An Integrated Decision Support Approach to the Selection of Sustainable Urban Drainage Systems (SUDS)

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Abstract
The decision-making process for the selection of Sustainable Drainage Systems (SUDS) for stormwater runoff management involves a variety of stakeholders within public and private sectors holding differing powers and opinions regarding the significance they attribute to differing control factors such as environmental, social, legal and economic criteria. The paper will outline the web-based multi-criteria analysis (MCA) approach incorporated into the SUDSLOC model developed within the SWITCH Stormwater Management theme. The MCA forms the core basis of the adaptive decision support system (DSS) to the SWITCH SUDSLOC selector tool and is intended to support stakeholder negotiation and the development of mutually acceptable sustainable solutions to the problem of control and treatment of urban surface water drainage. The MCA matrix methodology for the DSS and the SUDSLOC model are outlined and some of the advantages and limitations of the integrated modelling approaches are demonstrated.

Keywords: Decision support systems (DSS), Sustainable urban drainage systems (SUDS), urban stormwater drainage management, Multi-criteria analysis, Integrated modelling

1 INTRODUCTION

Decision support systems (DSS) have evolved significantly since their early development in the 1970s with their focus now being on how information technology can improve both the *efficiency* with which users reach a decision as well as improving the *effectiveness* of that decision. A DSS approach is particularly valuable when addressing complex, un- or semi-structured issues involving a variety of stakeholders holding differing, and even contradictory views on both approaches and solutions. The mental modes of stakeholders having various perspectives and experience lie at the heart of the decision process, defining what is a problem through to the interpretation of results and implementation of solutions. Personal and organisational perspectives now dominate DSS and frequently require a substantial "data warehouse" which normally comprises an integrated, subject-oriented, time-variant data bank/collection, which can be accessed for interactive "on-line" analytical processing. This allows the DSS to offer stakeholders an insight into the nature of the problem based on a wide variety of evidence and views to reflect the real dimensionality of the problem(s). A DSS approach thus combines analytical modelling with data access functions with an emphasis on flexibility and adaptability as a basis for enhancing user interaction and understanding. The approach nevertheless incorporates explicit procedures based on sets of principles and parameters that must justify the rationality of both the DSS structure and the proposed solutions.

Urban water infrastructure provision and management constitutes a "wicked" problem which is complex, having no clear obvious solutions with a variety of stakeholders having different interests and attitudes. Urban water management sits within a highly demanding decisional environment where optimal planning pre-supposes a synthesis of complex, heterogeneous information and data of varied spatial and temporal resolution but which must focus on site-specific implementation. It is generally argued that institutional stakeholders such as regulatory agencies, water companies etc., are primarily interested in power, hierarchy and centralisation of authority and delivery systems (Ashley *et al*., 2011). This tends to result in organisational "lock-in" to approaches and solutions as well as stationary regimes which inhibit innovation; in most instances, it is the regime that presents the real problem and not the institutional arrangements *per se*. Relevant and robust decision support approaches are a pre-requisite to address the "wicked" problem presented by the complexity of urban stormwater runoff control and management. Decision support structures must also meet the need for stakeholders to engage with the assessment procedure as well as in the delivery of proposed solutions and this frequently is the most difficult objective to achieve in the decision-making process. This paper outlines the basis and structure of a web-based adaptive DSS to identify appropriate sustainable urban drainage system (SUDS) solutions for urban surface water management. The DSS approach has been incorporated as a base component to the SUDSLOC drainage selection tool developed within the SWITCH Stormwater Management theme.

