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H. Udale-Clarke & R. Kellagher

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SUSTAINABILITY MEASURES APPLIED TO AN URBAN STORMWATER DRAINAGE SYSTEM

H. Udale-Clarke & R. Kellagher

HR Wallingford Ltd., Wallingford, Oxfordshire, UK

ABSTRACT

This paper describes the application of sustainability measures of hydraulic performance and water quality protection to a real-life urban stormwater drainage system. This includes details of the practicalities of applying sustainability measures to drainage designs, a summary of the InfoWorks CS hydraulic model results, and a discussion of how these results were applied using tools developed as part of the WaND project.

1. Introduction

1.1 The WaND project

As part of the EPSRC's WaND (Water cycle management for New Developments) project, Work Package 2 (WP2) was aimed at developing a new approach to the design and evaluation of the performance of stormwater systems in new developments as part of an integrated approach to the water cycle. The work package developed various measures of sustainability which considers social, environmental, and economic factors.

Activities in WP2 included the development of methodologies supported by tools to enable a range of indicators to be used to measure the sustainability performance of urban stormwater drainage systems. These methodologies and tools were tested/ demonstrated using an InfoWorks CS model on the stormwater drainage system at Elvetham Heath in Hampshire, which is a large modern housing development.

1.2 The case study

Elvetham Heath provides a recently completed development with a number of sustainable drainage system (SUDS) components and was used as a case study for several of the WaND work packages, including domestic water forecasting, wastewater collection, and behaviour of SUDS. For WP2, the focus of the case study was on the evaluation of hydraulic and water quality performance from the perspective of sustainability, rather than just the level of service, which focuses on protection against sewer flooding. The outputs from the case study have been used to illustrate elements of the sustainability evaluation procedure developed.

2. Summary of approach

A sustainability measure (often also referred to as a sustainability indicator) is a practical and measurable attribute that provides information of the performance of the system and is selected to show how well the system conforms to some aspect of a sustainability criterion. These criteria were grouped into 4 main categories by the WaND project under the headings of social, environmental, economic and technical.

The case study focused on the evaluation of hydraulic performance and water quality protection, which primarily inform some of the environmental and social criteria of sustainability.

Both present and future rainfall conditions with an allowance for climate change were used to assess the system performance for three different drainage scenarios. These were:

1. The “as built” drainage solution including existing SUDS;

2. A traditional (piped) drainage solution with underground storage; and
3. A "best practice" solution that increases the use of SUDS and includes rainwater harvesting and use.

Two Microsoft Excel/Visual Basic tools were developed to assist with the measurement of sustainability: one for measuring hydraulic performance and the other to measure water quality protection. These are non-commercial, research tools that will be publicly available through the WaND project. These are described more fully later in this paper.

3. Drainage scenarios

3.1 As built scenario

The modelled catchment area was 21 hectares and included both residential and commercial areas, including a public house, supermarket, petrol station and school.

The majority of the catchment drains via a conventional stormwater piped system directly to a retention pond (which also acts as the village pond providing recreation potential for the residents). A residential area south of the pond covering 2.7 hectares drains to a detention basin, which in turn drains into the pond. A further residential area north-west of the pond covering 1.25 hectares drains to a series of swales, which in turn drain to the pond. These swales provide very little infiltration potential and behave more like detention basins, with inflow and outflow points.

Permeability tests recorded infiltration rates for the whole site ranging from $5.5\text{x}10^{-6}$ m/s to $4.7\text{x}10^{-8}$ m/s (between 20 mm/hr and 0.2 mm/hr), which is relatively low for infiltration based components. Based on these results, an infiltration loss coefficient of $1.0\text{x}10^{-6}$ m/s (3.6 mm/hr) was applied to the model for all swales and detention basins and for areas of the pond above the normal water level.

Back gardens were excluded from the model as no runoff from these areas is considered to take place.

