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Using a systematic, multi-criteria decision support framework to evaluate sustainable drainage designs

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Abstract

The conventional drainage design approach does not address sustainability issues. Moving forward, an alternative approach using green infrastructures is recommended. In addition to flow and flood management provided by the conventional methods, green infrastructures can bring multiple benefits such as increased amenity value and groundwater recharge. Unlike the traditional practice, the new approach lacks supporting technical references and software. Stakeholders are discouraged by the uncertainty of performance and costs associated with green infrastructures. We aim to bridge this knowledge gap by providing a systematic decision support framework. This paper provides an overview of the evaluation framework with some application examples.

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Keywords: Sustainable drainage design, multi-criteria evaluation framework; green infrastructure; cost-benefit analysis.

1. Introduction

In the past, drainage network capacity and conveyance were the primary design criteria. The drainage industry relied heavily on regulation, technical guidance and best practice examples to determine the optimal size and slope

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of underground drainage infrastructures such as pipes and storages required to provide sufficient capacity and conveyance. For that purpose, HR Wallingford (1981) first described the iterative methodology in the Wallingford Procedures. The procedures had been successful and well-received by the drainage industry and government in United Kingdom. The systematic approach was appealing to decision makers, especially drainage engineers and planners. Related computer software packages became available in early 80's and most of the time-consuming tasks had been automated to streamline the workflow. After years of practice and refinement, computer-aided pipe and storage design became the industry standard.

Despite years of success, the traditional approach did not consider the long-term sustainability issues as key design criteria. Although it had been a valid and widely accepted approach in the past, we have to factor in the sustainability considerations from now on. An alternative approach using a combination of grey (e.g. pipes and storage) and green infrastructures (e.g. ponds, swales, wetlands) is being recommended to stakeholders and the public. Figure 1 below shows examples of traditional and sustainable drainage systems commonly found in UK.

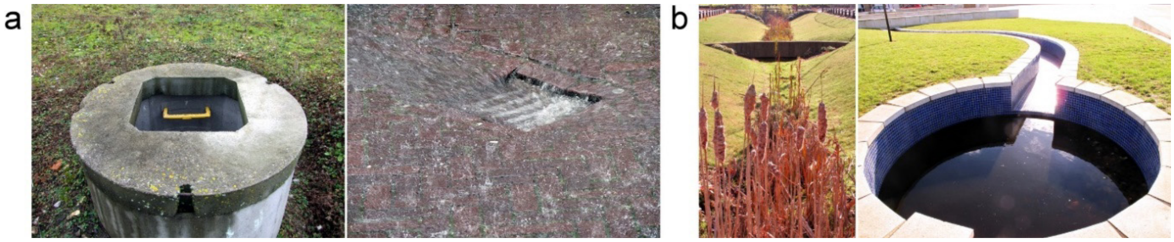


Fig. 1. (a) Traditional drainage systems; (b) Sustainable drainage systems. (Photo's courtesy of Micro Drainage Limited.)

The main advantage of the sustainable approach is the additional benefits such as environmental improvement, natural groundwater recharge, runoff reduction as well as energy savings. In UK, we generally regard sustainable drainage systems as SuDS (Woods-Ballard et al., 2007). Similar green drainage systems are called Low Impact Development (LID) or Best Management Practices (BMPs) in United States (USEPA, 2006). Water Sensitive Urban Design (WSUD) is the term commonly used in Australia (Brown et al., 2007). We continue to use the term SuDS in this paper for consistency.

1.1. Challenges in Implementing the Sustainable Design Approach

In UK, the additional benefits of using green infrastructures have already been communicated to government, drainage industry and the public (Hydro, 2013). Yet, there are still some key challenges we need to overcome in order to make the sustainable design approach practical.

