Supporting the choice, siting and evaluation of sustainable drainage systems in new urban developments

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Abstract
The work presented here forms part of the ongoing WaND research initiative in the UK aiming towards the implementation of sustainability principles in the planning of new urban developments. The paper describes the development of a decision support toolbox based on soft computing that assists the selection of promising sustainable drainage systems (SUDS), and their optimal siting within the context of new urban developments, through the creation of spatially variable suitability maps. It is suggested that the decision support toolbox, which includes the tools presented here as well as other tools developed within WaND can assist engineers and developers to take into account engineering, environmental and socio-economic characteristics and constraints in the design of more sustainable “SUDS” schemes.

Keywords
Fuzzy inference, multi-criteria decision analysis, optioneering, spatial decision support, suitability evaluation, sustainable urban drainage systems, urban water cycle

INTRODUCTION
The development of urban areas is known to cause permanent alterations to the stormwater and runoff regime of an area, resulting in greater peak flows and higher potential for flooding (Makropoulos et al., 1999). Historically, the guiding principle of urban drainage was to remove stormwater as rapidly as possible, with total discharge being the main concern handled by end-of-pipe solutions. Increased urbanisation in the UK has led to increased volumes of stormwater being discharged into the sewer network. The option of provision of larger sewer networks is now recognised as having a negative impact on the environment, with attention switching instead to methods of drainage which will attenuate and reduce the volumes of stormwater runoff (Butler and Parkinson, 1997; Butler and Davies, 2000). It has been extensively suggested (not least in International Conferences such as, for example, the 10th ICUD in Copenhagen in 2005) that the development of Sustainable Drainage systems (SUDS) can help to improve the quality of water prior to discharge, attenuate peak flows and volumes and to some extent mitigate flood events. SUDS may also be able to enhance natural environment through habitat creation, can provide water storage and can facilitate groundwater recharge. SUDS have also been receiving a high degree of attention outside Europe, within the context of Water Sensitive Urban Design (e.g. Wong, 2005) and Low Impact Developments (e.g. Wenstein, 2005).

The work presented in this paper falls within the framework of the WaND project (Water Cycle Management for New Developments, funded by the UK EPSRC), whose aim is “to provide guidelines and decision support tools for the implementation and assessment of efficient and sustainable water management interventions in new urban developments with due consideration to social, environmental and health associated factors”. The research described herein deals with two specific types of urban water management problems: the sustainable “option selection” problem and the “option location” problem. The sustainable option selection problem relates to the decision problem of choosing the most suitable technology given case-specific conditions and constraints with respect to technical, environmental social and economic objectives – in short “sustainability” objectives (Ashley et al., 2004). The option location problem is defined by Makropoulos & Butler (in press) as the determination of optimum locations for facilities in a given geographical area with respect to the abovementioned sustainability objectives. Such decision problems require decision
support tools which contain information on different options of water management technologies (e.g. knowledge bases) and are able to (1) compare the options on the extent that they meet the desired sustainability objectives (2) include mechanisms for the input and representation of spatial data, (3) perform synthesis and analysis of highly heterogeneous information and, (4) provide output results in a variety of spatial forms, such as maps. Such tools are known as Spatial Decision Support Systems (SDSS) (see for example Densham, 1991).

The paper discusses the development and application of two of the tools within the WaND SDSS – Toolbox: The “optioneering” tool supporting the selection of the most promising SUDS (from a knowledge library that contains different SUDS options) and the “suitability assessment” tool which supports the optimal siting of the SUDS within the context of new urban development planning through the creation of suitability maps. The suitability assessment tool can be used before or after the optioneering: In the former case we refer to it as the “screening tool”, whose function is to assess possible sites for new developments based on a number of criteria (including for example the possibility to apply a specific type or types of SUDS) at a catchment scale. The optioneering tool is then used to assess the sustainability of specific SUDS systems and their impact on the whole water cycle for the given site. In the latter case the suitability tool is used after the selection of specific SUDS systems by the optioneering tool to locate them within the site. A schematic of a decision-making process, within the context of new urban developments, linking catchment-scale “screening” tools, site-level “optioneering” tools and suitability evaluation tools, can be seen in Makropoulos et al. (2005). The usefulness of using optioneering tools in combination with suitability evaluation tools is also discussed in Makropoulos et al., (2005) and Ellis et al., (2005). In this paper we will present an example of the former case.

