Decision support tools for sustainable urban drainage systems: a systematic quantitative review

Des outils d'aide à la décision pour planifier des systèmes d'assainissement durables : une revue quantitative systématique

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RÉSUMÉ

Au cours des dernières décennies, une approche holistique a été développée pour la planification des systèmes de gestion des eaux urbaines. La prise en compte des concepts de durabilité a permis d'élargir les services rendus par les systèmes de gestion des eaux, qui excèdent aujourd'hui l'objectif traditionnel unique de contrôle des inondations urbaines (Scholz, 2014). Cette approche multi-objectifs a considérablement augmenté la complexité des réseaux : il existe aujourd'hui de nombreuses solutions pour un même problème de gestion des eaux urbaines (Rijsberman & Van De Ven, 2000). Plusieurs outils d'aide à la décision ont été développés pour aider les décideurs à planifier de manière durable les infrastructures de gestion des eaux urbaines, notamment pour définir l'emplacement, le type et les dimensions des techniques alternatives. Il existe de nombreuses approches d'aide à la décision; des matrices multi-critères aux algorithmes d'optimisation. Cet article propose un état de l'art et une analyse quantitative des méthodes d'aide à la décision pour planifier l'aménagement des techniques alternatives. Les résultats préliminaires (incluant les données de 52 documents) ont montré que la recherche dans ce sujet a été principalement effectuée en Amérique du Nord et en Europe. La majorité des outils vise à identifier la technique alternative la plus appropriée dans le contexte local. Bien que plusieurs critères soient souvent pris en compte, les objectifs en termes de quantité (volume d'écoulement) prévalent sur les objectifs de qualité d'écoulement, esthétiques, sociaux, de santé publique et de résilience. La revue a également révélé des manques de connaissance : seulement 5% des documents passés en revue prennent en compte le changement climatique et l'augmentation des surfaces imperméabilisées due aux effets de l'urbanisation.

ABSTRACT

During the last decades a holistic approach has been proposed for the design of urban drainage systems. The involvement of sustainability concepts has widened the possibilities in terms of obtaining simultaneous benefits that exceeds the sole objective of control of urban flooding (Scholz, 2014). This multi-objective approach became a high complexity issue: there exists multiple solutions to the same urban drainage problem (Rijsberman & Van De Ven, 2000). Decision support tools have been developed to help decision makers planning and operating Sustainable Urban Drainage Systems (SUDS) to decide location, suitable typologies and preliminar dimensions among others. There are multiple types of support decision tools, from multi-criteria matrices to optimization algorithms. The systematic review presented in this paper aims to understand and quantitatively summarize the state-of-the-art of the decision support systems applied to SUDS. A well-stated methodology is used to limit bias in the review. The preliminary results, which include information from 52 scientific articles, showed that research in this topic comes mainly from North America and Europe; most of the tools assist in answering the question "*Which* typology of SUDS should be implemented?". Although additional criteria are taken into account, the quantity component (in terms of volume of runoff) still prevails over runoff quality, landscape, social, human health, resilience and ecosystemic services components. The review revealed a gap in knowledge: only 5% of the reviewed papers considers the change in future hydrologic regime because of the combined effect of climate change and the increase of impervious area due to urbanization.

KEYWORDS

Best Management Practices, Decision Making, Low Impact Development (LID), Support Tools, Sustainable Urban Drainage Systems (SUDS)

1 INTRODUCTION

The sustainability concept (e.g. Council US Water Resources, 1973) has been gradually introduced during the last four decades. The later has progressively changed the approach from maximizing economic benefits at any cost, to the implementation of additional noneconomic objectives that considers future generations and a balanced distribution of costs and benefits (Simonovic, 1996). The migration from the concept of designing urban drainage systems with the sole objective of controlling floods, to more sustainable systems that mimic pre-urbanization hydrologic regime, have opened the possibilities to obtain additional simultaneous benefits such as social, cultural, and recreational (e.g. Scholz, 2014).