Unlike the traditional pipe and storage based approach with sufficient technical guidance and computer software packages available for decision support, the sustainable approach lacks the equivalent supporting documentation and software tools. The additional benefits of SuDS can be overlooked as the evaluation procedures are unclear and the long-term performance of SuDS is still uncertain to stakeholders. Although some software packages have already include hydraulic and water quality modelling modules for SuDS, the additional benefits such as amenity value and long-term cost-benefit are still missing from the practice.

1.2. Our Vision

We decided to bridge the knowledge gap in the market by carrying out a research project on developing a new decision support system for sustainable drainage design. The key objectives of our research are:

1. To replace the time-consuming process of repetitive checking and optioneering with a set of straight forward, easy-to-understand key performance indicators (KPIs) and graphics.
2. To develop a systematic, multi-criteria evaluation framework based on the KPIs.

3. To integrate the framework with common drainage design software platforms.
4. To promote a well-balanced design philosophy for drainage considering water quantity, quality as well as amenity.
5. To combine the framework with machine intelligence techniques for design optimisation.

In order to achieve our goals, we first summarised technical details from legislative requirements and best practice guidance in different countries. Using the summary, we translated the design criteria into numerical key performance indicators. We also included monetary measures which are associated with the KPIs and other characteristics of drainage systems so that a long-term, whole life cost-benefit analysis can be carried out in a systematical way.

In this paper, we describe the methodology of developing the evaluation framework in section 2. Then, some example applications of the framework are used to illustrate the evaluation process in section 3. Conclusion with recommendations can be found in section 4.

2. Methodology

In this section, we explain the methodology used for developing the systematic evaluation framework and the basic structure of the framework with some examples of equations involved.

2.1. Framework Structure

Figure 2 below shows the core structure of the evaluation framework. The framework begins with a drainage network model which is usually created using standard drainage design software. The characteristics of individual drainage components (e.g. type, size and location) are then taken from the model and used for KPIs calculation. At the moment, the KPIs are categorised into four main aspects: water quantity (volume), water quality, energy usage and impact on surrounding environment. This make it easier for stakeholders to compare different drainage design options at high level for quick evaluation. After the initial evaluation, stakeholders can continue to explore and look into individual KPIs for further investigation. Monetary measures associated with the drainage systems are also calculated within the same framework. In order to illustrate how different aspects of drainage systems are quantified, we list a few calculations examples in this section.

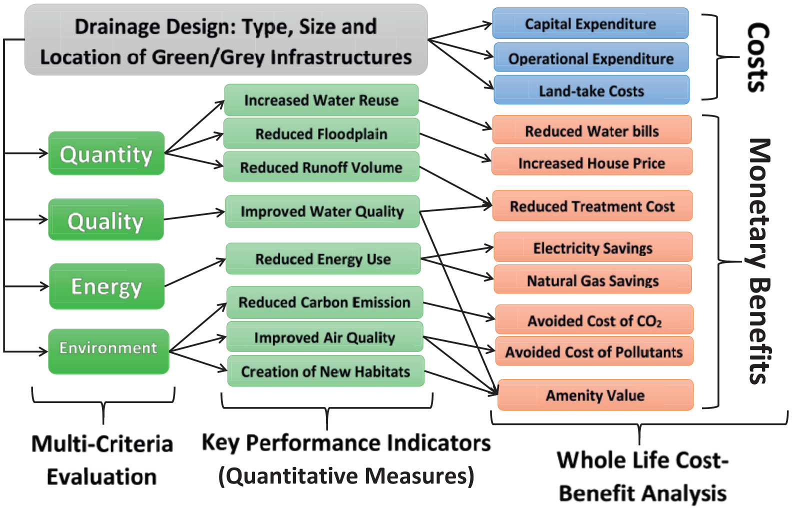


Fig. 2. Proposed systematic, multi-criteria drainage design evaluation framework.

2.2. Key Performance Indicators

KPIs calculations are functions based on best practice guidance and case studies from different countries. Table 1 below shows two example calculations.

Table 1. Example calculations of key performance indicators.

