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A model-based framework for selection and development of multi-functional and adaptive strategies to cope with urban floods

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Abstract

The main drivers increasing pressure on urban drainage infrastructure, are climate change and population growth. Changes in rainfall characteristics and increment of urbanization are consequences of these factors, which can affect directly the level of flood risk. Furthermore, the combined effect of these two drivers and the tendency followed by them suggest an important increment of future flood risk, in particular in urban coastal areas. Traditional approaches for decision making when selecting measures to cope with floods focus on local characteristics, and offer strategies with low flexibility for adaptation to the uncertain future. Moreover, the use of sustainable or non-traditional drainage measures, also called sustainable drainage systems (SuDS), have been increasingly suggested in the last years mainly due to the multiple benefits that they offer to the environment. In this work a framework for selection and development of drainage strategies is presented. This framework combines multi-criteria analysis, multiple benefits assessment, hydrodynamic models, multi-objective optimisation tools, flexibility concepts and multi-functionality evaluation to achieve multi-functional and adaptive drainage strategies for the urban space. The proposed methodology is seen as a useful approach for helping decision making processes which aim to reduce urban flood risk, while at the same time allow the improvement of other environmental aspects.

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Keywords: Urban drainage systems, adaptation, sustainable drainage systems, hydrodynamic models, multi-objective optimisation.

1. Introduction

The main drivers affecting the performance of conventional drainage systems, and as a consequence the level of present and future flood risk, are climate change impacts on rainfall characteristics, and population growth with the associated changes in land use and urbanisation [1,2]. The combined effect of these two drivers and the tendency followed for them suggest an important increment of future flood risk, in particular in urban coastal areas. As a consequence of climate change, climate conditions worldwide seem likely to change, greater number of heat waves, increment of heavy precipitations, more intense droughts and higher coastal water levels are expected in many regions around the globe [3]. In addition, according to United Nations [4] continued population growth until

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2050 is almost inevitable. Moreover, all regions of the world are expected to urbanize further over the coming decades. Therefore, as the world continues to urbanize, sustainable development challenges will be increasingly concentrated in cities [5].

The impact severity of climate extremes depends strongly on the level of the exposure and vulnerability to them. Consequently, vulnerability reduction is a central element of adaptation and disaster risk management. Adaptation to climate extremes in the long term is facilitated if social welfare, quality of life, infrastructure, livelihoods, and the incorporation of a multi-hazards approach are included into planning for disasters in the short term [3].

Sustainable planning and development is a relatively new area with a wide knowledge gap in design and implementation of solutions, in order to solve this, the constraints and impediments need to be locally identified. Moreover, for developing an efficient planning and design framework for sustainable urban drainage systems it is needed an interdisciplinary approach, including stakeholders in addition to decision makers [1].

The present work combines several concepts in order to develop a methodology which helps in decision making processes oriented to select, plan, locate, design and implement sustainable strategies for coping with floods in urban areas. The study is developed within the PEARL project (Preparing for Extreme And Rare events in coastaL regions, funded by the Seventh Framework Programme for Research and Technological Development FP7, of the European Union) [6].

2. Background

2.1. The development of strategies to cope with urban floods

Many of the strategies to cope with climate extremes produce co-benefits, for instance helping the achievement of other development goals, such as improvements in livelihoods, human well-being, and biodiversity conservation. While traditional pipe and storage based approaches count on enough technical support and tools for decision making, the sustainable approach or non-traditional measures for stormwater management, lacks sufficient supporting technical references and software tools. In particular, this support is lacking regarding the evaluation of additional benefits and long-term performances [3, 7].

The creation of urban resilience to extreme events is based in an integrated and interdisciplinary approach that needs more research, in particular to identify how to combine different measures. Even if several tools exist for planning blue / green infrastructure in order to reduce city's vulnerability, few of them are aligned with urban planning processes that allow to organise the retrofitting of the urban space, as well as the evaluation of possible solutions performance [8]. Moreover, in order to develop effective adaptation strategies for current and future scenarios, considering the potential co-benefits that can be reached through them, it is important to analyse and understand the possible measures applicable in each context. Regarding this, the measures have to be evaluated under different conditions, analysing their applicability for different contexts and their potential to achieve multiple benefits related with other ecosystem services and urban well-being, including the enhancement of benefits on urban ecology, energy use, landscape and socio-economic systems. As a consequence of its multi-functionality, these measures can help to reduce the fragmentation of flood management, and to improve collaboration among relevant management agencies [2,9].