2 AN URBAN STORMWATER DSS

Matrix-based, multi-criteria analysis (MCA) methodologies have been widely applied to multi-factor environmental problems, helping to make explicit the different alternatives and their respective performance evaluation in regard to differing criteria (Salminen *et al*, 1998; Ashley *et al*, 2001; Ellis *et al*, 2004a). MCA enables the handling of a large amount of information (both quantitative and qualitative) in a consistent way, increases the transparency of the decision-making process and facilitates stakeholder participation in the decision-making process which can be fully audited. The aim of the MCA approach in stormwwtser management is to assist decision-makers to identify preferred drainage control options through the ranking of SUDS alternatives including both structural and non-structural controls, short-listing alternatives for further detailed appraisal, or simply serving to distinguish acceptable from unacceptable possibilities. The MCA is not intended to be a SUDS drainage design approach and other hydraulic and water quality methodologies will need to be referred to in order to properly dimension individual SUDS devices. The MCA is essentially a linear additive modelling approach which will allow stakeholders to apply scores and weights to evaluate, prioritise and appraise preferred SUDS options set in a user-friendly methodological framework. The tool is informed by a knowledge-based library or "data warehouse" populated with SUDS control options and information/data on their characteristics/attributes, performance, maintenance and cost.

The DSS approach adopts generic sustainability criteria referenced against those parameters related to the water quantity, water quality and ecology/amenity functions influencing SUDS performance. The DSS structure defines a suite of "desirable" features or criteria that need to be satisfied in respect of the design, selection and location of SUDS mitigating measures. The identified criteria must also be defined by characteristic and measurable attributes. It may be however, that some of the "desirable" criteria cannot be readily characterised using strict quantitative values and so need to be defined in alternative qualitative relative scalar terms.

The controlling ***criteria*** (or Areas of Concern, AoC) for the MCA are Site Characteristics, Technical, Environmental, Economic, Operation and Maintenance, Social and Urban Community Benefits and Legal and Urban Planning. Site Characteristics are used for initial profiling and screening to delimit exclusion criteria which define acceptable/unacceptable SUDS alternatives. The remaining six criteria are subdivided into ***indicators*** and ***benchmarked*** using appropriate threshold values or units. The defining terms for the AoCs in the MCA matrix are interpreted as follows:

- ***Criteria***: major established factors on which the final judgement, evaluation or decision is made.
- ***Indicators***: diagnostic states or conditions which describe relevant and appropriate properties of the given criteria.
- ***Benchmark***: threshold value or condition (qualitative or quantitative) which can comprise a point of reference for decision-making and indicate an acceptable level of performance.

The indicators and benchmarking of the primary sustainability criteria (AoC) enables a comparison to be made between alternative mitigating options whilst preserving the multi-objective nature of the drainage infrastructure problem.

Table 1. Criteria and Indicators within the MCA

CRITERIA (AoC)	INDICATORS
Technical	Flood Control
	Pollution Control
	System Adaptability
Environmental	Receiving Water Volume Impact
	Receiving Water Quality Impact
	Ecological Impact
Operation and Maintenance	Maintenance and Servicing Requirements
	System Reliability and Durability
Social and Urban Community Benefits	Public Heath and Safety Risks
	Sustainable Development
	Public/Community Information and Awareness
	Amenity and Aesthetics
Economic	Life Cycle Costs
	Financial Risk/Exposure
	Long Term Affordability
Legal and Urban Planning	Adoption Status
	Local Building and Development Issues
	Urban Stormwater Management Regulations

Table 1 indicates the range of criteria and indicators that have been developed for use within the MCA. Whilst the choice of indicators has been derived following comprehensive discussion with a variety of end-users and the pragmatic need to satisfy a range of European partner concerns, it is recognised that alternative and/or additional indicators might be equally appropriate depending on local conditions and circumstances. It can be argued that the indicators do not provide a fully holistic understanding of sustainability in terms of the various SUDS options. They can have a narrow scope being focussed perhaps on particular policy intentions or pre-formed goals. The indicators may also be geographically and time-limited and vulnerable to socio-political changes.

One methodological issue here is related to the number of indicators and benchmarks included in the MCA. Too many could be discouraging to the end-user and involve exhaustive detail with weights distributed thinly across a large number of variables. The presence of too few variables poses the problem of dissimulation into an enlarged and generalised grouping. However, most policy decisions are essentially about choices between a limited number of discrete variables and thus the choice of 6 principal criteria and 18 indicators is considered to be reasonable. One particular advantage of the MCA tool is that it is possible to mix objective (quantifiable) and subjective (qualitative) information through development of appropriate scaling techniques. Table 2 illustrates an example of the range of benchmarks that could be considered to provide points-of-reference for the Technical and Environmental Criteria AoC group.