Top Tier KPI Aggregations	Type of Features	Name of KPI Components, Input Variables, Final KPI Outputs and Formulation	References
Quantity Reduction	Permeable Pavement	***Name of KPI Component:*** Runoff volume reduction due to infiltration in permeable car park. ***Inputs:*** AP – Annual Precipitation (inches) SA – SuDS Surface Area (foot^2) P – Percentage of Runoff Retained (80-100%) CF_1 – Conv. Factor 1 (144 inches^2 / foot^2) CF_2 – Conv. Factor 2 (0.00433 US gal / inches^3) CF_3 – Conv. Factor 3 (0.003785 m^3 / US gal) ***KPI Output:*** RR – Runoff Reduction (m^3) ***Formulation:*** $RR = AP\times SA\times P\times CF_1\times CF_2\times CF_3$ (1)	Previous studies from Booth et al. (1996), Bean et al. (2005), USEPA (2000) and LID Center (2000) showed that permeable pavement can infiltrate as much as 80-100% of precipitation.
Energy Savings	Green Roofs	***Name of KPI Component:*** Energy savings due to the use of green roofs. ***Inputs:*** ACDD – Annual Cooling Degree Days (^{o}F days) AHDD – Annual Heating Degree Days (^{o}F days) SA – Surface Area of Green Roof (foot^2) R_{con} – Thermal Resistance for Conventional Roof (11.34 foot^2 ^{o}F Hrs / Btu) R_{green} – Thermal Resistance for Green Roof (23.40 foot^2 ^{o}F Hrs / Btu) ***KPI Outputs:*** $S_{cooling}$ – Annual Cooling Savings (Btu) $S_{heating}$ – Annual Heating Savings (Btu) ***Formulation:*** $S_{cooling} = ACDD\times 24\times\left(\frac{1}{R_{con}}-\frac{1}{R_{green}}\right)\times SA$ (2) $S_{heating} = AHDD\times 24\times\left(\frac{1}{R_{con}}-\frac{1}{R_{green}}\right)\times SA$ (3)	Clark et al. (2008) showed that average annual energy savings on heating and cooling can be estimated with the assumption that insulation is provided by green roofs. The conversion to energy savings is then based on the reduction in heat flux due to insulation.

2.3. Capital Expenditure, Operational Expenditure and Land-take Cost

Monetary measures are calculations based on unit cost data collected from various case studies. At the moment, all the unit costs have been converted into March 2013 UK price using Consumer Prices Index in UK (Office of National Statistics, 2013) for applications in UK. With careful unit and currency conversion, the framework can be modified and made applicable for other countries. Using these monetary measures, the whole life cost of a drainage design with multiple drainage components can be estimated systematically. Table 1 below shows unit capital expenditure and operational expenditure for some common sustainable drainage systems in UK.

Land-take cost (not shown in this paper) is another important component in the cost-benefit analysis. As most sustainable drainage systems are designed to be used as surface features, the land-take costs associated with SuDS are considerably higher than traditional underground drainage systems. In UK, the residential land value data is made publicly available by the Homes and Communities Agency (HCA, 2013).

Table 2. Examples of annual unit CAPEX and OPEX of SuDS (March 2013 Price).