The new holistic approach for conceiving SUDS has widened the possibilities in designing urban drainage systems. Nowadays, there are multiple typologies that emerged in last decades, grouped under terms such as Sustainable Urban Drainage Systems (SUDS), Low Impact Development (LID) and Stormwater Best Management Practices (BMPs), among others (see Fletcher et al., 2014). These installations, besides managing stormwater, have additional functionalities that bring side benefits such as attractive ecosystem, provision of water resources and green spaces for tree planting.

Additionally, there is a large number of people from several backgrounds -engineers, water utility officials, stakeholders, land-user planners, politicians- that are involved in the decision making process (Makropoulos et al., 2006). Because of the multi-objective nature of the planning process of urban drainage systems, there are various sustainable solutions to the same problem (Rijsberman & Van De Ven, 2000). The large number of objectives, in additional with a large number of variables and criteria, transformed the decision making process into a highly complex problem. Support tools that identify an optimal solution arise from the need of evaluating multiple combinations of typologies, geographical configurations, dimensions, and SUDS train designs.

The subject of decision support systems for planning SUDS has been addressed since the 1980's decade (Mays & Bedient, 1982). From then, a variety of methodologies have been proposed: from matrix-based tools using criteria that evaluates the suitability of a typology in specific cases (e.g. Scholz, 2006 and Scholz, 2007) to much complex optimization techniques, such as scatter search and other meta-heuristic search techniques (e.g. Lee et al., 2012).

Recent review papers focused on the classification of decision making tools for SUDS planning, focusing on specific aspects such as water quality impact (Blumensaat & Staufer, 2012), cost-benefit relations (Jayasooriya & Ng, 2014) and sustainability (Zhou, 2014). Lerer *et. al.* (2015) classified the tools in terms of the questions they can assist in answering; they identified three groups: "*How Much*"-tools, "*Where*"-tools and "*Which*"-tools. Their papers were used as input to the systematic review conducted in this study, whose aim is to understand and quantitatively summarize the state-of-the-art of SUDS decision support tools.

2 METHODS

A systematic quantitative literature review is a valuable methodology to locate, appraise and synthetize evidence of a specific issue; it helps limiting bias in the review of literature, by deciding specific criteria to include and exclude studies (Petticrew, 2001). This methodology have been widely used in medicine and social sciences (e.g. Petticrew & Roberts, 2006), but it is applicable to any area of knowledge (Petticrew, 2001). The methodology allows to quantitatively appraise methods and results obtained and to identify a gap in knowledge, as well as to assess the geographical spread of literature (CDR, 2009).

The review question addressed in this study is *"How are support tools for decision making regarding SUDS being conceived?"* The objectives are: (i) Understand which methodologies are being/were used, (ii) Determine whether future scenarios are evaluated, and (iii) Understand which level of detail is reached by these studies (e.g. What? Where? Design of typologies?).

2.1 Literature search

Specific electronic databases were searched for original peered-review papers published in English language. The literature review was done using three methodologies: (i) searching in a limited list of electronic databases: Scopus, Science Direct, ProQuest, ASCE (American Society of Civil Engineering), ICE (Institution of Civil Engineering), IWA, Sage, Taylor and Francis, Google Scholar and Google; (ii) by citation searching, which involves the selection of key papers already identified and included in the review and then searching for articles that have cited these papers and (iii) handsearching key journals, by scanning the content of specific volumes and issues relevant for the study area.

The following search terms were used in each database: *'urban water management', 'decision support tool/systems', 'urban water resilience', 'urban drainage management decisions', 'planning and design urban drainage', 'SUDS location decision', 'green infrastructure (GI) for stormwater management decision', 'water sensitive urban design (WSUD)', 'low impact development for stormwater management' and 'BMP for stormwater management'*. The inclusion/exclusion criteria of the search were (i) the paper must be useful for decision making, (ii) the paper must be specific for stormwater (although other urban water cycle elements may be present), (iii) the paper must be a tool or guidance document (e.g. decision tree, matrix, model), not a framework, review or experience report, specific for a single case study whose results cannot be extrapolated.

