real-life scenario. Providing an in-depth study on one representative residential site, the case study analysis also allows gaining theoretical validation as well as statistical validation obtained through comparison with the responses in the questionnaire survey [35].

The identified representative case study was then re-designed using MicroDrainage, industry standard drainage design software [39] in order to demonstrate the implementation of SUDS source control measures within residential developments based on existing design standards. The purpose of the re-design was to implement source control SUDS features to treat and attenuate surface water run-off in a more natural way in accordance with the SUDS principles. The SUDS measures implemented in the re-design have been selected in accordance with the Simple Index Approach Tool [14], to ensure adequate and sufficient management of the pollution arising from the proposed development. The re-designed network was modelled utilising commercially available software [39] and was analysed for the cases of:

- 50 mm/hour rainfall intensity
- Summer and winter storm durations of 15, 30, 60, 120, 240, 360, 720, 1440, 4320, and 10,080 minutes
- 1 in 30-year precipitation event + 30% climate change, and
- 1 in 200-year precipitation event + 30% climate change

As required by the current design standards and the Water Authority [25–28].

Cost Analysis and Comparison

Additionally, the re-design allowed for a comparison between the originally adopted and the re-designed solution for the case study site to determine the effect of cost on the selected choice of SUDS. This comparison was also aimed at ascertaining if cost is a major factor influencing the SUDS design, especially when viewed through the lens of the responses received in the questionnaire survey. The costs comparison included construction costs associated with individual plot constructions for driveways as well as the adoptable roads and drainage features implemented.

The indicative cost estimates for both the original and the re-design SUDS measures were based on [40] and were exclusive of VAT and professional/statutory fees to allow for like-for-like comparison rather than comparing commercial costs of different products. The cost estimates were based on the same site layout drawings of driveways, roads, and drainage and did not include the drainage network costs as these were likely to be similar for both designs.

RESULTS

Questionnaire Survey

The validity of the views expressed in the questionnaire survey was confirmed with 92.9% of the respondents having declared knowledge of SUDS prior to the survey while for 7.1% of respondents this survey introduced the concepts associated with SUDS. Of the majority of respondents with SUDS experience, 42.9% were professionals with more than 8 years' experience in SUDS, 32.1% had 3–8 years' experience, while 17.9% had less than 3 years' experience in SUDS. These results indicate that many respondents have extensive prior knowledge of SUDS which gives confidence that the responses received can be considered reliable.

The respondents (71.4%) indicated that basins and swales were the most common SUDS features within the residential developments they had experience with (Table 3). On the other hand, features such as porous paving, ponds, and filter drains were indicated as the least common in the residential developments with a response rate of 21.4% to 25%. These results support the findings of the case study review of existing residential sites (Figure 2) carried out identifying SUDS features within existing developments. This also shows that the SUDS management train principles are not followed, as many sites are drained via site control features and do not implement source control SUDS in accordance with the SUDS design philosophy.

The results also indicate that there is no clear and obvious third common SUDS feature implemented on the residential developments in Scotland, as 35.7% of respondents have stated storage crates, 25.0% stating filter drains, and 21.4% stating ponds and porous paving. Five participants who did not answer this open-ended question were homeowners who did not fully understand the concepts and features of SUDS.

After identifying that end-of-line SUDS as the most common features implemented in residential developments, we analysed the responses to identify what type of SUDS stakeholders specify most often or adopt most frequently.

Table 3. Frequency of SUDS specification or adoption by relevant stakeholders.

SUDS feature	Frequently	Occasionally	Infrequently	Never	N/A	Total
Rainwater Harvesting	0	2	13	8	5	28
Green Roof	0	2	13	8	5	28
Soakaway	6	11	6	0	5	28
Porous Paving	8	9	5	1	5	28
Storage Tank	8	12	3	0	5	28
Filter Drain	7	13	4	0	5	28
Swale	17	4	2	0	5	28
Basin	19	4	0	0	5	28
Pond	15	4	4	0	5	28

Table 3 shows that the respondents do not frequently specify or adopt rainwater harvesting or green roofs within residential developments. Around two thirds of the respondents stated that a detention basin is frequently specified or adopted, followed by swales, and ponds in terms of frequency of specification or adoption. From the other SUDS features, porous paving or storage tanks were reported as frequent choices with around one third of the respondents opting for their adoption. The results also show that at some point every one of the respondents has adopted or specified basins, swales, or ponds as SUDS feature for a residential development. Almost 18% of the respondents answered, 'not applicable', which is likely to be attributed to the homeowners who participated in the survey and who are not involved with SUDS design. These results further support case study review of existing residential sites (Figure 2) where almost 68% of the surveyed who very frequently specify or adopt an end-of-line SUDS basins. On the other hand, the source control features such as green roofs or rainwater harvesting were either selected infrequently (46.4%) or never selected (28.6%). The high percentages of adoption of end-of-line features shows that the SUDS design philosophy discussed in the introduction/background is not being implemented effectively within the existing residential developments in Scotland.