The modelled impermeable area was 47% of the total contributing area. The proportion of paved area (i.e. roads, driveways, pavements, car parks, flat roofs of some commercial properties only and an "all weather" playing field) compared to roof area is higher than for a typical urban area: 78% of impermeable area is paved and only 22% is roof area. These figures reflect the new requirements for high density residential developments in England.

3.2 Traditional drainage scenario

A conventional pipe system was modelled, which was based on the "As Built" drainage system, but without the SUDS components. Pipes were increased in size to ensure no sewer flooding up to a 30-year return period and a limiting discharge was set on the outfall. An off-line tank at the downstream end of the system was provided to retain stormwater to ensure compliance with the criterion on peak discharge rate of 7 l/s/ha required of the site drainage system for the 50-year return period event.

3.3 Increased use of SUDS and rainwater harvesting

A third model was produced, which was again based on the "As Built" drainage system, but with additional SUDS units and rainwater harvesting for domestic properties. The purpose of this model was to demonstrate the improvement that could be achieved in hydraulic performance and water quality protection by increasing the number of SUDS components on the site and using rainwater harvesting.

Areas within the catchment that were identified as car parks (not individual property driveways or pavements) were modelled as pervious pavements with all runoff going to infiltration. The roof areas of the public house and supermarket were also redirected to infiltration. As a result, an area of 2.057 ha (22.5% of the total impermeable area, i.e. roads and roofs) was reassigned to infiltration.

An effective storage depth of 100 mm was assumed for all new pervious pavements and an infiltration loss coefficient of 3.6 mm/hr applied, corresponding with the existing SUDS units.

Only domestic roofs were redirected to rainwater harvesting. This amounted to a total roof area of 1.503 ha (18 % of total impervious area, 73% of all roof area).

Rainwater storage volumes were based on 1m^3/bedroom. A total storage volume of 512 m^3 was added to the model, distributed based on property locations. This storage volume equates to on average 29 m^2 of roof area per bedroom. (Excluding the blocks of apartments, the average roof area for a property is 62 m^2.) When the storage volume is fully utilised, any additional runoff is discharged to the stormwater drainage system.

Domestic usage of rainwater was assumed to be 50 l/bedroom/day. For simplicity, this usage was applied in the model at a constant rate over 24 hours. This estimate relates to typical consumption for toilet flushing and use in washing machines. Most rainwater harvesting systems only have filtration and no secondary treatment. Therefore usage is limited to activities such as toilet flushing, garden watering and car washing. Current figures show that total water consumption is of the order of 150 l/day per person.

3.4 Modelling the greenfield site

In order to compare the three drainage scenarios with greenfield conditions, a fourth InfoWorks CS model was created: a simple one node catchment model was used to represent the greenfield site. The area of the catchment corresponded with the total area of the “As Built” model. A single runoff surface was used representing pervious area and using the New UK Runoff Volume Model (also known as the Variable UK Runoff Model).

The New UK Runoff Volume Model was used in the absence of anything better being currently available in InfoWorks CS. In the future, the Flood Estimation Handbook (FEH) (Institute of Hydrology, 1999) variable runoff model should be available to use, but it is yet to be incorporated into InfoWorks CS. The runoff model was calibrated against the FEH model. The model was run using a single FEH design storm with a 10-year return period and 12-hour duration and calibrated for peak flow and percentage runoff against IH124 (Marshall & Bayliss, 1994).

Despite this calibration exercise, the results produced using this model should be treated with caution and be considered as providing indicative results only. The methodology described in this paper is best used as a means to compare alternative drainage designs rather than to set an absolute performance standard against greenfield conditions.

4. Hydraulic performance

4.1 Approach

Existing design criteria for stormwater drainage are based on protecting people and property against sewer flooding from extreme rainfall. With the introduction of the Water Framework Directive increased importance is being placed on the morphological and water quality effects on rivers caused by drainage. The hydraulic design of stormwater drainage for developments should be based on the concept of the river regime being maintained in its natural state, by minimising the difference between the developed and undeveloped runoff that drains directly off the site during “ordinary” as well as extreme events and, therefore, there needs to be a move away from the traditional use of design storms.