All papers that may be useful for answering the review question and that fulfill the inclusion/exclusion criteria were collected. If after reading the whole paper, the review question is not answered or/and the inclusion criteria are not fulfilled, the paper was excluded from the review.

2.2 Data extraction

Once the papers that fully meeting the inclusion criteria were selected, the following data were extracted from each document: i) Author, (ii) Journal, (iii) Year of publication, (iv) Study location (city, state, country, continent), (v) Future scenarios component (climate/urbanization), (vi) Methodology, (vii) Scale (for example typology, city, catchment or residential block), (viii) Question the tool assist in answering (Which?, Where?, dimensions?) and (ix) Analysis dimension (quantity, quality, urbanism, landscaping and human health).

3 RESULTS

The systematic review proposed in this work is still under development. The results presented in this section are partial results obtained during two-months of literature search and data extraction. A total of 84 papers were collected from the literature review, using the three search methodologies mentioned in section 2.1. However, only 52 of them fulfilled the inclusion criteria. From these 52 papers, the data (i) Author, (ii) Journal, and (iii) Year of publication was easily extracted. A careful reading was developed for 21 from these 52 papers (randomly selected). The additional information required in the data extraction was gathered (this is, from iv to ix points mentioned in section 2.2).

This initial analysis showed variability among tools and techniques used for the decision making process. Methodologies can be classified in two differentiated categories: (i) topographic and hydraulic parameters evaluation and selection of SUDS based on suitability to site specific characteristics (e.g. Zhen, Yu, & Lin, 2004) and, (ii) pre-selection of SUDS alternatives and posterior evaluation of suitability and selection (e.g. Scholz, 2007). Tools included GIS-based models (e.g. Makropoulos et al., 2006) , Excel spreadsheets, Matlab and Simulink (e.g. Makropoulos *et.al.* , 2008), optimization search algorithms (e.g. Lee et al., 2012), fuzzy sets and multi-criteria evaluation (e.g. Makropoulos, Butler, & Maksimovik, 1999) among others. This variability is explained by the different tool users needs, as they are developed for specific sites and tackled diverse objectives.

The conservative division of seven continents was used to report the sites where the tools have been applied: North America (United States, the Caribbean Islands, Central America and the Canada), South America, Africa, Europe, Asia, Australia (including New Zealand, Papua New Guinea, Fiji, Solomons, Micronesia, Melanesia and Polynesia, and South Pacific islands), and Antarctica. *Figure 1* shows that the majority of the papers gathered was developed and applied for Europe and North America. Only one paper was obtained for Asia (reported in China) and one in South America (reported in Brazil), any paper was found in Africa.

Figure 2 shows the percentage of papers included in the review per year. According to these preliminary results, papers production of decision support tools for SUDS planning started in 1982, and the number of publications have progressively increased, with 2013 being the more productive year in terms of papers published. The papers included so far in the review belong to 29 journals; *Table 1* resumes the most frequent journals used in this review.

Another interesting result was that 43% of the decision support tools under study are designed to address issues at watershed scale, other frequent scales where residential areas (10%), neighbourhood (10%) and households (10%). The 95% of the reviewed papers did not include any future scenarios component: they do not consider growing population nor climate change effect. Also, 67% of the decision support tools answer the question *"Which?",* which aim at defining the SUDS typology more suitable for the specific case study. The 50% answer the question "*Where?",* these support tools help decision makers to implement SUDS in the optimal location. Other decision support tools assist in answering the question "*Which scenario?"* (the user defines a SUDS configuration and the tool determine which is the optimal), "*How many"* (the user establish the typology and the tool determines how many and where should be placed in the study area, and *"Dimensions",* in this case, the tool not only determine which typology but also gives the optimal dimension of such typology.