Table 2. Examples of Indicators and Benchmarking

Criteria	Indicator	Benchmark	Units
Technical	Flood control	Overflow frequency	1...n
		Design storm return interval	RI yrs
		Extreme event control	H/M/L
	Pollution control	Dissolved pollutant capture	%; H/M/L
		Solid(s) pollutant capture	%; H/M/L
	System Adaptability	Ease of retrofitting	H/M/L
		Design freeboard	% ; Volume, m^3
Environmental	Receiving Water Volume Impact	Downstream erosion	H/M/L
		Thermal effects	C°
		Groundwater levels	Depth; m
	Receiving Water Quality Impact	Compliance with RWQ standards	%; mg/l
		Threshold pollutant concentrations	mg/l
	Ecological Impact	Biotic diversity	Biotic scores

The benchmarks represent "targets" or thresholds which indicate an acceptable level of performance to all stakeholders and with the selected threshold unit or value being scaled by reference to available national or other standards or determined through re-iterative discussions with experts in the specific AoC. Figure 1 illustrates the benchmarking scaling technique approach used within the current MCA methodology in respect of the Flood Control Indicator based on the "Level of Protection" (LoP) as determined by the design storm return interval (RI). The RI value which is used as an exemplar in Figure 1, provides an understandable and widely used threshold reference in SUDS design procedure and is of relevance to the performance-capacity of different SUDS forms. The benchmark scaling methodology is simple in principle and follows the appropriate allocation of a utility score to a given level of protection with a value of 1.0 reserved for the maximum level of protection (LoP).

It has been common practice within many European countries and in North America to adopt an upper flood protection limit of 1:100 recurrence interval (i.e the 1% annual probability) and this is the *defacto* minimum LoP adopted by the US and UK national flood insurance programmes. This level has been set on the basis of cost, desire of the community, potential damage, environmental impact and other factors. Nevertheless, it still can be considered as being a relatively modest target level as there is a 26% chance that that a scheme designed to contain the 1:100 event will be at design capacity at least once every 30 years. For high density urban areas (especially if at risk of tidal flooding) recommended standards for urban drainage trunk systems are frequently set at 1:200 years with urban branch systems set at 1:50 years although in the Netherlands for example, river dykes are designed to 1:1000 year discharges.

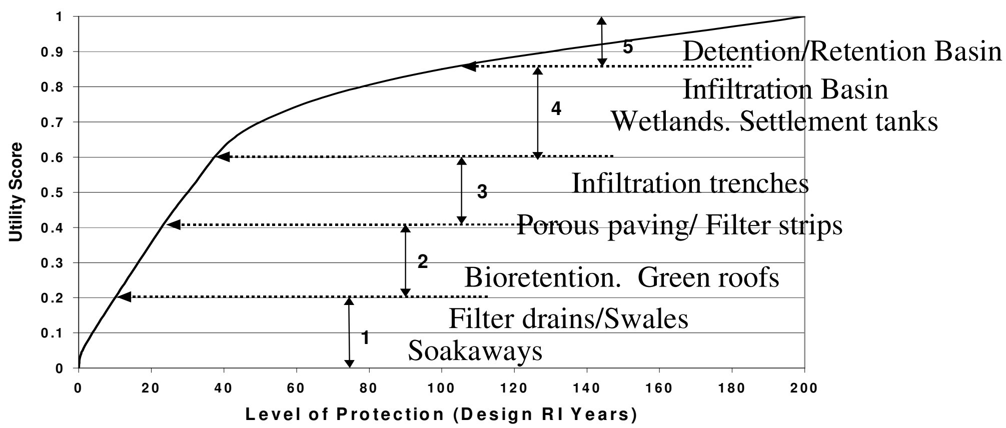

Figure 1. Derivation of MCA Utility Scores and Ranking Value for the Flood Control Indicator