Scarcity of water and the need for groundwater recharge is now seen as a very important part of sustainable development. Up to now, this has not been taken into consideration as a criterion in the design of stormwater drainage.

Sustainable stormwater drainage requires the inclusion of site storage to limit the flow rate and volume of runoff that drains directly off the site, and to allow infiltration to groundwater. Therefore the three sustainability measures (or indicators) used for measuring hydraulic performance were flow volume, peak flow rate and infiltration volume. The principle applied for assessing hydraulic performance is that the developed site should replicate as closely as possible the undeveloped site, i.e. “greenfield” conditions, for these three measures.

As stated earlier, the performance of the greenfield site predicted by the model needs to be treated with caution. The application of this criterion should therefore only be used to show the relative merits of different drainage solutions. It should be noted that replication of the site drainage behaviour to greenfield response on an event basis is not possible due to the different processes taking place.

4.2 Runoff modelling

The characteristics of greenfield runoff are a function of the rainfall (intensity and duration), the soil type and the antecedent conditions (i.e. the wetness of the catchment prior to a rainfall event). However, urban runoff is not significantly related to either soil or antecedent conditions. Therefore, the best way to compare the performance of the developed site with greenfield conditions is to compare the predicted runoff from hydraulic modelling using a time series of rainfall events.

Each of the drainage scenarios listed earlier was compared with greenfield conditions. The analysis was undertaken using design storms, individual events from both 5-year and 100-year rainfall series, and a continuous 5-year series. These different rainfall events were used so that comparisons could be made regarding appropriateness for use in this type of assessment.

The accuracy of predicted greenfield runoff is particularly poor for relatively small events; the runoff model is only appropriate for use with extreme events. However, this approach does provide an objective basis for evaluating the hydraulic performance of a stormwater drainage system.

Comparing results from a rainfall series should not be undertaken on an individual storm by storm basis. As stated earlier, greenfield runoff varies due to a number of parameters that have little influence on urban runoff. A comparison was therefore carried out by ranking all of the results and then comparing the ranked results, e.g. the largest flow volume predicted for the greenfield site is compared with the largest flow volume predicted for the developed site.

There are at least two conditions of interest: response to extreme events where exacerbation of river flooding needs to be protected against; and morphological characteristics of the river, which is a function of “ordinary” events. Theoretically, comparisons could be carried out by using a continuous 100-year series (or longer). However, to save on computing effort, a separate measure of the extreme event and ordinary event performance can be made by sampling the time series accordingly.

The volume of water passing to groundwater needs only to be compared on an annual basis. However, this can only be determined with any degree of accuracy using a continuous series.

In total five hydraulic measures were used. These being:

1. Peak flow rate for extreme events (top 100 events from a 100-year stochastic rainfall time series)
2. Peak flow rate for frequent events (top 100 events from a 5-year stochastic rainfall time series)
3. Volume of runoff for extreme events (top 100 events from a 100-year stochastic rainfall time series)
4. Volume of runoff for frequent events (top 100 events from a 5-year stochastic rainfall time series)
5. Annual volume of infiltration (5-year continuous stochastic rainfall time series)

Each of these measures was determined for the Elvetham Heath stormwater drainage system for present day conditions and future conditions with climate change.

The results from the top 100 events in the 5-year time series compared very favorably with the results from the continuous 5-year time series. As use of the top 100 events requires less computing time and resources, this is the more practical approach for analysis of peak flows and flow volumes. However, the 5-year continuous series is needed for determining the annual volume of infiltration, and also to accurately predict rainwater harvesting effects.

4.3 Tool

Peak flows and flow volumes for alternative drainage scenarios and greenfield conditions were determined for the top 100 events from a 5-year and 100-year rainfall time series (both present day and future conditions with climate change) using InfoWorks CS. Peak flows and flow volumes for each event were imported into a new hydraulic performance tool that ranked and compared the results from the drainage scenarios with the greenfield model results.