2.2. Decision making processes in front of multiple objectives and future uncertainty

The impacts of climate change and urbanisation on drainage systems are still uncertain. For instance, until now it is not well known how the pervious/impervious ratio, retention/detention storage reduction and rainfall increase due to urban heat island effect, and their complex combination, are impacting the performance of these systems. In front of this reality, seems adequate to focus on revising the design process looking for more integrated planning and place based design frameworks that can help decision makers. These methods should include flexible adaptation options to cope with an uncertain future, and local applicability analysis [1,10].

Conforming to Price and Vojinovic [11], decision making processes related to urban drainage systems usually comprise several objectives which are often contradictory among themselves. Is in these cases when multi objective optimisation methods are useful. The result when applying these techniques includes many possible solution. Multi-objective optimisation is the process of searching the best possible solutions considering different objectives (represented by objective functions), in a defined domain and under defined constraints. In the case of a multi-objective optimisation process with contradictory objectives, the improvement of one objective will compromise the achievement of another one. As a consequence, the result is a set of compromised optimal solutions visualized through Pareto fronts [12–15]. The representation of optimal solutions through Pareto plots is a very useful tool for decision making processes, in particular regarding urban drainage solutions. This is seen as an advantage over single objective optimisation techniques [16,17]. However, more research is necessary to apply this technique for the development of flexible and adaptable flood risk strategies [18]. The reason for this is that drainage infrastructure has long term service life and its modification is costly, this combined with the change of external drivers as climate change, generates high uncertainty related with decisions for investments. Hence, the planning for modification of these systems should allow to design for and build in flexibility, in which systems are able to learn and adapt to a changing context [10,18].

2.3. The multiple benefits approach

Urban environments are defined as the intersection of the natural environment, the built environment and the socio-economic environment. In order to achieve effective urban environmental management, it is needed to manage these three aspects, but also it is required to understand their interdependencies and linkages. Specifically, for a climate adaptation plan to be successful it has to address social, economic and spatial factors. For instance, greening urban spaces has a positive effects on the human physical and psychological health, as well as positive effects by conserving biodiversity, fighting microclimate effects, improving air quality, offering public education opportunities, and making the city more attractive. These are ecosystem services that offer multiple benefits and are critical for planning and designing sustainable cities [19–21].

The multiple benefits approach also allows a better communication about the need of environmental outcomes, in this regard a valuable way for dialogue is obtained through the approach of ecosystem services. Furthermore, the consideration of societal benefits may help to engage broader sectors of society in the discussion about possible solutions, considering the advantages of ‘win–win’ solutions. Because ecosystem services are related to the benefits that people obtain from ecosystems, this approach can be evaluated from a monetised point of view [22]. This is important considering that one of the most important barriers for decision making processes regarding innovation, is the perception of investment risk from the stakeholders involved. Therefore, consideration of costs and benefits in the decision process, including flexibility and resilience, allows a complete evaluation that can avoid this issue [23].

Benefits are the positive impacts, including the capacity to avoid damages when an option is implemented. These benefits can be grouped in direct economic value, added aesthetic and amenity value, environmental or ecosystem value, and social benefits. Although the estimation of total benefits from applying SuDS is challenging, it is an important step for making SuDS financially attractive when comparing with traditional drainage systems [25, 26]. As a positive aspect, the contribution of these elements for natural capital (the direct provision of benefits or the enhancement of human well-being) and economic development is seen as particularly important, mainly in urban areas. However, there are not agreed methods for estimating the benefits of SuDS. Moreover, the amenity value commonly associated with vegetated SuDS measures, is still considered as of secondary importance when selecting SuDS [23]

A holistic approach to the use of water-related ecosystem services can have a synergic effect. These synergies between SuDS for stormwater management and other benefits have the capacity of saving costs while bringing multiple benefits to urban spaces, besides these solutions appear as cheaper in terms of one-off and maintenance costs than purely technical solutions. Therefore, is through the use of multifunctional landscape frameworks for sustainable planning of green infrastructures, that the functions of the urban green space can be optimised. Whereas this is commonly applied for agroecosystems, there are few examples for urban ecosystems [23,26–30].