The EU Commission has recently proposed concerted action to improve protection against flooding given that over 200 major flooding events involving 700 deaths and at least £25B in insured economic losses were incurred by member states between 1998 and 2002, with the UK 2007 summer floods being responsible for 13 deaths and over £3B insured damage (Pitt, 2008). Given the increasing scale of flooding and associated losses resulting from urban expansion and climate change, urban communities in the future may well wish to move towards more extreme design levels and favour the concept of acceptable risk rather than LoPs defined by specific probability of occurrence. Acknowledging the above arguments, the maximum benchmark scale for the flood control indicator within the MCA has been set at a 1:200 RI value (Figure 1). It recognises that higher design standards may need to be adopted for the protection of bridges, roads and other services (e.g power pylons etc..) within the catchment but also acknowledges a level of reasonableness in terms of the capability and cost for provision of flood storage within new and retrofitted developments. Protection against 30 RI events (3.33% annual probability) was considered as being adequate for most urban developments during the 19th century and is the basis for UK surface water sewer design and this LoP has been allocated a utility score value of 0.5. Relative to this, the 1:50 RI and 1:100 RI events are given values of 0.7 and 0.85 respectively. The 100% annual probability (1:1 RI event) is the highest probability event that might be considered to ensure that flows to the receiving water are tightly controlled for these more frequent but dominant channel-forming events. The utility curve plotted from these allocated values may appear somewhat arbitrary to some stakeholders but end-users have the possibility of substituting their own utility plots based on local required LoP or acceptable risk standards.

The final step in the procedure is the determination of the range of LoPs afforded by varying SUDS controls based on consideration of their volumetric capacity and storage/attenuation potential for varying levels of storm recurrence intervals (Figure 1). This has been determined by reference to the literature as well as considerations provided from expert group analysis. Clearly, infiltration systems such as filter drains, infiltration trenches and soakaways have the lowest storage potentials with porous paving hardly able to cater for 1:5 year events although surfacing with reservoir structures are able to handle 1:10 events and higher. The largest storage potentials and LoPs will be afforded by storage basins including infiltration basins, detention/retention basins and wetlands which can provide the highest protection up to and beyond the 1: 100 RI event and which would thus attract a utility score of 1.0 (or a maximum score of 5). It is possible to directly use the utility score as derived from the plot or to standardise the MCA matrix scoring within a grouped scaling (e.g 1 –5) as shown in Figure 1. Initial groundproofing of the methodological approach with stakeholders suggests that the latter approach may prove more flexible as a negotiating tool but both approaches are shown in Figure 1. A score of 5 would be allocated to the highest performance (in this case protection greater than 1:100 RI) and 1 to the lowest (less than 1:10 RI).

The Water Quality Control Indicator has been developed by benchmark referencing to the SUDS performance for the removal of a full suite of stormwater priority pollutants (TSS, BOD, COD, nutrients, faecal coliforms, metals, PAHs, pesticides and other organic pollutants (Scholes *et al*, 2005). In this instance the utility score is benchmarked by the ranking of the SUDS in terms of its performance as determined from a detailed physico-biochemical consideration of the efficiency potential of the primary removal processes for each pollutant (adsorption, sedimentation, filtration, microbial degradation, solubility, volatilisation, photolysis and plant uptake) in respect of each SUDS type. The pollutant removal and SUDS performance rates are initially classified as high, medium or low (or non-applicable) using a scaling technique (Scholes *et al*., 2008). This classification is then converted into a quantitative scale by summing the individual pollutant and SUDS removal process potentials to derive an overall single value for each SUDS device which can then be ranked to the common 1 to 5 scale. Figure 2 illustrates the outcome of this procedure for TSS removal performance with facilities capable of receiving, holding and treating large discharge volumes such as infiltration basins (IB) and constructed wetlands (CW) having the highest potential. Swales (SW), Filter Strips (FS) and Settlement Tanks (ST) have successively lower potentials.