Figure 1 is an example of the results obtained for the three drainage scenarios compared to the greenfield site. For this particular measure of flow volumes for extreme events, there is little difference in performance of the "As Built" scenario compared to the Traditional (referred to in the figure as Fully Piped) drainage scenario. The performance of the Increased SUDS and Rainwater Harvesting scenario is significantly closer to the performance of the greenfield model.

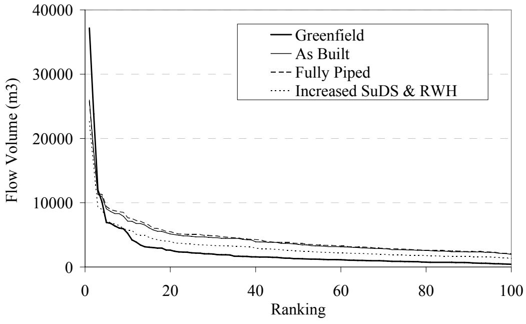

Figure 1 Comparison of flow volumes for extreme events (present day rainfall)

Annual infiltration for alternative drainage scenarios was determined by continuous simulation of a 5-year rainfall time series again using InfoWorks CS. The resultant daily infiltration volumes were imported into the same hydraulic performance tool and the average annual infiltration volume determined. The tool then compared this with a greenfield infiltration volume determined using a simple volumetric model developed in Excel/Visual Basic, as described in Section 4.3.1.

Finally, the five hydraulic measures (as listed earlier) for each drainage scenario were given a sustainability index (or score) to provide a qualitative comparison of drainage scenarios against greenfield conditions. These sustainability indices range from 1 to 5, with 1 being best and 5 being worst.

4.3.1 Greenfield infiltration

It is not possible to model the infiltration for a greenfield site realistically using InfoWorks CS. Therefore, a simple model had to be developed for carrying out the comparison with the drainage scenarios.

The model needed to consider the important hydrological processes but keep data requirements as simple as possible.

Only soil types 1, 2 and 3 from the Winter Rain Acceptance Potential (WRAP) map for the UK are used. The soil type influences the amount of infiltration and surface runoff. Selection of one of these soil types defines the infiltration coefficient (i.e. the permeability of the soil), field capacity of the soil (i.e. the amount of water that the soil can store against gravity) (FAO, 1998), percentage runoff and decay factor for calculating API_{30}. However, these characteristics can be over-written by the user. The only input is daily rainfall.

It should be noted that the model has been developed with information appropriate to the UK.

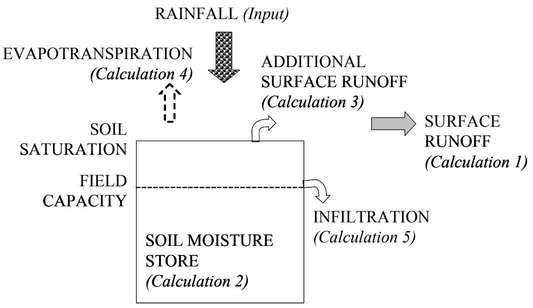

Figure 2 Representation of infiltration model

Figure 2 provides a simplified representation of the calculations included in the infiltration model. Firstly, the surface runoff is calculated from the rainfall (calculation 1) and the residual rainfall volume is added to the previous day's soil moisture store (calculation 2). If soil saturation is exceeded, any excess is added to the surface runoff and the soil moisture store reduces accordingly (calculation 3). Evapotranspiration is then subtracted from the soil moisture store (calculation 4). If the remaining soil moisture store exceeds the field capacity, any excess is taken as being infiltration (calculation 5). The final soil moisture store then becomes the initial store for the next day and the process is repeated.

4.4 Results

4.4.1 Sustainability indices

The results for each drainage scenario were compared with the corresponding greenfield results for each hydraulic measure to give the corresponding "sustainability coefficient".