The results of the analysis of the responses about the reasons for frequent adoption of the different SUDS features are shown in Table 4. Almost 43% of the respondents stated that a detention basin was very frequently selected as this is a cost-effective install, it is easier to obtain approval from the local authority and governing bodies plus has low maintenance costs throughout its life cycle. These results clearly show that a detention basin is often selected to avoid encountering unnecessary problems throughout the approval process with the local and water authorities.

Table 4. Reasons for frequently adopted SUDS within residential developments.

SUDS feature	Reason	Count	Percent
Basin	• cost-effective and low maintenance • easier to obtain approval	12	42.9%
Porous Paving	• natural looking drainage system	1	3.6%
Green roofs	• no requirement to maintain	1	3.6%
Basin and Swale	• Water authority do not adopt private SUDS	1	3.6%
Storage tank	• Underground and provides usable space	1	3.6%
Response discounted	-	6	21.4%
Not Applicable	-	6	21.4%

Six of the responses did not state which specific SUDS feature the answer related to and had to be discounted from the results. Another six respondents did not respond to this question which is likely to be associated with the homeowners who were participating in the questionnaire survey and had no role in adoption or specification of the SUDS features.

When homeowners were asked to ascertain if they are aware of the maintenance requirements of private SUDS features within their property boundary, only 16.7% of them claimed awareness of these requirements while the rest (83.3%) were unaware of the maintenance requirements for the private SUDS features. This identifies a lack of knowledge within the public with regards to SUDS and their role in flood management and water quality enhancement. Furthermore, when asked if they would be willing to maintain private SUDS features within their property boundary, only half of the home-owners responded that they would be willing to carry out the maintenance duties associated with private SUDS within their property boundary. This identifies that there is a lack of public knowledge which contributes to a negative attitude towards SUDS and the role everyone should undertake with regards to flood protection and water quality enhancement.

Review of Industry Databases and Selection of a Case Study Site

The review of industry databases has identified that an end-of-line (site control) SUDS solution is most commonly incorporated within residential developments across Central Scotland (Figure 2) which supported the views and confirmed the representability and robustness of the data from the questionnaire survey. A number of existing residential sites with units ranging from 44 to 228 have been identified as utilising end-of-line SUDS with some of the sites incorporating a detention basin and the others incorporating a detention basin and swale in tandem. The requirements of the SUDS features will be dependent on each individual site layout and date of construction to satisfy the requirements of industry guidelines to obtain approvals.

(a)