**METHODOLOGY**

Solving an option selection or object location problem within the urban environment involves taking into account numerous criteria and is dominated by a high degree of imprecision and uncertainty as well as value judgement by decision-makers. Uncertainty in such complex problems is commonly derived from the fact that much of the knowledge about the situation is expressible in linguistic descriptive variables (Klir and Folger, 1988). In order to quantify and deal with decisional uncertainty, the SDSS developed is based on the principles of multi-criteria decision making (MCDM) (Eastman, 1997; Malczewski, 1999) and is supported by fuzzy set theory (Yager, 1993; Cox, 1999), which is able to give a consistent representation of subjectively perceived and linguistically formulated knowledge and still be able to carry out problem-solving in a mathematically robust manner (Makropoulos et al., 2003; Makropoulos and Butler, 2004).

The overarching goal of the developed tools is to provide a new urban development with optimally situated facilities for urban drainage, in a way that makes them more efficient and sustainable. Operationalising sustainability is a difficult and ambiguous process and the approach adopted here is the selection of appropriate criteria linked to specific indicators. A criterion represents a measure against which option performance is assessed along with the degree to which stated objectives are achieved. Indicators constitute a means of measuring the level to which criteria are satisfied. The criteria-indicators approach adopted in this work, relates to the framework developed within the Sustainable Water industry Asset Resource Decisions (SWARD) project (Ashley et al., 2004) which focuses on sustainability for the water industry as well as sustainability principles incorporated into the UK planning regulations. The decision problem also involves different technologies/options that could be applied as part of an urban drainage management scheme. For the purposes of this work SUDS were categorised into three main groups:

- Those that work by allowing infiltration of stormwater directly into the ground at source (e.g. swales and infiltration trenches)
Those that store water allowing for release over an elongated period of time (e.g. retention ponds) and
Those that prevent runoff from developing (e.g. rainwater harvesting).

An (non-exhaustive) example of suitability criteria associated with each major type of SUDS can be seen in Table 1.

<table>
<thead>
<tr>
<th>Siting Criteria</th>
<th>Infiltration SUDS</th>
<th>Storage/Retention</th>
<th>Prevention</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil permeability</td>
<td>Public Space availability</td>
<td>Public health/risk in the vicinity of schools and playgrounds</td>
<td>In house space availability</td>
</tr>
<tr>
<td>Proximity to existing buildings with respect to the prevention of undermining of foundations and possible subsidence</td>
<td></td>
<td></td>
<td>Need for/acceptance of non-potable water use within the household</td>
</tr>
<tr>
<td>Distance to the water table</td>
<td>Land price</td>
<td></td>
<td>Resident’s financial potential to maintain the system properly</td>
</tr>
<tr>
<td>Proximity to contaminated sites (in hydrogeological terms) with respect to groundwater pollution</td>
<td>Slope and site morphology</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Local ground stability</td>
<td></td>
<td>Downstream location with respect to impact of storage to the drainage system’s performance</td>
<td></td>
</tr>
<tr>
<td>Proximity to groundwater vulnerability/protected zones with respect to water abstraction.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slope and site morphology</td>
<td></td>
<td></td>
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</tbody>
</table>

There can be two major kinds of evaluation criteria: factors and constraints (Eastman, 1997). The criteria in Table 1 are examples of factors that enhance or detract from the suitability of a specific alternative and are most commonly measured on a continuous scale. Within our work these factors are used as fuzzy criteria and are assessed through the use of fuzzy inference systems (FIS) (e.g. Makropoulos et al., 2005; Argyrou et al., submitted). Constraints on the other hand, serve to limit the alternatives under consideration, and dichotomize alternatives into two (Boolean) categories: acceptable and unacceptable (Bana e Costa, 1990; Malczewski, 1999). Some of the criteria in Table 1 could also act as (crisp, as opposed to fuzzy) constraints if the decision-maker believes that there is a clear cut-off value above or below which the application of a SUDS scheme is unquestionably unsuitable. For example, if a well capture protection zone has been established, the siting of infiltration-type SUDS may be legally prohibited. A more detailed description of both the optioneering and the suitability evaluation tools used to support SUDS application is included next.

**Optimal Site Selection and Suitability Evaluation**

At the catchment level, an initial screening of sites for new developments using, for example, the criteria from Table 1, can indicate the best sites for SUDS application and facilitate the site-level assessment. The WaND toolbox contains the suitability evaluation tool, which is termed “screening tool” that allows for such an analysis. Initially, each SUDS strategy, or set of options, is broken down into a (superset) of criteria, which directly influence its applicability at a given location (similar to Table 1). From this superset, the user chooses the criteria to be taken into account, subject to data availability. Criteria that are to be handled as constraints are also identified at this point and their cut-off points defined. Due to the heterogeneous scales with which different attributes are measured, each selected attribute is imported into the system as a map layer and is then standardized into a suitability map for the relevant strategy. This is performed through a fuzzy
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inference system (FIS) (Figure 1). For example, the soil permeability criterion map of an infiltration option will be transformed into a suitability map with respect to soil permeability. The output suitability maps are measured on a [0, 1] scale and are thus comparable and ready for further analysis.