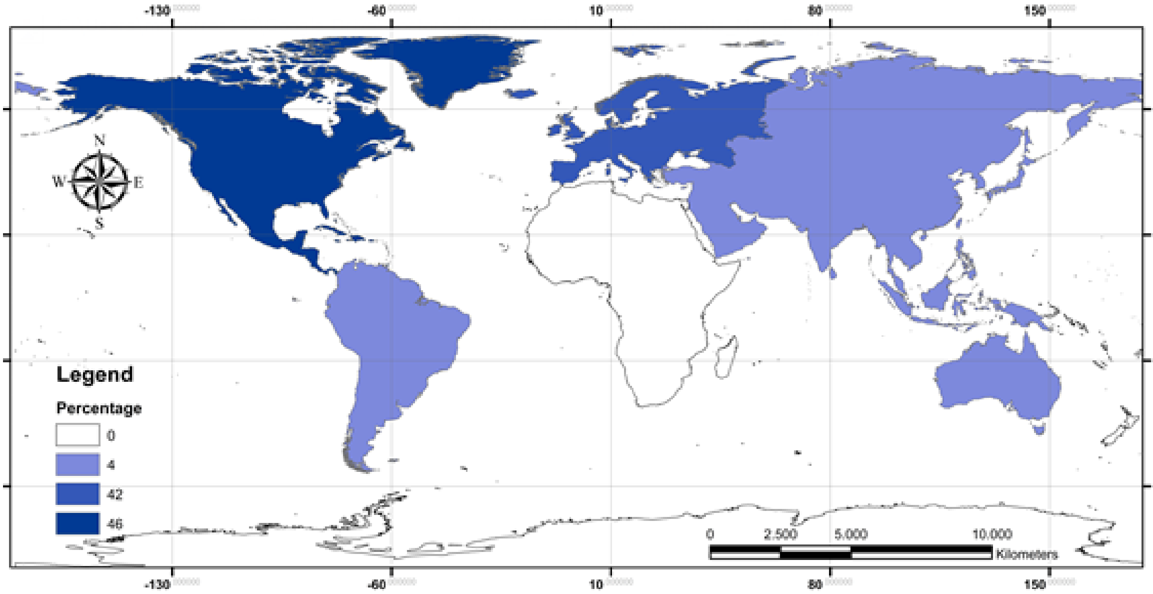

Figure 1. Geographical spread of literature reviewed regarding SUDS decision support tools

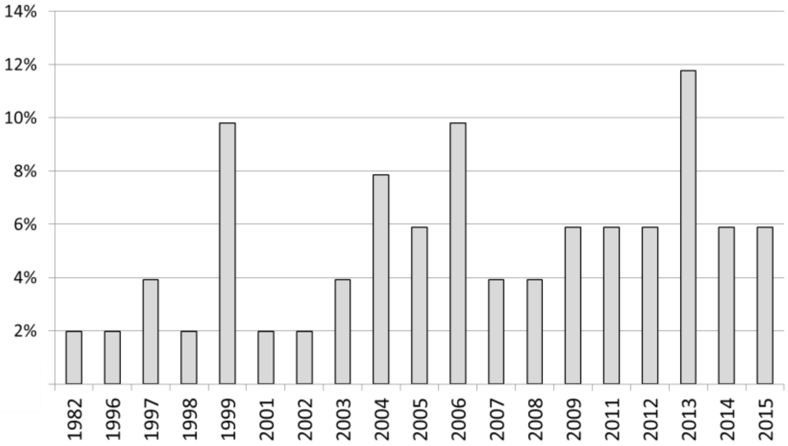

Figure 2. Percentage of papers included in the review per year

Table 1. Most frequent journals containing papers found in the review

Journal	Percentage
Water Science and Technology	14%
Journal of Water Resources Planning and Management	12%
Water Resources Research	8%
Environmental Modelling and Software	6%
Journal of Environmental Management	6%
Science of the Total Environment	6%
Computers, Environment and Urban Systems	4%
Water Science Technology	4%

All the papers analysed took into consideration the *quantity* component as part of the decision making process, showing that the runoff volume is still the main concern in urban drainage systems. However new criteria are being incorporated: *Runoff quality* was found in 28% of the decision support tools described in the analysed papers. Other criteria, such *ecosystemic services* (17%), *human health* (6%), *resilience* (11%), *landscape* (6%) and *social aspects* (6%) were also included in the reviewed papers.