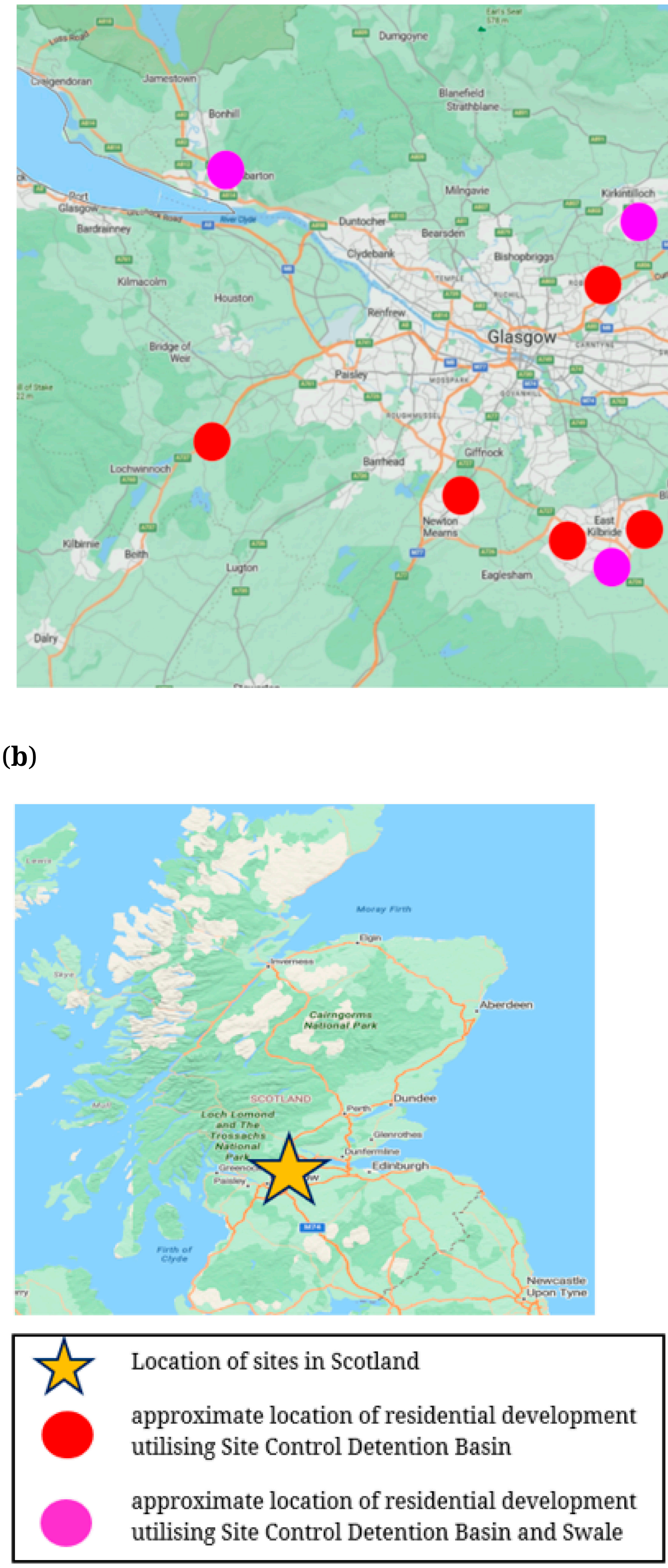


Figure 2. (**a**) OS Map (Bing Maps) Central Scotland: Identified SUDS features adopted/designed for the existing residential development sites (**b**) OS Map (Bing Maps) Scotland.

A residential site located in Falkirk, Scotland was selected as representative case study from the list of existing developments based on the designed features and the size of the development. The drainage for the existing 44-unit residential development has been constructed utilising a traditional gully and piped drainage system that drains to an end-of-line detention basin to treat and store the surface water run-off prior to discharge into the existing drainage network owned by the water authority located in the North-East corner the site (Figure 3).