**Figure 1:** Example of an attribute map standardized into a suitability map through the corresponding FIS procedure

The standardized suitability maps for each criterion of a given SUDS option are aggregated to produce a composite suitability map for the option’s application. The decision-maker is presented with different options of aggregation techniques including standard weighted averaging (SWA), ordered weighted averaging (OWA), and spatial ordered weighted averaging (SOWA). The SOWA technique (Makropoulos and Butler (in press)), has the major advantage of being able to include within the aggregation process a spatially variable risk index, which in the case of SUDS siting could be flood risk or health risk to sensitive population (linked to, for example, proximity to schools). The risk index can be used, through a set of linguistic FIS rules, to “bias” the applicability of specific options (e.g. “reduce” the applicability of ponds “near” schools). The composite suitability map for the option under evaluation then undergoes a “masking” process, imposing the selected constraints. Based on the composite suitability maps, the tool provides the option of making a final recommendation as to the best possible (optimal) solution to the problem, which in this case is the location of a site that is best suited for the particular SUDS application. The user can specify the area that the site needs to have, on the basis of which the tool calculates and identifies which location (cluster of cells) within the entire study area is the most favourable for applying the particular technology and provides a breakdown of the scores of the selected site with respect to the criteria. The user can therefore see the strong and weak points of the proposed site and modify his/her weightings or risk perceptions if needed.

**Sustainable Option Selection**

Following the selection of a site at a strategic level, there remains the issue of their application within the site (including for example, issues of scale of application). Within a given site, infiltration SUDS and prevention SUDS, can be implemented both at a household scale, at a cluster
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of households scale or at a large/development scale. Moreover, the “prevention” type of SUDS (e.g. rainwater harvesting) have a fundamental impact on the urban water cycle since, being essentially recycling technologies, and thus directly affect both the potable water demand of the site and the production of wastewater. There emerges, therefore, a need to take a more holistic view, allowing water supply, wastewater disposal, and stormwater drainage to be considered as components within a single system. Mitchell (2001) acknowledges that such an approach is rarely considered within the same modelling framework.

The abovementioned issues are all addressed within the context of the ‘optioneering tool’ which is part of the WaND Toolbox. It aims to:

- investigate and quantify the interactions and transformations of the three water flows within the same modelling framework,
- facilitate the selection of combinations of water saving strategies and technologies
- support the delivery of integrated, sustainable water management for new developments.

The optioneering tool is based on a Matlab/Simulink water mass balance model, and an Excel-based ‘Technology Library’. The Simulink model simulates the urban water cycle and the Technology Library, is a database which contains information on the performance of several water saving, water recycling and SUDS technologies in the form of sustainability indicators associated with the technologies. The selection of the most sustainable combination of technologies is achieved through an optimisation procedure which was developed to allow the tool to find the optimal composite strategy for sustainable water management with respect to the users’ preferences towards the achievement of various objectives. The optimisation is achieved through an evolutionary strategy – using a genetic algorithm–, an approach increasingly used to solve real world, ill-structured problems, such as those faced in decision support systems (e.g. Makropoulos and Butler, 2005; Deng and Tsacle, 2000; Kuo et al., 2000; Matthews et al., 1999). The genetic algorithm minimises any single user defined (sustainability) objective, for example: runoff produced, operational cost or social acceptability or a combination thereof. The sustainability indicators that are used to drive the selection process are treated as fuzzy criteria through the use of fuzzy inference systems (FIS). The user, prior to the execution of the optioneering tool, is asked to:

- Set any constraints (e.g. only localised SUDS, or only swales but no infiltration trenches). This step is not necessary but renders the optioneering tool flexible to solve any real case scenario problem. If no constraints are input the tool is free to select any option stored in its library.
- Decide on the relative weight of the various sustainability objectives.