3 MCA APPLICATION

The MCA performance matrix can be displayed on-line following user connection to the DSS website with the matrix cells carrying either pre-assigned default values (Mode 1) or values can be entered by the user (Mode 2). Figure 3 illustrates part of the screen display prior to the assignation of any values or weightings. The highlighting (which appears in red on the actual display screen) of specific BMPs in the title columns indicates that these have been pre-identified as being inappropriate from consideration of the initial Site Characteristics screening. Despite this warning, the user can nevertheless enter values in the matrix for such controls should they wish to examine these systems further in the light of local knowledge and stakeholder interests.

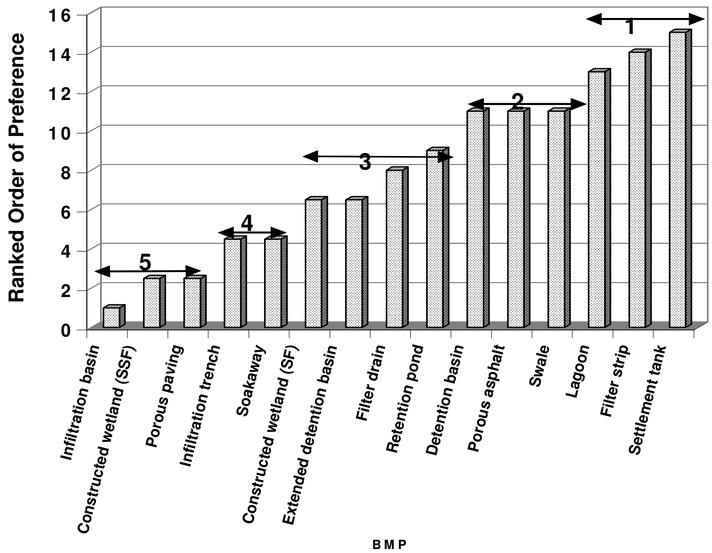

Figure 2. Scaling and Scoring for SUDS Total Suspended Solid (TSS) Removal Potential

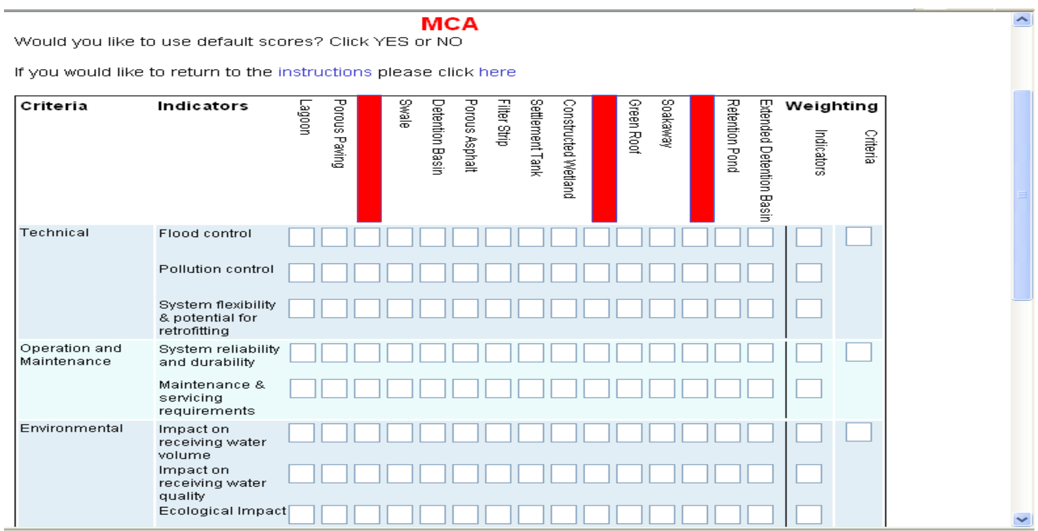

Figure 3. Screen Display of the MCA Matrix

Following completion of the matrix scores, weightings can be applied to reflect the importance placed on each criterion and/or indicator by the stakeholders. If a particular criteria or indicator is not to be considered within the MCA for some reason, it can be eliminated by allocation of a 0% weighting. If for example, flood control were to be the only criterion for consideration, then this indicator in the Technical AoC cell would be allocated a 100% weighting and all other indicators would be 0%.