The peak flow rate coefficient for extreme events (PFC_{EE}) was calculated using Equation 1 (units being l/s/ha).

$$PFC_{EE} = \frac{\sum_{i=1}^{N} |Di - Gi| / A}{N} \tag{1}$$

where Di = development peak flow rate of event i (l/s); Gi = greenfield peak flow rate of event i (l/s); A = site area (ha); and N = total number of events.

The peak flow rate coefficient for frequent events (PFC_{FE}) was calculated in exactly the same way.

The runoff volume coefficient for extreme events ($\mathrm{RVC_{EE}}$) was calculated using Equation 2. Again, the runoff volume coefficient for frequent events (RVC_{FE}) was calculated in exactly the same way.

$$RVC_{EE} = \frac{D - G}{G} \tag{2}$$

where D = development runoff volume from the sum of all events; and G = greenfield runoff volume from the sum of all events.

The infiltration volume coefficient (IVC) was calculated using Equation 3.

$$IVC = \frac{D - G}{G} \tag{3}$$

where D = development infiltration volume from the sum of all events; and G = greenfield infiltration volume from the sum of all events.

The coefficient values were then grouped to represent a value in the range of 1 to 5, which is referred to as the sustainability index.

The sustainability indices determined for each of the drainage scenarios are presented in Tables 1, 2 and 3. A value of 1 is excellent and 5 is very poor.

Table 1 Sustainability indices for the five hydraulic measures for the "As Built" drainage scenario

Measure	Sustainability Index	
	Present	Future
Peak flow rate extreme events	3	3
Peak flow rate frequent events	2	2
Runoff volume extreme events	1	1
Runoff volume frequent events	5	4
Annual infiltration volume	4	4

Table 2 Sustainability indices for the five hydraulic measures for the Traditional drainage scenario

Measure	Sustainability Index	
	Present	Future
Peak flow rate extreme events	4	3
Peak flow rate frequent events	4	4
Runoff volume extreme events	1	1
Runoff volume frequent events	5	4
Annual infiltration volume	5	5

Table 3 Sustainability indices for the five hydraulic measures for the Increased SUDS and Rainwater Harvesting drainage scenario

Measure	Sustainability Index	
	Present	Future
Peak flow rate extreme events	3	3
Peak flow rate frequent events	1	2
Runoff volume extreme events	1	1
Runoff volume frequent events	4	2
Annual infiltration volume	3	3

These results can be compared to determine the relative hydraulic performance for each drainage scenario, as shown in Figure 3.

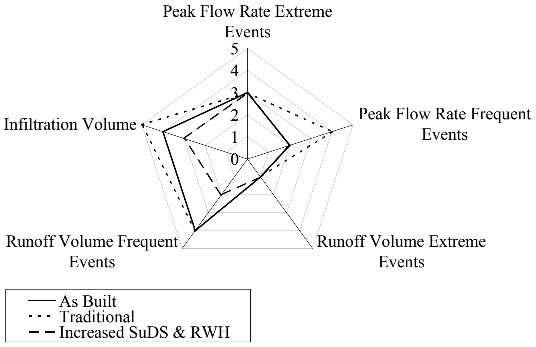

Figure 3 Comparison of sustainability indices for hydraulic performance (using future rainfall) for the three drainage scenarios

These results show that the qualitative scoring of the runoff volumes for extreme events is too insensitive as it stands at the moment; a score of 1 is intuitively too good for a traditional drainage system. This will be refined before the end of the study.

4.4.2 Groundwater recharge

Table 4 provides a summary of predicted annual average infiltration depths.

Table 4 Annual average infiltration

Scenario	Infiltration (mm)	
	Present	Future
Greenfield	103	109
As Built	35	30
Traditional	0	0
Increased SUDS & RWH	63	65

It should be noted that these comparisons are based on the infiltration of runoff via SUDS units (i.e. swales, detention basins or pervious pavements) and does not include direct infiltration from permeable areas. Therefore, the greenfield infiltration has been calculated for the equivalent paved area.