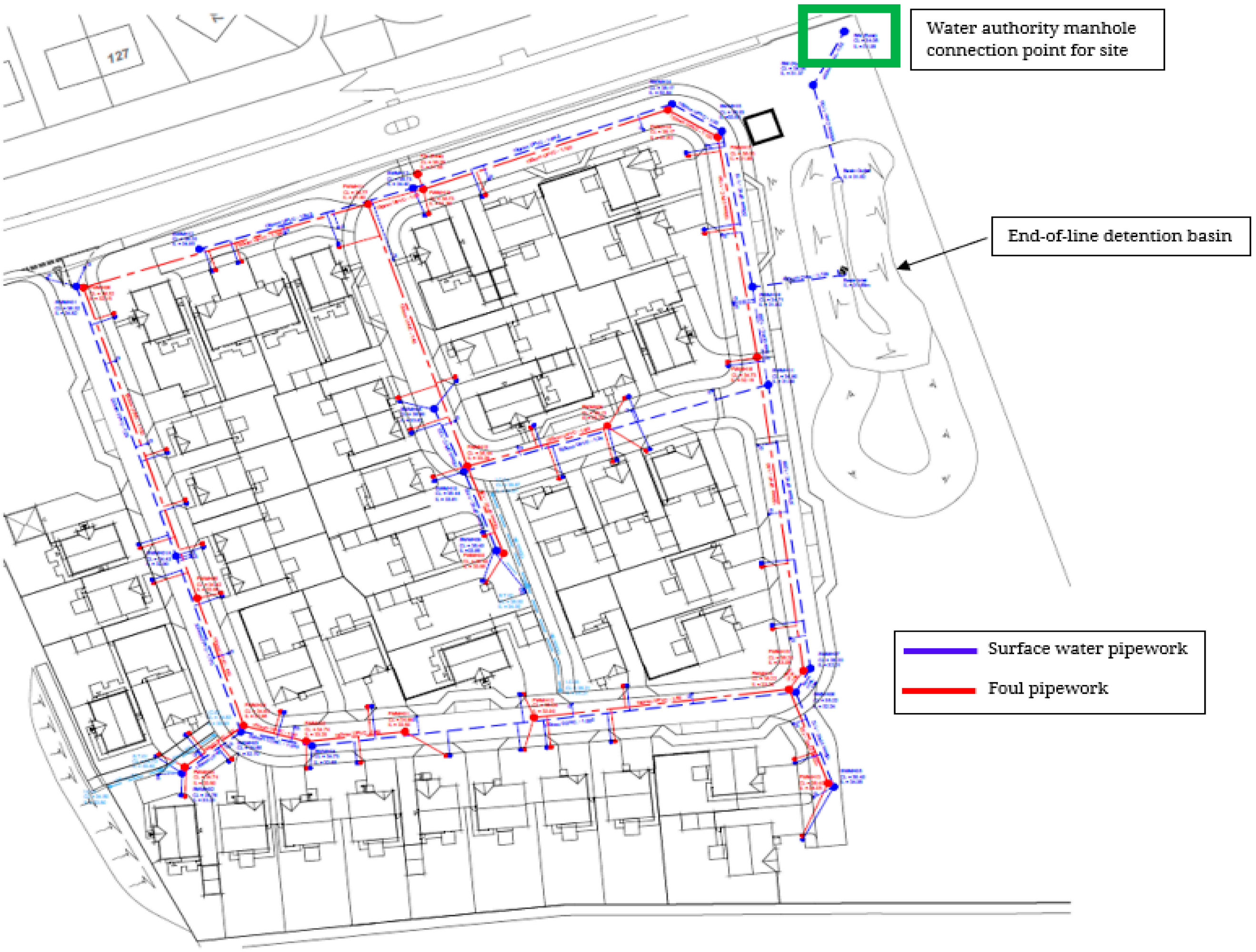


Figure 3. General arrangement (original design) for the case study site.

The results of the Simple Index Approach (Table 5) showed that adopting porous paving is a suitable approach towards individual plot control to manage the surface water run-off from each individual house and driveway. Similarly, the results of the Simple Index Analysis for the adoptable roads showed that roadside swales can be used in the re-design as source control SUDS to manage the surface water run-off.

Table 5. Simple Index Approach results (a) individual plots (b) adoptable roads.

(a) SUMMARY TABLE		**(b) SUMMARY TABLE**	
Land Use Type	Individual Driveway	Land Use Type	Low Traffic Roads
Pollution Hazard Level	Low	Pollution Hazard Level	Low
Pollution Hazard Indices		Pollution Hazard Indices	
TSS	0.5	TSS	0.5
Metals	0.4	Metals	0.4
Hydrocarbons	0.4	Hydrocarbons	0.4
SuDS Component Proposed		SuDS Component Proposed	
Component 1	Pervious Pavement	Component 1	Swale
SuDS Pollution Mitigation Indices		SuDS Pollution Mitigation Indices	
TSS	0.7	TSS	0.5
Metals	0.6	Metals	0.6
Hydrocarbons	0.7	Hydrocarbons	0.6
Combined Pollution Mitigations		Combined Pollution Mitigations	
TSS	0.7	TSS	0.5
Metals	0.6	Metals	0.6
Hydrocarbons	0.7	Hydrocarbons	0.6
Acceptability of Pollution		Acceptability of Pollution	
TSS	Sufficient	TSS	Sufficient
Metals	Sufficient	Metals	Sufficient
Hydrocarbons	Sufficient	Hydrocarbons	Sufficient

SUDS Re-Design

To implement the principles set out in the SUDS management train in terms of recreation of natural drainage effects by utilising a variety of SUDS elements in sequence while managing the volume and quality of surface run-off, we carried out a redesign of a representative existing residential site.

The driveways of each individual residential plot are envisaged to be constructed from porous paving to drain the surface water run-off from the hard paved areas within the plot boundary. This will enable the surface water to fall onto the porous paving and infiltrate through the gaps in the block surface and pass through the gravel layer below. The surface water from the roof will be conveyed into the rainwater pipes and gutter system which will outfall into the gravel layer below the driveway. This approach supports the principles of the SUDS management train and utilises source control SUDS features to limit the surface water flowing downstream into the network. The extent and layout of the porous paving can be seen in Figure 4.