3. A framework for the development of strategies to cope with urban floods

The main aim of this framework is to help in decision making processes for the development and selection of stormwater/flood management strategies, based on multi-objective, multi-functional and adaptive system concepts. The framework is divided in three phases:

- a procedure to select promising measures for coping with floods, taking into account local constraints and environmental aspects.
- The analysis of optimal and adaptive strategies combining hydrodynamic models and multi-objective optimisation, defining long-term adaptation pathways.
- a method for selecting among optimal measures and strategies, through the evaluation and integration of multiple benefits and multi-functional landscape development (considering location, implementation times and design of selected measures in the urban space).

Figure 1 present the whole process that needs to be followed for selecting, designing and implementing long term adaptation solutions for flooding. The first step in this process consists in the definition of the problem, to identify if risk assessment is needed or not. In cases where the problem is small and well known, to develop a complete flood risk evaluation could be avoided. However, in most of the cases where urban floods occur, it is required to understand the hazards and vulnerabilities related to the flood risk. This is the second stage, represented in the process as diagnostic study. Once the diagnostic is completed, the assessment of possible solutions begins. Is in this stage (solutions study) where the framework for strategies development presented in this work is applied, whit the three phases previously mentioned. Therefore, this framework cannot be isolated from the complete methodology for decision making, it has previous and later stages that need to be followed in order to develop effective strategies.

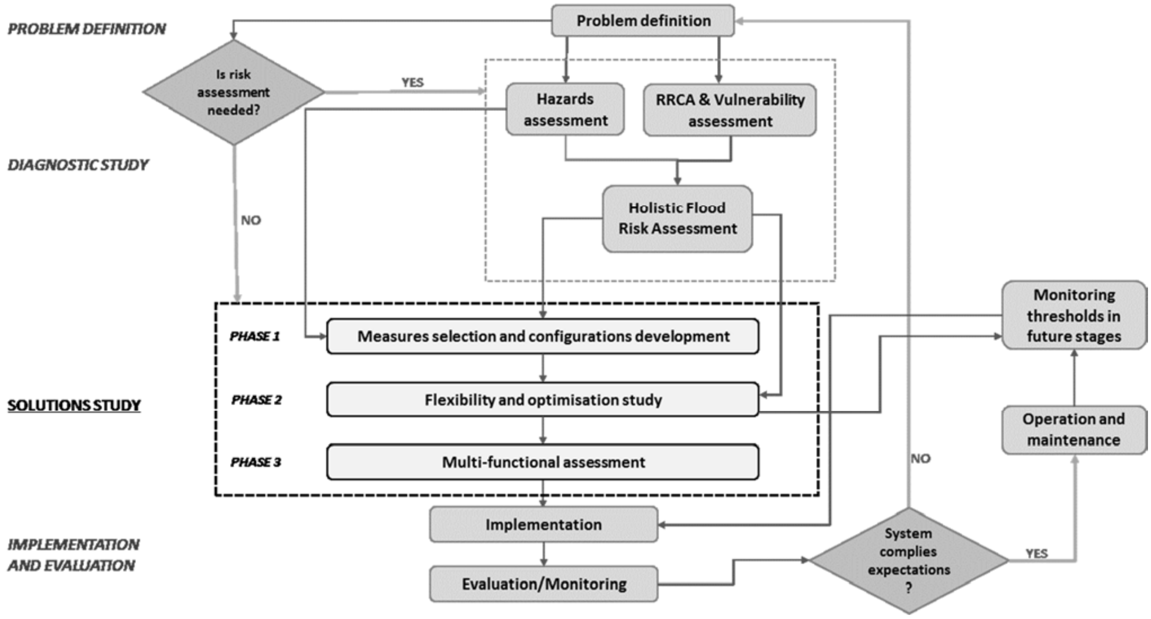

Fig. 1. The framework for strategies development (solutions study) inside the complete process for decision making.