4 DISCUSSION

Preliminary results have shown a great variability in the decision support tools developed worldwide. Different methodologies and tools have been developed for specific case of studies regarding diverse topographic, social, among other, issues. The review showed that there is a concentration of research in North America and Europe, while the other continents count on one or none papers. The review also showed that papers production in this topic started in 1982 and have been increasing since that year and that most papers have been published in water specific journals such as *Water Science and Technology* and *Journal of Water Resources Planning and Management.* Moreover, the 67% of the tools assist to answer the question *"Which?",* and the 50% assist the question *"Where?"*

Despite of the variability regarding decision support tools and taking into account the growing interest in climate change and urbanization effects on urban water cycle, only the 5% of the reviewed papers included the component of future scenarios. This evidences that the tools are being developed for decision making processes under present conditions only and that do not consider long term changes. This can be considered an important limitation, because it ignores the fact that runoff volume will not remain unaltered: urbanization will increase impervious areas and climate change will lead to extreme precipitation events. This finding may be pointing a gap in knowledge: incorporate climate change and urbanization concepts in the decision tools design. Including this important component, the decision tools will be capable of assisting the design of SUDS that are resilient to future extreme events.

It is difficult to suggest which is the most complete decision support tool, nor what characteristics should it have. It is evident that the majority of the tools have a good performance when they are evaluated for the case of study for which it was developed. However, when the tool is used in a new and considerable different scenario, difficulties start appearing (e.g. gathering particular information, validity of basic assumptions and restrictions, different urban policies or social aspects). When this happens, another case-specific tool is demanded. Based on this fact, we consider that the most valuable characteristic of a decision support tool should be its applicability to diverse cases. Similarly, the tool should be capable of simultaneously handling different (main) objectives. We consider flexibility characteristic the most important in appraising a decision support tool. A flexible decision support tool should be useful in a general context, i.e., applicable to different scenarios. Another important characteristic of a good decision tool would be of being capable of evaluating all possible outcomes, including that of combining SUDS with conventional sewer system, or even recognizing that SUDS are not the best option at all.

In the specific case of urban areas in developing countries, which is where there is a larger knowledge gap regarding decision support tools, especial considerations should be mentioned. In the first place, there is an accelerated dynamic of urban changes and an unequal distribution of welfare. Also, the population in urban centres of fast developing cities is growing at a high rate, as well as construction and creation of impervious areas (at the beginning with some lack of planning). This considerable high rates of change can be seen as (i) a challenge because of uncertainty in changes of impervious area and urban hydrology, but also (ii) a good opportunity to introduce SUDS in the design of new urban spaces (or in urban renewal plans).

SUDS in developing cities should be designed in order to increase green public areas (which are proxy of welfare), especially in those places where there is a bigger lack of green areas. SUDS should be implemented strongly based on social inclusion, allowing people to integrate with and appropriate the project. Taking into account that SUDS maintenance is difficult, dealing with social pressures is a principal concern; consequently, the problem should be tackled before investment. Under these considerations it will be possible to design a decision support tool for developing countries' primary objectives regarding urban drainage: (i) minimise urban flood frequency and (ii) improve water runoff quality.

5 CONCLUSIONS

The methodology for a systematic quantitative review of decision support tools regarding SUDS was established. Such methodology is being used in order to appraise the methods and tools used worldwide. The geographical spread of the literature have been assessed, pointing that research production is concentrated in two continents while the others have a low research production in the topic. Preliminary results showed an incremental on peered-review production since 1980's and revealed that most publications are done in some specific journals. Also, it was stated that the majority of the included papers answer the question "*Which?*", and that the *quantity* criteria was analysed in the totality of the papers, pointing to the fact that the main concern of the decision support tools is still the runoff volume. The review, so far, have revealed a knowledge gap, which is the implementation of climate change and urbanization effect in the design of support tools. Involving this component will assist the design of resilient SUDS.