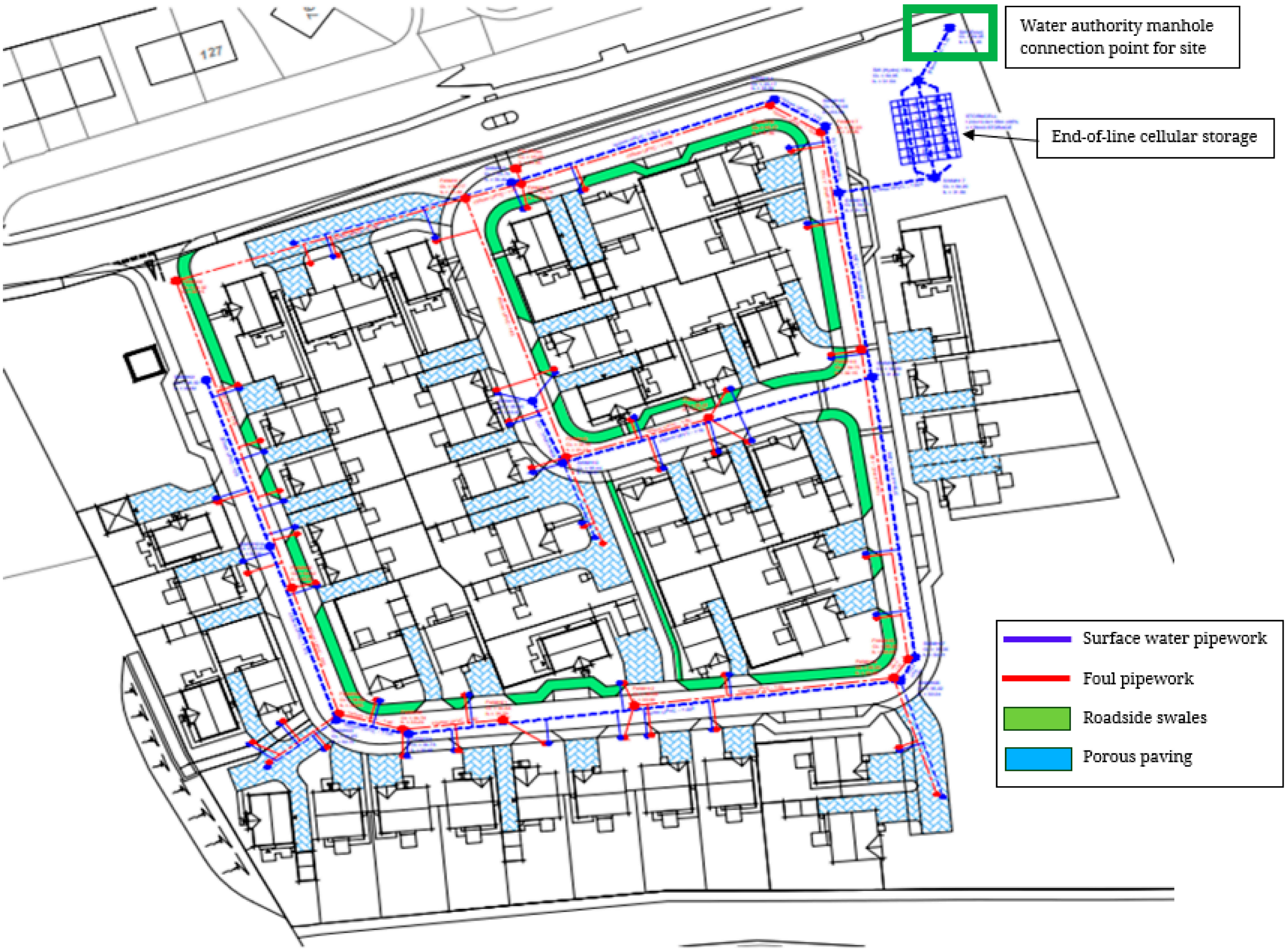
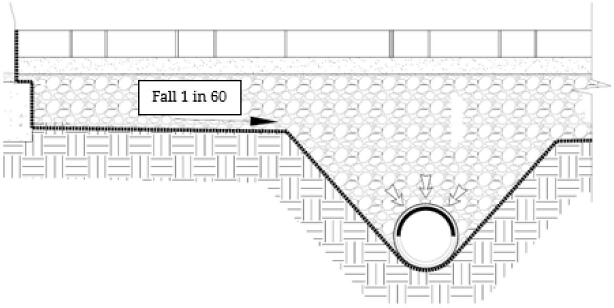


Figure 4. Redesigned case study site.

The surface water that passes through the porous paving (Figure 5) will be treated and attenuated within the gravel sub-base layer below and act as a temporary storage layer to reduce the effects on the downstream network. Below the gravel layer, a permeable membrane will be installed to allow partial infiltration into the ground if the existing sub-soils permit and prevent the sub-soil blocking the clean gravel drainage layer. The run-off will gradually flow through the voids in the gravel sub-base layer, partially infiltrating into the ground below, and flowing to the lowest point of each driveway as a treated runoff. At the lowest point of the driveway, a perforated piped outfall will be placed to allow the treated run-off to connect into the main piped drainage network and flow into an existing outlet point owned by the water authority.



Source control specification

- 200 x 100 x 60 mm permeable concrete block paving. Architect to determine colour.
- 6 mm gaps between faces of blocks to be infilled using 6mm washed aggregate.
- 50 mm layer of 6mm washed aggregate well compacted.
- 150 mm layer of 20 mm washed graded aggregate well compacted.
- Impermeable membrane laid on 50 mm layer of sand new perforated pipe to be wrapped in permeable material to prevent passage of excessive fines.
- Perforated distribution pipe to be installed at a depth of 450 mm minimum cover to crown of pipe.

Figure 5. Porous paving detail and specification.

The run-off from the road network which will be adopted by the local authority is envisaged to be treated and attenuated using roadside swales (Figure 6). The roads are designed with a cross-fall to one side were dropped kerbs will be installed to allow the run-off to pass into the swale system. The surface water is designed to be pre-treated as it passes through the sloped sides of the swale and will be further treated as it infiltrates through the sand filter layer. The run-off from the roads will gradually pass through the sand filter layer and into the perforated pipe below to allow the flows to be conveyed to the existing outlet owned by the water authority. At each driveway crossing location a pipe will be connected below (Figure 7) to allow continuity of the flows passing under any such location.