Finally, the implementation stage begins. Continuous evaluation and monitoring processes are needed to identify possible failures of the system in accomplishing the expected benefits. If the designed and implemented system achieves the goals, continuous operation and maintenance plans are needed to preserve this condition. Also, threshold monitoring is needed to take into account the flexibility that was assumed during the design process. If the forecasted thresholds are not reached, future implementation plans have to be revised and adapted to the real circumstances.

3.1. Selection of measures considering local constraints and multiple benefits

The phase 1 of this framework includes the selection of measures among all the options listed in an extensive knowledge based being developed for PEARL project (link). This selection considers flood types as well as physical and environmental local characteristics. As can be seen in Table 1 the complete list of measures is classified into six different groups in relation to their main process or characteristic, in the table some examples are shown.

The first step in this phase consists in measures screening, the options that do not fulfil the requirements according to flood type and physical local constraints are discarded from the list. For instance, if the soil in the area is impervious, infiltration measures are most likely eliminated from the list of possible applicable measures.

The second step consists of ranking the remaining measures according to two factors. The first one analyses local space characteristics to look for the measures that better fit into the urban shape. The second one considers the benefits these measures provide, and which of them are identified as relevant for the area according to local preferences. Finally, in the last step the best options are combined to develop the best strategies. This combination is done considering different characteristics, for instance trying to integrate centralised and decentralised measures. Figure 2 shows the different steps followed for this procedure.

Table 1. Measures classification.

Classification	Measure
GREENING MEASURES	Green Roofs Green Walls / Facades /Green noise barriers City trees, parks, forest
BLUE MEASURES	Open water channels and rills Retention ponds / Buffering ponds Water / Blue Roofs
BUFFERING AND INFILTRATION MEASURES	Pervious Pavements Rain gardens / Bio-retention area Infiltration Trenches Wetland area
STORAGE MEASURES	Rainwater Harvesting / Rainwater tank Open detention basin / reservoir
(BUILDINGS) FLOOD PROOFING	Dry Flood Proofing (sealing, shielding) Elevation of Buildings / Stilt houses Amphibious Housing
TRADITIONAL MEASURES	Dikes / Walls / Tidal barriers / Levee Closed conduits / Pipes / Tubes Flood gates, walls