An initial screening analysis can be applied by only entering appropriate weightings in the final Criteria column of the matrix and ignoring the indicator benchmarking (by entering zero values). Such analysis might be helpful for initial scoping discussions with stakeholders during strategic master planning to identify generally acceptable or unacceptable BMP alternatives. An example of this baseline approach, but using an extended Criteria listing, for a site at Blanc-Mesnil in the Siene Saint-Denis area of Paris intended for the construction of a SUDS highway drainage control device is given in Ellis *et al*, (2004b). The DSS methodology has also been applied to the Eastside development area within the SWITCH demonstration city of Birmingham, UK (Viavattene *et al.*, 2008). Full detail of the DSS structure and the MCA methodology can be obtained from Ellis *et al.*, (2008) and Revitt *et al.*, (2008b).

Each end-user chooses to arrange their weights in order of perceived importance and magnitude, with the possibility of including zero values. If a consensus on weights cannot be reached, the MCA may be repeatedly run using different weightings which reflect differing views to ascertain the effect that this has on the generated BMP order of preference. Although the MCA method greatly facilitates the comparison of drainage alternatives and scenarios against a wide range of criteria in a quantifiable and auditable manner, the problem of defining the level of sustainability of each individual option still remains. This is primarily due to limitations in the current state of knowledge whereby an absolute target value of sustainability for a given set of criteria within a given situation is very difficult to determine. In addition, the generated results are not directly comparable in terms of the values produced i.e the MCA may inform that option one is more preferable than option two, but it cannot identify the degree of distinction (or sustainability) between them.

4 SUDS SELECTION AND LOCATION

The matrix analysis provided by the MCA procedure can indicate which SUDS devices will be appropriate for a particular development site but there is still a question of where they should be optimally located within the development site or urban catchment. The SUDSLOC tool developed within the SWITCH Stormwater Management theme has utilised the web-based GIS platform to deliver a methodology developed to integrate the MCA approach with the specified site characteristics and storm profile(s) to the combined 1D/2D modelling of sewer and surface (overland) flows (Vivattene *et al.,* 2008).

The structure and component modules of the SUDSLOC tool are outlined in Figure 4 which illustrates the various modelling and data inputs which are processed within the modelling program. The outputs from the analytical tool include a variety of surface flood maps (distribution, depths, flow paths, velocities) as well as enabling stakeholders to identify appropriate SUDS types and locations within a specified development or retrofit site. The SUDSLOC tool has been successfully trialled within the 170ha Eastside urban regeneration area of the SWITCH demonstration city of Birmingham, UK and a companion paper within the current UNESCO workshop proceedings describes the application in further detail (Viavattene and Ellis, 2011).

5 CONCLUSIONS

The DSS is essentially a screening tool that can be applied by planners and developers on a catchment scale, but also serves as an "optioneering" tool at site level offering alternative drainage solutions. In addition, it serves as a suitability evaluation tool in