These results show that the “Increased SUDS and Rainwater Harvesting” scenario approximately doubles the amount of infiltration achieved with the “As Built” scenario.

The reduction in infiltration predicted for the “As Built” scenario under future conditions is likely to be the result of higher intensity storms. These storms will result in a greater pass forward flow, which will reduce the volume available for infiltration.

By increasing the infiltration loss coefficient to 30 mm/hr from 3.6 mm/hr, there was an increase in total infiltration, but this increase was only in the order of 20-30%. The increased infiltration rate resulted in infiltration being quicker, but due to the large amount of storage provided by the SUDS units a significant proportion of the runoff goes to infiltration even if the infiltration rate is low. Another consequence of increasing the infiltration rate was that the swales and detention basin were empty for more days each year.

4.4.3 Performance of SUDS

As mentioned above, significantly greater infiltration was achieved overall with the “Increased SUDS and Rainwater Harvesting” scenario compared to the “As Built” scenario. However, the infiltration at the swales, detention basin and pond was lower than that for the “As Built” scenario. This was the result of stormwater being used in rainwater harvesting and infiltration taking place in the pervious pavements. Because of this, the swales and detention basin are empty for much longer with the “Increased SuDS & Rainwater Harvesting” scenario.

For the “As Built” scenario, the swales and detention basin were empty on average 13 days/year (88% of these days were during the summer) under present day conditions. This increased to 32 days/year (81% of these were during the summer) under future conditions with climate change. For the Increased SUDS and Rainwater Harvesting scenario, the swales and detention basin were empty on average 60 days/year (72% of these are during the summer) under present day conditions. This increased to 94 days/year (65% of these are during the summer) under future conditions with climate change.

Table 5 shows how runoff volume was split between the SUDS components, rainwater harvesting and the outfall, for the three drainage scenarios, under present day conditions.

Table 5 Percentage of total runoff volume draining to alternative destinations for each drainage scenario

Runoff destination	Drainage Scenario		
	A	T	S
Discharge to outfall	80	100	52
Swale, detention basin & pond infiltration	20	0	13
Pervious pavement infiltration	0	0	21
Rainwater harvesting & use	0	0	14

A = As Built
T = Traditional
S = Increased SuDS and Rainwater Harvesting

4.4.4 Rainwater harvesting

Under present day conditions, the storage provided for rainwater harvesting was never full. The maximum capacity predicted was 97%. For future conditions the storage was full for only nine days in five years, at which point excess runoff would overflow to the main drainage system. These nine days occurred in both summer and winter. On two occasions the storage was full for two and three consecutive days due to the storage not emptying quickly enough for subsequent rainfall events.

On average the storage was 20% full for present day conditions, increasing to 22% for future conditions. (The individual event time series were run with initial storage conditions set at 20% as a consequence of these results.)

Increasing the available storage had negligible impact on the performance of the system, as the storage volume was so rarely exceeded.

Under present day conditions, water was not available from the rainfall harvesting storage for 78 days per year on average (21% of the year). This increased to 106 days (29%) for future conditions. Approximately two-thirds of this time was during the summer.

There was no significant trend with respect to monthly usage over the 5 years for present day conditions. However, there was a more pronounced dip in usage under future conditions for the summer months, especially for July, a consequence of less rainwater being available.

5. Water quality protection

5.1 Approach

Literature reviews on stormwater pollutant loads and the performance of SUDS for water treatment show extreme variability in pollutant loads, the conclusion being that the performance of SUDS units varies greatly depending on the site, variability of rainfall, seasonal effects, construction methods, maintenance regimes, etc. Therefore a quantitative approach is not realistic and a qualitative approach is recommended.

Tool

A tool has been developed that provides a simple, practicable method to estimate the relative stormwater runoff treatment potential and assess the suitability of alternative stormwater drainage schemes, based on:

- Classifying land use types in terms of pollution indices;
- Classifying SUDS units by water quality mitigation indices; and
- Calculating a gross site index in terms of water quality using area weighting.