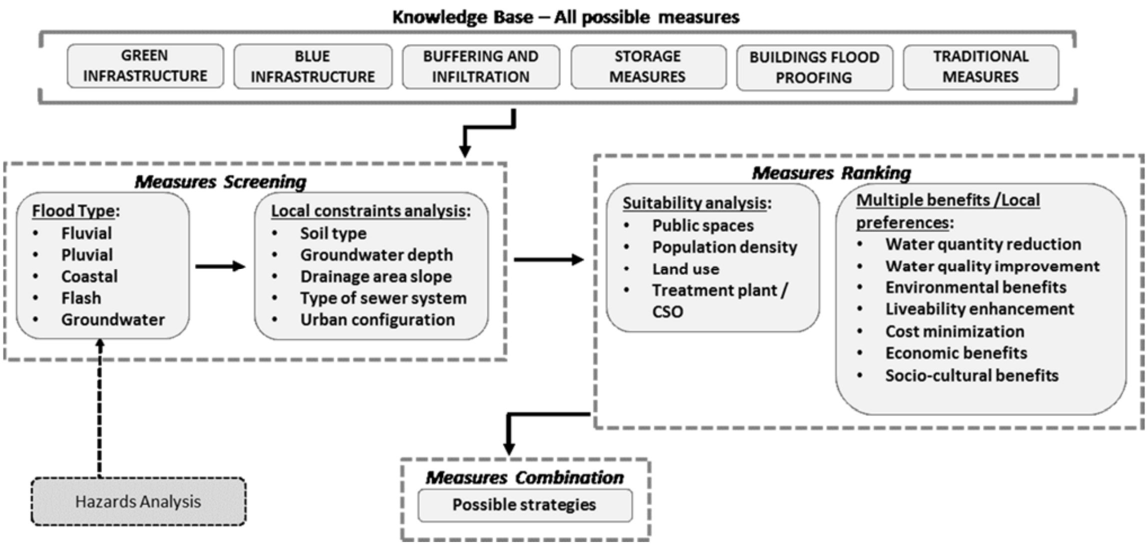

Fig. 2. Selection of measures considering local constraints and multiple benefits.

3.2. Linking optimal solutions with adaptive implementation pathways

The second phase combines hydrodynamic models with optimisation tools to compare among the previous defined strategies. In this stage, the minimisation of damage and minimisation of investment costs are considered, as well as the maximisation of quantifiable secondary benefits that can be obtained from applying SuDS. These benefits are the same already considered for ranking during Phase 1, but this time they are quantified and evaluated from an ecosystem services point of view. The comparison of Pareto fronts for each strategy is used to select the best configuration.

It is clear that SuDS provide added benefits than their primary water quantity and quality management functions, these benefits increase the societal value mainly in urban areas, through benefits on economic, environmental and social aspect [23]. The concept of ecosystem services is seen as attractive because it helps to understand the ways that humans are linked to, and depend on, nature. Ecosystem services have a significant impact on the quality-of-life in urban areas and should be addressed in land-use planning. But it is also challenging, because the connections between people and nature are in general complex [31, 32]. Considering these reasons and the fact that costs and benefits of traditional measures are well known, the attention in this work is focused on these extra benefits that can be achieved from non-traditional measures, and the link between these benefits and the services provided by ecosystems. To achieve this analysis, and in order to allow comparability, it is important to develop benefits measurements and reporting practices. In this regards the development of consistent and comparable socio-economic valuations of ecosystem services is crucial [32]. The present framework compares among different strategies considering, among other factors, the quantification of the benefits that can be obtained from sustainable measures.

Afterwards, adaptation and flexibility are studied with the objective of developing sustainable long term strategies. Figure 3 shows the main idea behind this concept. In the upper part of the figure the concept of adaptive pathways is represented. The strategy is defined considering stages in the implementation process, or implementation levels. Through the evaluation of certain thresholds along the time, it is defined which implementation level is necessary. This approach allows the reduction of uncertainty, about for instance the effects of climate change, through the consideration of flexible systems that can be adapted according to future scenarios. The lower part of Figure 3 shows the differentiation among the traditional robust or precautionary approach, and the adaptive approach applied in this work.