The optioneering tool is then able to compare the performance of the various SUDS technologies that are stored in the Technology Library, applied at all possible scales - from an infiltration trench for each single house, to an infiltration pond for the entire development. A flow chart diagram representing the optioneering procedure can be seen in Figure 2.
Simulink water mass balance model
User defined constraints: engineering, social or economic

Tech Library: lists several SuDS options and sustainability indicators for their performance

Figure 2: An example flow chart representing the rationale of the optioneering tool of the WaND toolbox

Based on the outcome of the optimisation procedure, the optioneering tool suggests the optimal SUDS option, given the case specific conditions and constraints and the user’s attitude towards the various aspects of sustainability. The final output of the optioneering tool is a table with the promising technologies chosen, and a sustainability assessment of the performance of the final solution towards the different sustainability objectives. This assessment is carried out by comparing the optimal solution to the performance of a benchmark solution (which in this case is a no SUDS solution) and the result is presented in the form of a graph, similar to the one depicted on the lower right corner of Figure 2.

RESULTS AND DISCUSSION

An example of the application of the screening tool for a case study area (using semi-hypothetical data) can be seen in Figure 3. The tool was applied to identify a site of a specific size (1km²) for a new urban development, using as criterion the maximisation of the potential for application of infiltration-type SUDS. The analysis (Figure 3) has been performed using two sets of weights: Equal weighting without risk inclusion (Figure 3a) and equal weighting combined with flood risk as the spatially variable index applied through a SOWA process (Figure 3b).
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As seen in Figure 3, in each case, the tool has identified a different site, and returned its location and an assessment of its performance with respect to criteria selected by the user. In this case, the criteria selected, as an example of suitability assessment for infiltration-type SUDS, were: Slope, Soil Permeability, Proximity to Contaminated Land and Proximity to Sensitive Environmental Areas. In Figure 3b where the spatially variable risk perception (in this example flood risk) is included, the results are biased to suggest more caution in flood-prone zones, thus the resulting optimal site is not only at a different location (farther away from flood zones), but is also rated with lower absolute suitability scores, as a result of the flood risk “caution” factor. Figure 4 presents a sustainability evaluation of (a specific solution of) local and centralise infiltration facilities for the site selected in Figure 3a using the optioneering tool. Since this is a multi-criteria evaluation, the solutions evaluated can be seen to differ in a number of criteria and as they represent non-dominated solutions, they are not directly comparable. A further selection requires more input from the decision makers, either through formal/informal negotiation or through the suggestions of weights or both. If the decision maker is prepared to provide weights for the different criteria and thus allow for a trade-off between them, the evolutionary algorithm discussed above can be employed to drive the problem to a single “optimal” solution. The evolutionary optimisation element of the tool will not be discussed here. In Figure 4, the performance of the proposed solution is compared with a benchmark system configuration which represents the “business as usual scenario”, which in this case, as suggested earlier, assumes a pipe drainage system and no SUDS. The better a solution’s performance is as compared to the benchmark, the further away it is from the beginning of the axis.

Figure 3: Composite suitability map for Infiltration-SUDS including optimal location identification and criteria assessment: (a) equal weighting/no risk index (b) equal weighting with spatial risk index (flooding).
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Figure 4: Sustainability assessment using (part of) the SWARD criteria for infiltration SUDS at a site level.

CONCLUSIONS

Clearly, the use of these and other similar DSS tools require site-specific data as well as information on their performance within the context of a sustainability assessment (including for example technical, social, economic and environmental characteristics and constraints). Such data and information are not always available and although common technology libraries (such as the ones developed within the WaND Project (Makropoulos et al., 2005)) can provide a level of transferability between cases, sustainability assessment remains very much a site-specific issue. On the other hand, more and more reliable data at smaller and smaller scales are becoming available every day (Dworak et al., 2005) and tools like the ones presented here can support and promote data collection efforts by illustrating the use of high quality spatial data in supporting sustainable decision making. Since both applications of the tools presented here were performed in semi-hypothetical data, the actual numbers generated are not significant per se. What is important is the ability of the toolbox presented to handle engineering and socio-economic information and linguistic rules and assumptions to support multi-criteria decision making and multi-stakeholder negotiations. Such negotiations require inter alia two important prerequisites: information and preference. The tools reveal the need to make both prerequisites explicit and in so doing indirectly support decision making even before they are applied. The tools are flexible enough to allow for inclusion of both new (site-specific) information and (decision maker-specific) preference in a transparent way and guarantee reproducibility of the analytical process, while capturing linguistic uncertainty and ambiguity, which is always present in everyday decision-making. When such information is available and preference is allowed to be made explicit, these tools, together with other tools developed within the WaND initiative (Makropoulos et al., 2005) can assist engineers, planners and developers to take into account environmental, socio-economic and engineering site-specific, “soft” and “hard” characteristics and constraints in the design of more sustainable “SUDS” schemes.

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REFERENCES