The fact that the level of treatment needed varies depending on the receiving water and the pollution risk associated with the size of the development are also taken into account.

A performance indicator is used to assess the level of treatment provided. The performance indicator is a function of site area, percentage of impervious area, land use type (i.e. residential, commercial or industrial), drainage outfall discharging boundary (i.e. stream or high class river, large river, estuary or sea) and the drainage treatment components (e.g. detention basins, green roofs, filter strips, infiltration trenches, pervious pavements, oil interceptors, ponds, soakaways, swales, wetlands, etc.).

Unlike the hydraulic performance assessment, the runoff water quality is not being compared with greenfield conditions and there is no attempt to compute pollutant concentrations. It is assumed that runoff is only contaminated from man-made surfaces. Green areas are excluded.

5.3 Results

Table 6 shows the water quality scores and resultant sustainability indices for the three drainage scenarios.

Table 6 Water quality scores and sustainability indices for each drainage scenario

	Drainage Scenario		
	A	T	S
Water quality score	1.74	6.43	1.14
Sustainability index	4	5	3

A = As Built
T = Traditional
S = Increased SuDS and Rainwater Harvesting

These results can then be included with the hydraulic performance measures to give an overall set of sustainability indices for each drainage scenario, as shown in Figure 4.

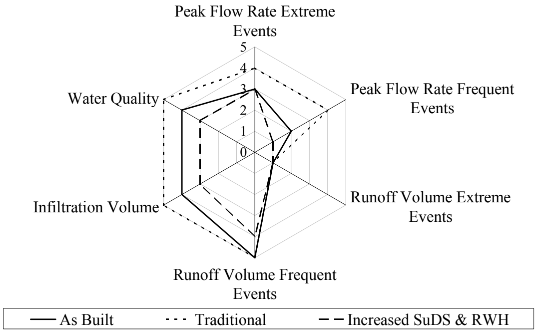

Figure 4 Comparison of sustainability indices for hydraulic performance and water quality (using present day rainfall) for the three drainage scenarios

6. Conclusions

1. The Elvetham Heath case study has demonstrated the use of a completely new approach to assessing the performance of a drainage system using the concept of sustainability indicators rather than designing for a level of service. This test catchment study has demonstrated its effectiveness for comparing the sustainability of various options. It has also drawn attention to the possibility of using infiltration as a new measure of performance.
2. Rainwater harvesting traditionally has been seen as a means to provide water conservation by reducing demand for treated water, but to have no benefits for stormwater management and control. However, this research has demonstrated that the use of rainwater harvesting can significantly reduce the flow rate and volume of surface water runoff from a developed site and minimise the size of stormwater management control components at site and regional scales. This has not only been demonstrated using the Elvetham Heath case study, but

with additional InfoWorks CS modelling using time series rainfall data and a range of tank sizes and consumption rates (Kellagher & Maneiro Franco, 2005).

3. Due to the limitations of hydraulic modelling of greenfield runoff, caution is needed in comparing alternative drainage designs with greenfield conditions. However, the approach presented in this paper is a useful means of comparing the relative performance of alternative drainage designs.
4. The comparative analysis on volumetric performance for runoff volumes for frequent events shows only a small distinction between options. This result, together with the high level of uncertainty of the greenfield runoff model for these small events, suggests that this indicator of system performance is of limited value.
5. The qualitative scoring of the runoff volumes for extreme events appears to be too insensitive as a score of 1 is intuitively too good for a traditional drainage system. This needs refining.

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NOTES

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HR Wallingford
Working with water

HR Wallingford Ltd
Howbery Park
Wallingford
Oxfordshire OX10 8BA
UK

tel +44 (0)1491 835381
fax +44 (0)1491 832233
email info@hrwallingford.co.uk

www.hrwallingford.co.uk