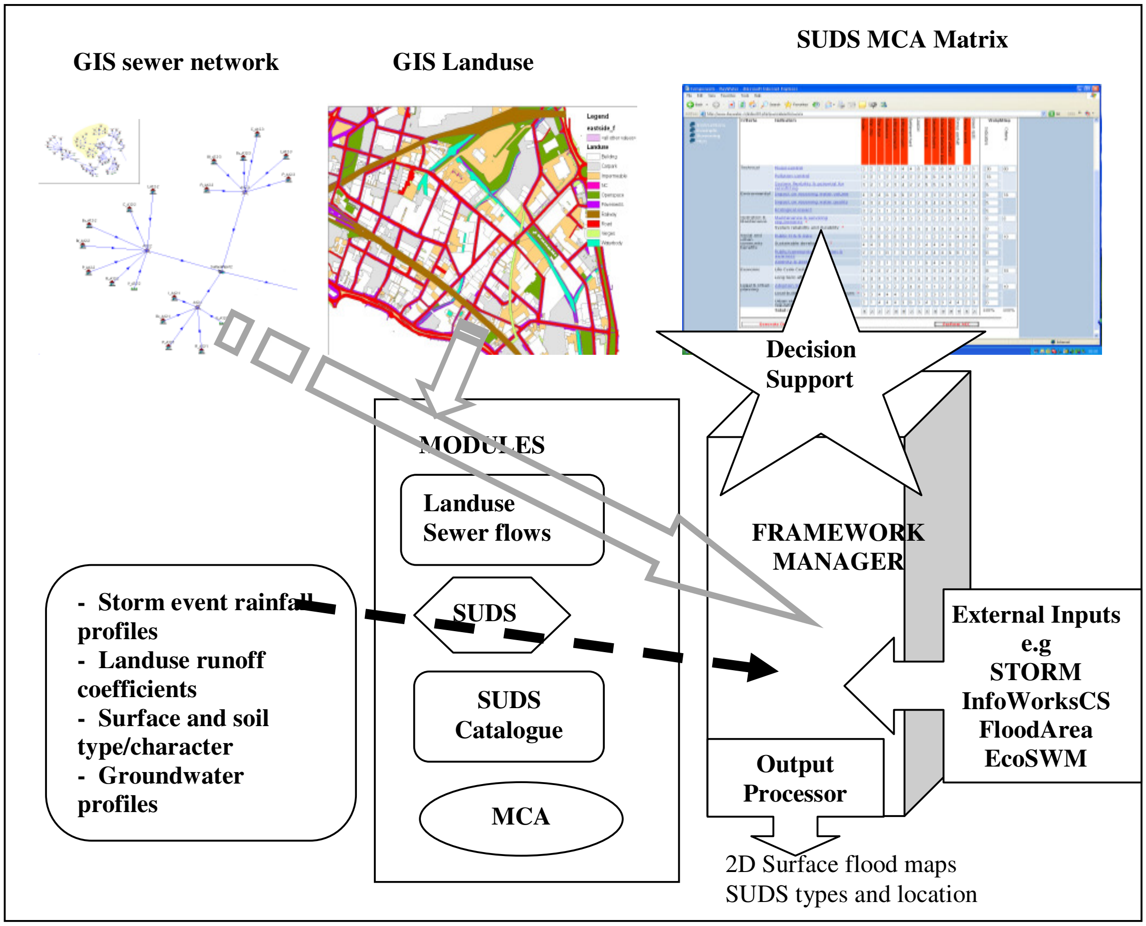

Figure 4. The SUDSLOC modelling structure

that the SUDSLOC component can be used by local authorities, drainage engineers and developers to select and locate drainage options at a site scale. The DSS methodology allows for adaptability forced as as result of climate change or urban creep as well as the introduction of potential regulatory requirements such as rainwater harvesting or attenuation storage for increased flood resilience. Such tools are of increasing importance in urban water management planning as practice moves towards decentralized but context and stakeholder driven solutions. Whist the DSS facilitates the decision-making process, it also helps to ensure the process is transparent, documented, reproducible and robust, providing a coherent guidance framework to explore various options and solutions.

Although the MCA method greatly facilitates the comparison of drainage alternatives and scenarios against a wide range of criteria in a quantifiable and auditable manner, the problem of defining the level of sustainability of each individual option still remains. This is primarily due to limitations in the current state of knowledge whereby an absolute target value of sustainability for a given set of criteria within a given situation is very difficult to determine. Therefore it might be unclear how the results of the analysis should be interpreted particularly if stakeholder groups hold trenchant views regarding the priority weighting of individual indicators. The MCA cannot show that an action adds more environmental improvement than it detracts, thus the "best" option need not be consistent with improvement, so the "do-nothing" or conventional drainage option could still in principle be preferable. It is clear that the increasing complexity and competitiveness of environmental decision-making renders decision support a difficult exercise. Despite the popularity of DSS approaches, the ultimate success of DSS development is still uncertain and can undoubtedly be unsuccessful when applied to unstructured problems having a variable quality "data warehouse".