SuDS	Range of Annual Unit Cost (£)		Unit of Measurement	References
	CAPEX	OPEX		
Filter Drain	130.8 – 183.1	0.3 – 1.4	/m^3 stored volume/year	HR Wallingford (2004), Royal Haskoning (2012)
Infiltration Trench	73.2 – 83.7	0.3 – 1.4	/m^3 stored volume/year	HR Wallingford (2004), Royal Haskoning (2012)
Soakaway	130.8 (avg.)	0.1 (avg.)	/m^3 stored volume/year	HR Wallingford (2004), Royal Haskoning (2012)
Permeable Pavement	287.7 – 418.5	0.6 – 1.4	/m^3 stored volume/year	HR Wallingford (2004), Interpave (2006), EA (2007), Royal Haskoning (2012)
Infiltration Basin	15.7 – 20.9	0.1 – 0.4	/m^3 stored volume/year	HR Wallingford (2004), Royal Haskoning (2012)
Detention Basin	20.9 – 26.2	0.1 – 0.4	/m^3 stored volume/year	HR Wallingford (2004), Royal Haskoning (2012)
Wetland	31.4 – 41.8	0.1 (avg.)	/m^3 stored volume/year	HR Wallingford (2004), Royal Haskoning (2012)
Retention Pond	31.4 – 52.3	0.6 – 2.0	/m^3 stored volume/year	HR Wallingford (2004), Stovin and Swan (2007), Royal Haskoning (2012)
Swale	15.7 (avg.)	0.1 (avg.)	/m^2 surface area/year	CIRIA (2007), EA (2007), Stovin and Swan (2007), Royal Haskoning (2012)
Filter Strip	5.2 (avg.)	0.1 (avg.)	/m^2 surface area/year	HR Wallingford (2004), Royal Haskoning (2012)
Green Roof	57.5 – 120.3	0.2 – 0.7	/m^2 surface area/year	Solution Organisation (2005), Royal Haskoning (2012)

2.4. Monetary Benefits of Green Infrastructures

Table 3 below shows two examples of how monetary benefits can be calculated. The monetary benefits calculations are based on physical attributes, environmental factors and local assumptions.

Table 3. Calculation examples of monetary benefits linked to sustainable drainage design.

Top Tier KPI Aggregations	Name of Monetary Benefits, Input Variables, Final Outputs and Formulation	References
Quantity Reduction	***Name of Monetary Benefits:*** Potential Increase in Property Value ***Inputs:*** P – Local Average House Price (£) A_{before} – Area of Existing 100-year Floodplain before Development / Retrofitting (ha) A_{after} – Estimated Area of 100-year Floodplain after Development / Retrofitting (ha) D – Anticipated Properties Density (Properties / ha) R – Estimated Range of Price Increase Rate (2-5%) ***Outputs:*** B – Estimated Range of Monetary Benefits (£) ***Formulation:*** $B = P \times (A_{after} - A_{before}) \times D \times R$ (4)	Bin et al. (2008) suggested that properties outside the 100-year event floodplain were on average 7.8% more expensive than those within the floodplain. Center for Neighborhood Technology (2010) recommended a range between 2 to 5%.
Energy Savings	***Name of Monetary Benefits:*** Direct cost savings on electricity / natural gas ***Inputs:*** AEC – Avoided Energy Consumption(Btu) UC – Unit Cost of Energy (£/Btu) ***Outputs:*** S – Direct Cost Savings on Electricity or Natural Gas (£) ***Formulation:*** $S = AEC \times UC$ (5)	Based on the estimation of energy savings by Clark et al. (2008), the direct cost savings can then be estimated using unit costs from local energy suppliers.

2.5. Remarks on Methodology

The framework was originally designed for small, local scale (i.e. typical development sites) application. Yet, with careful assessment of price variation and local knowledge from design experts, the framework can be expanded to evaluate bigger, catchment scale schemes which are more important for local government and water companies. The cost-benefits analysis on large scale sustainable drainage design schemes for both new developments and retrofitting can help stakeholders to better estimate potential long-term benefits and to better justify investment planning strategy. We hope that this approach will encourage stakeholders to compare trade-offs of using green infrastructures and to identify the most desirable option which maximises multiple benefits.