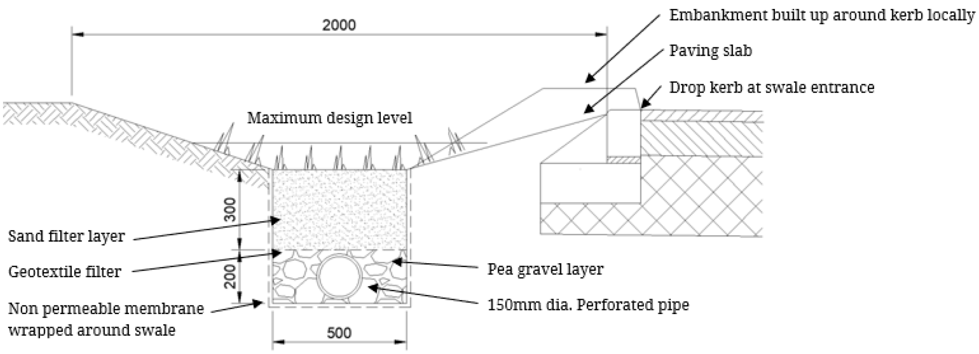


Figure 6. Roadside swale detail.

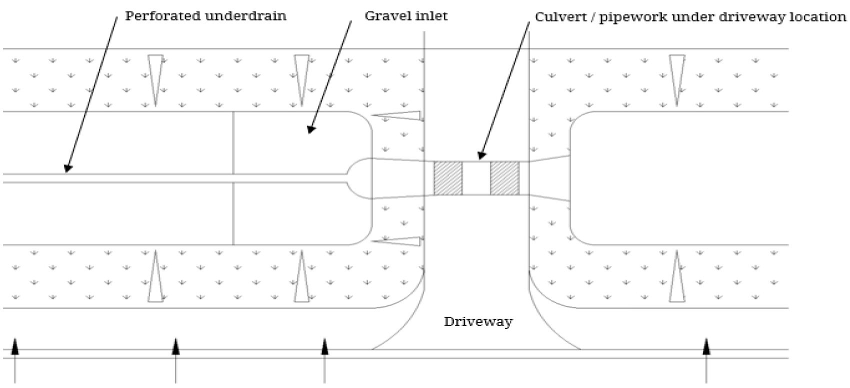


Figure 7. Typical driveway crossing schematic detail.

Prior to discharging the proposed surface water into the existing drainage network infrastructure, the flows will be attenuated and limited to an agreed flow rate of 13 l/s per second to match the existing greenfield run-off from the site. This will ensure the proposed site recreates the current flows to the existing network and will not provide a detriment to the system. A hydro-brake flow control device will be fitted within the last manhole on the system to ensure the agreed flow rate is maintained.

The re-design drainage network has been modelled utilising commercially available software [39] which has highlighted that a minimum of 170 m^3 storage capacity must be provided within the drainage network system to ensure no flooding occurs. This has been modelled by incorporating porous paving and swales at source, which limits the concentration of flows entering the end of line storage. To minimise the risk of flooding down-stream, an end-of-line cellular storage tank (Figure 8) has been designed. By implementing different SUDS features in sequence, this has reduced the requirement of the end-of-line storage capacity from 410 m^3 to 170 m^3 resulting in a net reduction of 58% as the flows are being temporarily stored and restricted at the point of impact.