However, it is noteworthy to recall that the results obtained so far may be modified as further literature is included in the review. Also, it must be considered that the data extraction process of the included papers is not complete. At the present time, authors are extracting information for already incorporated papers and simultaneously enlarging the list of papers under study.

LIST OF REFERENCES

Blumensaat, F., & Staufer, P. (2012). Water quality-based assessment of urban drainage impacts in Europe-where do we stand today? Water Science & Technology. 2012, 66,304-313

Centre for reviews & dissemination (CRD). (2009). Systematic reviews: CRD's guidance for undertaking reviews in health care. Centre for Reviews and Dissemination

Council, US Water Resources (1973). Water and Related Land Resources: Establishment of Principles and Standards for Planning. Federal Register, 36.

Fletcher, T. D., Shuster, W., Hunt, W. F., Ashley, R., Butler, D., Arthur, S., … Viklander, M. (2014). SUDS, LID, BMPs, WSUD and more – The evolution and application of terminology surrounding urban drainage. Urban Water Journal, 9006(September), 1–18.

Jayasooriya, V. M., & Ng, A. W. M. (2014). *Tools for Modeling of Stormwater Management and Economics of Green Infrastructure Practices: a Review.* Water, Air, & Soil Pollution, 225(8), 2055.

Lee, J. G., Selvakumar, A., Alvi, K., Riverson, J., Zhen, J. X., Shoemaker, L., & Lai, F. (2012). *A watershed-scale design optimization model for stormwater best management practices.* Environmental Modelling & Software, 37, 6–18.

Lerer, S. M., Arnbjerg-Nielsen, K., & Mikkelsen, P. S. (2015). *A Mapping of Tools for Informing Water Sensitive Urban Design Planning Decisions—Questions, Aspects and Context Sensitivity.* Water, 7(3), 993-1012.

Makropoulos, C., Butler, D., & Maksimovic, C. (1999). *GIS supported evaluation of source control applicability in urban areas*. Water Science and Technology, 39(9), 243–252.

Makropoulos, C. K., Morley, M., Memon, F. A., Butler, D., Savic, D., & Ashley, R. a. (2006). *A decision support framework for sustainable urban water planning and management in new urban areas.* Water Science and Technology, 54(6-7), 451–458

Makropoulos, C. K., Natsis, K., Liu, S., Mittas, K., & Butler, D. (2008). Decision support for sustainable option *selection in integrated urban water management.* Environmental Modelling & Software, 23(12), 1448–1460.

Mays, L. W., & Bedient, P. B. (1982). Model for optimal size and location of detention. Journal of the Water Resources Planning and Management Division,108 (3), 270-285.

Petticrew, M. (2001). *Systematic reviews from astronomy to zoology: myths and misconceptions.* BMJ (Clinical Research (Ed.), 322(7278), 98–101.

Petticrew, M., & Roberts, H. (2006). Systematic reviews in the social sciences: A practical guide. Malden, MA: Blackwell.

Rijsberman, M. a., & Van De Ven, F. H. M. (2000). D*ifferent approaches to assessment of design and management of sustainable urban water systems.* Environmental Impact Assessment Review, 20(3), 333–345.

Scholz, M. (2006). *Best Management Practice: A Sustainable Urban Drainage System Management Case Study.* International Water Resources Association, 31(3), 310–319. Scholz, M. (2007). Development of a practical best management practice decision support model for engineers and planners in Nordic countries. Nordic Hydrology, 1–17.

Miklas Scholz (2014) *Rapid assessment system based on ecosystem services for retrofitting of sustainable drainage systems,* Environmental Technology, 35(10),1286-1295,

Simonovic, S. I. (1996). *Decision support systems for sustainable Management of Water Resoures: General*

Principles. Water International, 21(4), 223-232

Zhen, X.-Y. “Jenny,” Yu, S. L., & Lin, J.-Y. (2004). *Optimal Location and Sizing of Stormwater Basins at Watershed Scale.* Journal of Water Resources Planning and Management, 130(4), 339–347.

Zhou, Q. (2014). *A review of sustainable urban drainage systems considering the climate change and urbanization impacts.* Water, 6(4), 976-992