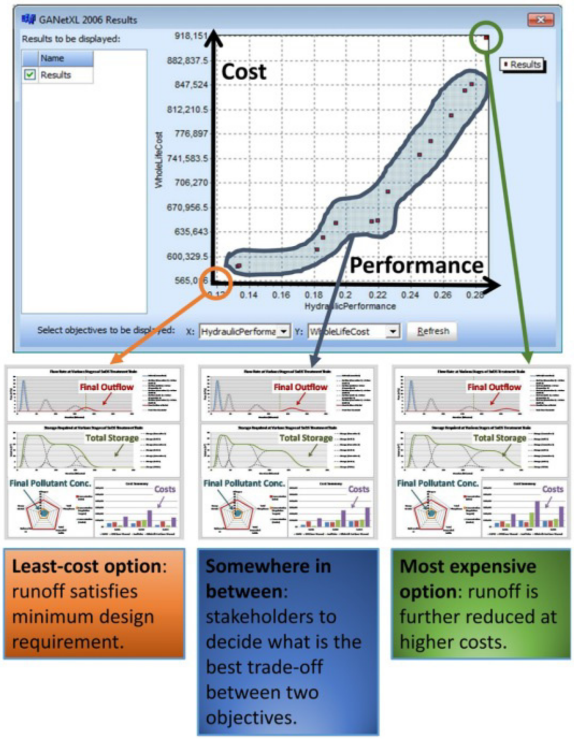
3. Application Examples

In this section, we begin with a simple example of identifying trade-offs between only two design criteria (e.g. performance and cost). Then we illustrate how the comparison can be done when multiple performance and monetary measures are considered with a second example.

3.1. Identifying Trade-Offs between Cost and Performance

One common approach to identify trade-offs between two objectives is to look at the Pareto-front of possible solutions. Figure 3 below shows a prototype of the decision support framework developed using GANetXL, an Excel add-in for quick optimisation framework prototyping (Savić et al., 2011). In this example, the Pareto-front is shown when the numerical measures of hydraulic performance and whole life cost of different drainage design options are compared and displayed together on a two-dimensional chart.

From the chart, we can first identify two extreme situations from the Pareto-front. The least cost design option which satisfies minimum requirements for runoff reduction at the bottom left corner and the most expensive solution which improved hydraulic performance at the other end. Between those two extreme options, a number of designs with varying costs and performance measures can be found.



Select objectives to be displayed: X: HydraulicPerforma Y: WholeLifeCost

Least-cost option: runoff satisfies minimum design requirement.

Somewhere in between: stakeholders to decide what is the best trade-off between two objectives.

Most expensive option: runoff is further reduced at higher costs.

Fig. 3. Identifying trade-offs between cost and performance.

With the drainage designs evaluated and compared using a software framework as described above, stakeholders can systematically go through different design proposals and narrow down a list of most desirable options which maximise common interests.

3.2. Multi-Criteria Evaluation and Comparison

We have shown the two-objective comparison with the first example above. Now we illustrate the framework application for multi-criteria evaluation with the following example. Understandably, when more objectives are added to the mix, the process becomes slightly more complicated than the two-objective case. However, the comparison process can still be done and visualised using a technique called parallel coordinates (Inselberg, 1985). Figure 4 below shows the layout of the three designs, the comparison of multiple benefits using parallel coordinates and the annualised cost-benefit analysis.

In this example, we evaluate three different drainage designs:

- Design A consists of two traditional (impermeable) car parks. The runoff from the car parks is drained into a vegetated swale followed by a pond.
- Design B has a vegetated swale upstream. The swale is connected to a permeable car park which infiltration is allowed. A storage tank is used to store excessive runoff temporarily.
- Design C has a smaller permeable car park when compared to Design B. Green roof is used in the adjacent building. The system ends with a bioretention cell.