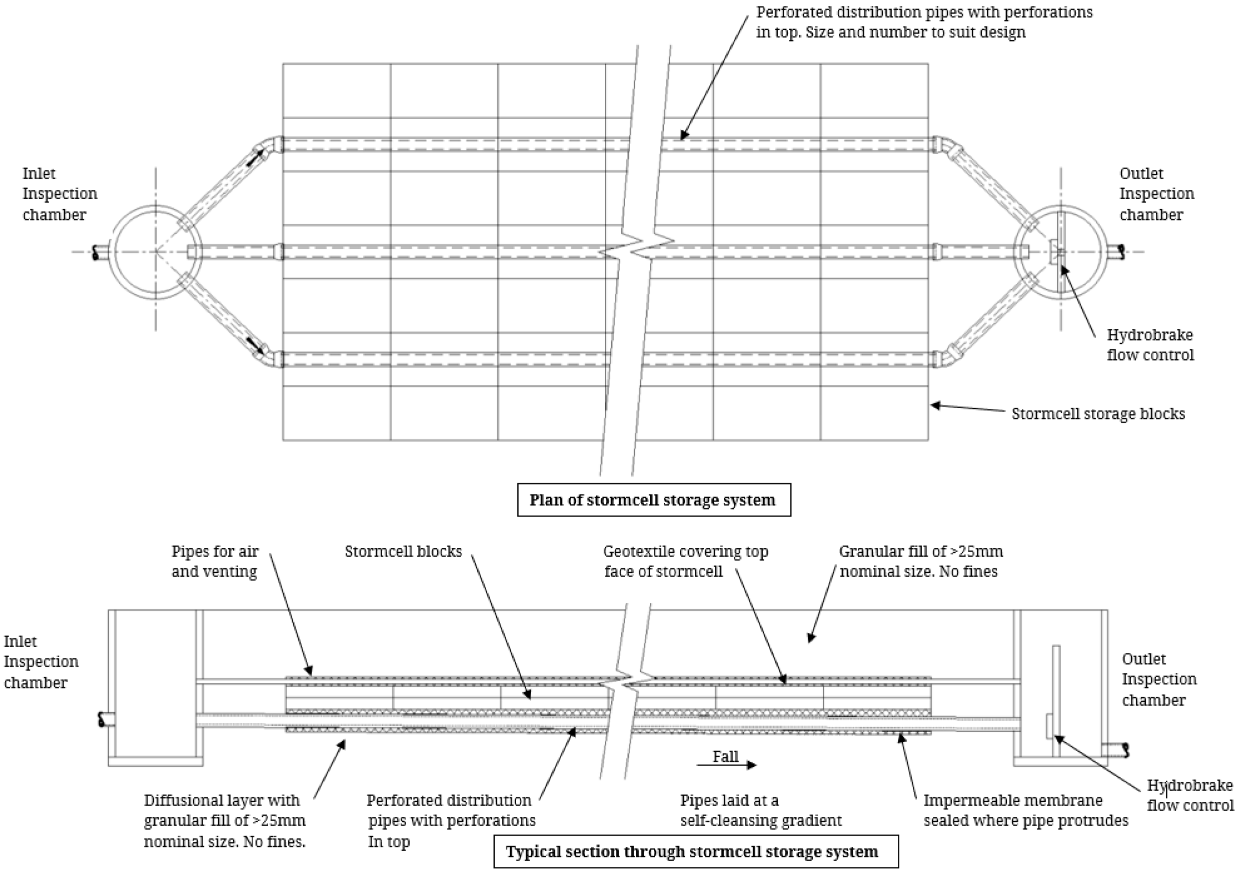


Figure 8. Cellular storage system detail (Source: Hydro International [40]).

By adopting the source control SUDS features in accordance with the SUDS management train, this has created an additional 1600 m^2 developable plan area to allow an additional 4-units to be constructed whilst maintaining the minimum open-space requirements for this development.

Cost Analysis and Comparison

A cost comparison between the original and the re-design was carried out with particular focus on the cost difference between installing a standard driveway construction and a porous car park construction. Consideration was also given to the cost difference of installing roadside swales and cellular storage featuring in the re-design against a formed detention basin which was the solution adopted for the original design.

The cost analysis (Table 6) indicated that there is a 28% increase in the cost to install a porous driveway construction with an indicative total sum of £180,000 against £143,000 to install a standard driveway construction. This analysis highlighted that there is also an 8% higher initial investment to install the road box, footpaths, swales, and cellular storage with an approximate total sum of £429,000 against £396,000 to install the road box, footpaths, and detention basin. The cost analysis identified that there is a higher initial construction cost associated with implementing various source control SUDS features and this could be a deciding factor for developers when selecting SUDS features for their developments.

Table 6. Cost comparison between the original design and re-design construction activities.

Original Design		**Re-Design**	
Feature	**Cost Estimate (GBP)**	**Feature**	**Cost Estimate (GBP)**
Driveway	143,000.00	Porous Driveway	180,000.00
Adoptable Roads	300,000.00	Adoptable Roads	300,000.00
Adoptable Footpaths	72,000.00	Adoptable Footpaths	36,000.00
SUDS Basin	24,000.00	Roadside Swales	43,000.00
		Cellular Storage	50,000.00
TOTAL	539,000.00	TOTAL	609,000.00

Notes: Drainage network costs not included as this remains similar for both options; All costs are exclusive of VAT and professional/statutory fees; Costs are based on site layout drawings of driveways, roads, and drainage only; Costs are indicative only; Costs estimates are based on [41].

DISCUSSION

The results of the case study and questionnaire highlighted that more than 2/3 of the respondents indicated that end-of-line SUDS basin and swales are the most common features implemented within residential developments. The results (Table 3) indicate that end-of-line features are frequently specified with source control features such as green roofs and rainwater harvesting infrequently or never specified which is not dissimilar to the published literature [9,10]. There is also a common consensus (Table 4) that end-of-line features are implemented as they are cost effective, easier to obtain approvals from governing bodies, and have low maintenance costs throughout their life cycle [10].