References

Ashley, R M., Smith, H., Jowitt, P W., Butler, D., Blackwood, D J., Davies, J W., Gilmour, D J and Foxon, T. 2001. A multi-criteria analysis/risk management tool to assess the relative sustainability of water/wastewater systems: SWARD (Sustainable Water Industry Asset Resource Decisions). In Pratt, C J., Davies, J W and Perry, J L (Eds): *Proc. 1st National Conference Sustainable Drainage*. 221 – 231, Coventry University, Coventry.

Ashley, R. M., Blanksby, J., Newman, R., Gersonius, B., Poole, A., Lindley, G., Smith, G., Ogden, S and Nowell, R. 2011. Learning and action alliances to build capacity for flood resilience. *Journ. Flood Risk Mangt.*, (In Press).

Ellis, J.B., Scholes, L and Revitt, D.M. 2004a. The development of a multi-criteria analysis for the evaluation of urban surface drainage options. 70 – 75 in Walters, G., Savic, D., Khu, S-T and King, R (Edits): *Decision Support in the Water Industry Under Conditions of Uncertainty*. Proc. Research Network Seminar ACTUAI2004, Centre for Water Systems, University of Exter, Exeter. UK. ISBN 0953914011.

Ellis, J B., Deutsch, J-C., Mouchel, J-M, Scholes, L and Revitt, D M. 2004b. Multi-criteria decision approaches to support sustainable drainage options for the treatment of highway and urban runoff. *Science of the Total Environment*, **334/335**, 251 – 260.

Ellis, J.B., Revitt, D.M and Scholes, L. 2008. The DayWater multi-criteria comparator. Cht.9, 87 – 96 in Thevenot, D (Edit): DayWater; *An Adaptive Decision Support System for Urban Stormwater Management*. IWA Publishing Ltd., London, UK. ISBN 1843391600.

Pitt, M. 2008. *Lessons From the 2007 Floods.* The Cabinet Office, London, UK.

Scholes, L., Revitt, D.M and Ellis, J.B. 2005. Predicting the pollutant removal potentials of sustainable drainage systems. 199 – 210 in Newman, A.P., Pratt, C.J and Blakeman, J.M. (Edits): *Proc 3rd National Conf. Sustainable Drainage*. University of Coventry, Coventry, UK. ISBN 1846000076).

Scholes, L., Revitt, D.M and Ellis, J.B. 2008a. A systematic approach for the comparative assessment of stormwater removal potentials. *Journ. Envir. Mangt.*, 88(3), 467 – 478.

Revitt, D.M., Scholes, L and Ellis, J.B. 2008b. Assessment criteria for sustainable urban driange systems. Cht.7, 65 – 78 in Thevenot, D (Edit): DayWater; *An Adaptive Decision Support System for Urban Stormwater Management*. IWA Publishing Ltd., London, UK. ISBN 1843391600.

Salminen, P., Hokkanen, J and Lahdelma, R. 1998. Comparing multi-criteria methods in the context of environmental problems. *European Journal of Operational Research*, **104**, 485 – 496.

Viavattene, C and Ellis, J.B. 2011. *Proc. The Future of Urban Water: Solutions for Livable and Resilient Cities*. January 2011. SWITCH Conference, UNESCO, Paris.

Viavattene, C., Scholes, L., Revitt, D.M and Ellis, J.B. 2008. A GIS- based decision support system for the implementation of stormwater best management practices. 1 – 9. *Proc. 11th Int. Conf, Urban Drainage (ICUD11)*. August 2008. Edinburgh, Scotland. CD ROM, IWA Publishing Ltd., London, UK. ISBN 978 1899796 212