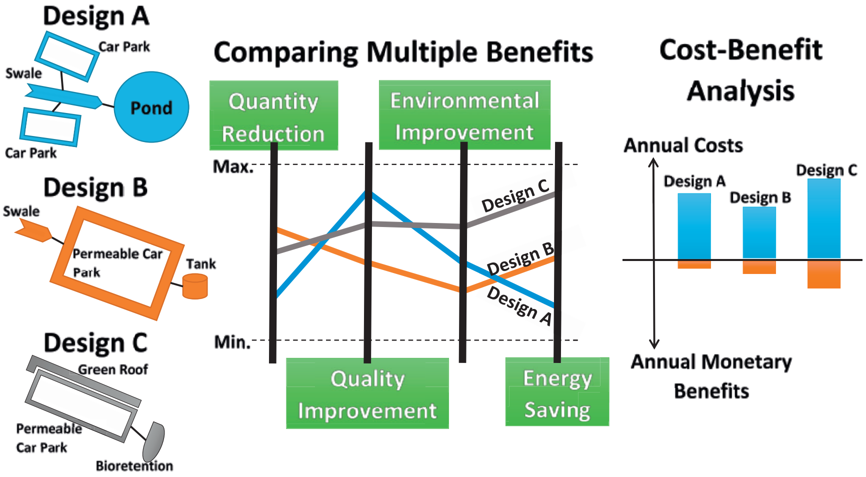


Fig. 4. Multi-criteria comparison and cost-benefit analysis.

For design A, the runoff sedimentation in the proposed pond results in a high score in water quality improvement. Yet, the lack of infiltration opportunity means a lower score in water quantity reduction.

When compared to other two designs, design B has a large permeable car park for reducing runoff via infiltration. That performance is recognised with a high score in quantity reduction. Unfortunately, there is not much water treatment process involved in the proposed design B and hence a lower score in quality improvement.

In contrast, option C is a moderate performer in both quality and quantity aspects. However, the key benefits of design C come from the use of green roof and bioretention cell. As a result, lower energy bills and increased amenity values can be expected from this design.

In additional to the direct comparison of multiple benefits mentioned above, the cost-benefit comparison gives stakeholders a view from another angle of the big picture. For example, looking at the costs alone, design C can be less desirable as it is more costly to construct and maintain when compared to other two options. However, when we factor in monetary benefits such as energy bills reduction, design C has higher potential to offset the cost in the long run.

3.3. Remarks on Framework Application

We hope that the framework will assist stakeholders to make evidence-based decisions for sustainable drainage design. Beyond the direct and quantifiable benefits described above, stakeholders might also look at drainage design projects from a much wider perspective. The positive image of a green business, increased tourism and new education opportunities are relevant yet indirect benefits associated with using green infrastructures. Those indirect benefits can be valuable assets that are appealing to government, investors as well as the general public (Natural Economy Northwest, 2008).

Although it may not be feasible to quantify and include all of those indirect benefits within one framework, we hope that our systematic approach will encourage stakeholders to consider both direct and indirect benefits from sustainable drainage design during early stages of a project.

4. Conclusions

The availability of well-documented technical guidance and computer software tools led to an era of successful applications of conventional drainage design practice in the last few decades. Yet, going forward, the lack of long-term sustainability consideration in the traditional approach is something we need to address as soon as possible.

Drainage design using green infrastructures has been recommended as a better alternative to address sustainability issues. However, there is a knowledge gap in supporting technical documentation as well as computer software tools. Discouraged by the uncertainty in system performance, long-term cost-benefit as well as funding and support from government, stakeholders are reluctant to adopt the new drainage design approach with confidence.

In order to bridge the knowledge gap, we proposed and developed a systematic evaluation framework for sustainable drainage design. In this paper, we explain the background and basic structure of the framework with some application examples.

Our project aims to provide a better, easy-to-use decision support tool for the drainage industry worldwide. We hope that the proposed multi-criteria evaluation framework will become part of the new industry standard. Most importantly, we hope that the newly available software tool will encourage stakeholders to consider the use of green infrastructures and to maximise multiple benefits whenever possible.

Further work is required to better understand the sensitivity of the performance and monetary measures. We are currently developing case studies with drainage design practitioners based on their recent projects in different countries. We also planned to implement machine learning techniques to optimise the green infrastructure selection process in the next stage of the project.

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