However, the re-design of the existing site showed that by implementing the principles set out in the SUDS management train [24–28], managing the volume and quality of surface run-off will be easier as this will be captured at source initially. This will reduce the pressure on the downstream network as each individual plot will be temporarily stored and treated within their boundary via porous paving (Figure 4) leading to a 58% net reduction of the end-of-line storage requirements prior to discharge. By implementing source control treatment, this has created an additional 1600 m² developable space to allow for 10% more residential units to be constructed.

The cost comparison analysis (Table 6) has indicated that there is a lower construction cost associated with installing an end-of-line detention basin (£24,000) within residential developments compared to a cellular storage system (£50,000). The 13% higher cost of the cellular storage system could be a critical factor for developers when designing SUDS features as they often look to keep construction costs as low as possible.

In terms of achieving the objectives of this study, the review of the company database and personal experience of working on similar projects as well as using a questionnaire to collect opinions of industry experts (Senior Engineers in a multi-disciplinary consultancy, Senior Architects, Water Authority Engineers, and Local Authority Engineers) helped in establishing a broad understanding of the construction practice and the design preferences of the drainage engineers. It also helped in mapping of relevant and representative construction projects in Central Scotland which highlighted twelve different residential sites have implemented end-of-line detention basins and swales. This approach also allowed identification of relevant stakeholders involved in SUDS design and, similarly, to published studies [9,10], confirmed that the SUDS elements being implemented are dependent on the willingness of the external stakeholders to buy into what the developer is trying to achieve. Obtaining approval from the stakeholders is often difficult due to their unwillingness to change as there is often limited practical evidence to prove the effectiveness of SUDS schemes. The results (Table 4) stated that a detention basin was frequently selected as this is considered a cost-effective install, easier to obtain approval from the local authority and governing bodies. These results support the findings from the literature [13,18] and clearly show that a detention basin is often selected to avoid encountering unnecessary problems throughout the approval process with the water and local authorities.

These results triggered the re-design of the SUDS features of one representative case study, where the principles of SUDS are satisfied and are in accordance with current industry standards, i.e., comprising different SUDS features to be implemented in sequence to treat the run-off at the point of impact rather than conveying all run-off to an end-of-line treatment source. The re-design was carried out based on personal experience as well as utilising the information gathered throughout the review of the relevant projects. The design principles were based on implementing various elements in sequence to manage the volume and quality of the run-off in accordance with the SUDS management train. The design implemented porous paving (Figure 5) for every plot to treat all run-off within the individual plot boundary. The run-off from the roads would be treated via roadside swales (Figure 6) to ensure all run-off was being treated as close to the point of impact [14,17,18,20].

The re-design was followed by cost comparison, focusing on the cost difference between installing a standard driveway construction versus a porous car park construction with a consideration given to the cost difference of installing roadside swales and cellular storage against a formed detention basin. The results of the analysis (Table 6) highlighted that there is a lower construction cost associated with installing an end-of-line detention basin within residential developments compared to a cellular storage system. This could be a critical factor for developers when designing SUDS features as they often look to keep construction costs as low as possible.

The limitations of this study in terms of breadth and representability are acknowledged. However, in order to overcome these in the future, a survey covering broader geographical and professional target audience should be carried out. The advent of Building Information Modelling (BIM) should allow for easier identification and monitoring of the construction and performance of SUDS. Although it is envisaged that the future cost comparison will be hindered by commercial data protection, it is recommended that future studies carrying out cost analysis should use the raw costs for comparison of different SUDS options where the analysis should cover the whole life of the SUDS system. In parallel with this, training and awareness-raising on SUDS planning, design, construction and operation should be provided to all relevant stakeholders in order to improve the take-up and increase the knowledge on SUDS [42]. The training should be based on more and broader in-depth interviews with Local Authority and Water Authority personnel involved in the design process which should explore the gaps in knowledge of the steps considered when approving design, the efficiency of source control SUDS features for different developments as well as the land-take, maintenance and up-keep requirements of these SUDS [43]. The latter should be also explored and shared with the homeowners who should better understand the role SUDS on their properties has with combating the effects of flooding and climate change.

CONCLUSIONS

End-of-line SUDS features are often implemented within residential developments and there are many stakeholders involved in the design process. This can lead to difficulties gaining technical approval for implementing different SUDS features and often results in a very limited range of solutions being adopted in the design of SUDS. Prevention techniques and source control features should be implemented before end-of-line SUDS because their features are considered to suit the criteria set out in the SUDS design philosophy and management train. Using source control SUDS, at least for residential construction projects in Central Scotland, can provide more long-term benefits but the lower construction cost associated with installing an end-of-line detention basin (a cellular storage system could cost up to 13% more) could be an acute factor which can sway the design away from source control solutions.

DATA AVAILABILITY

No data were generated from the study.

AUTHOR CONTRIBUTIONS

MM designed the study. MM carried out the design and calculations. MM and SM analyzed the data. MM and SM wrote the paper.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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