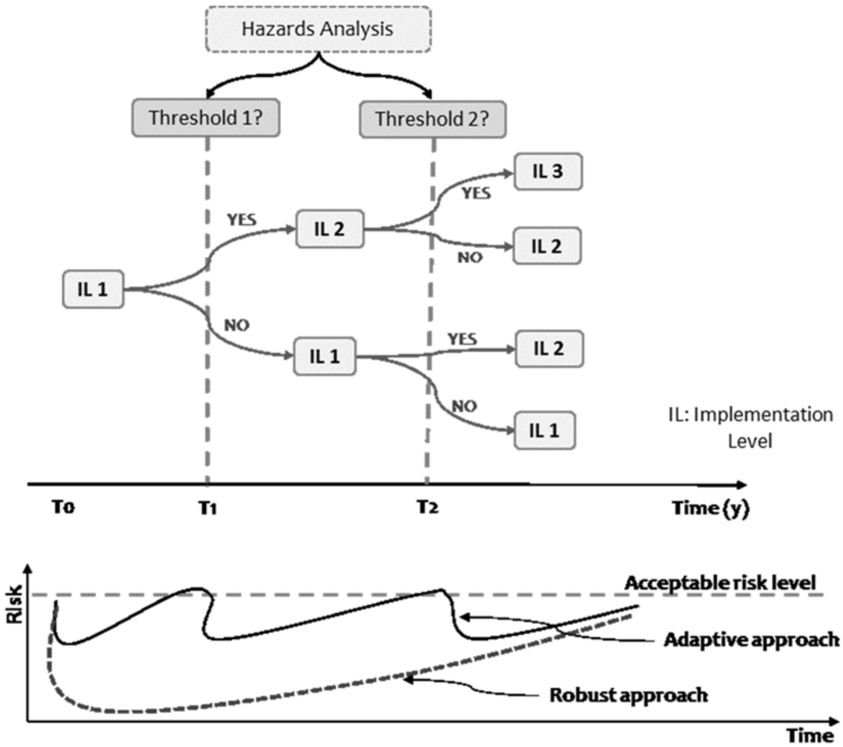

Fig. 3. Flexibility analysis, the adaptive approach (adapted from Gersonius et al. [33]).

3.3. Multi-functional assessment and the maximization of multiple benefits

In this phase several considerations are integrated to select among optimal solutions. Factors regarding sustainability, flexibility, level of risk and resilience are combined allowing a better comparison among optimal solutions. Case specific priorities are inputs to choose the best strategy.

Finally, the selected strategy is evaluated considering local aspects of the urban environment as well as multifunctional landscape design, to take the maximum advantage of the urban space. In this phase different local issues are identified in order to locate and design the measures trying to maximize possible benefits. As an example, spatial data about heat stress, sewerage and water supply issues, lack of public spaces, etc., can be combined with flood data to design measures that cope with more than one problem at the same time. With this approach more advantages than just the reduction of vulnerability to flood events can be achieved. These measures are conceived from a multifunctional point of view, adding value to various aspects of the urban environment.

4. Conclusions

The proposed framework aims to simultaneously reduce urban flood risk and improve other environmental aspects. This is achieved by integrating the assessment of SuDS benefits and the use of hydrodynamic models and multi-objective optimisation. Furthermore, it involves the development of novel methods to integrate flexibility and adaptation capacity to guide the decision makers in the selection of strategies for the maximisation of multi-functionality and infrastructure implementation in the urban landscape.

The framework consists of a three-step process. Firstly, the selection of measures considering local aspects for their applicability, as well as qualitative assessment of the possible added benefits obtained from them. This is considered as a fundamental first step in the process for selecting locally adjusted and sustainable strategies. In the second step flexibility and adaptation capacity are included into the design of infrastructures, along with the optimisation of solutions. This approach is fundamental; taking into account that uncertainty about future drivers is expected to increase [26].The final step recognises links between landscape and ecosystem characteristics, besides possible indicators to measure the capacity of ecosystems to provide services. Moreover, it is proposed to visualize and identify spatially ecosystems/landscapes functions and services, together with local environmental issues. From this, it is defined the last part of the methodology which allows the integration of local issues with SuDS multi-functionality in the urban space, through a spatial analysis approach oriented to get the maximum advantage of SuDS implementation.

Our next steps is to demonstrate the effectiveness of the proposed framework through its application on PEARL project case study sites. The results of such test will be presented in a journal paper in the near future. .

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References

[1] Z. Yazdanfar, A. Sharma, Urban drainage system planning and design – challenges with climate change and urbanization: a review, Water Sci. Technol. 72 (2015) 165. doi:10.2166/wst.2015.207.
[2] Z. Vojinovic, Floor Risk: The Holistic Perspective, IWA Publishing, 2015.
[3] IPCC, Managing the Risks of Extreme Events and Disasters To Advance Climate Change Adaptation, 2012. doi:10.1017/CBO9781139177245.
[4] United Nations, World Population Prospects, Key findings and advance tables., 2015.
[5] United Nations, World Urbanization Prospects, 2014.
[6] PEARL, PEARL (Preparign for Extrme And Rare events in costaL areas), Http//www.pearl-fp7.eu/about-Pearl/wp/ [Accessed Oct. 10, 2015]. (2014).
[7] J. -f. Chow, D. Savić, D. Fortune, Z. Kapelan, N. Mebrate, Using a Systematic, Multi-criteria Decision Support Framework to Evaluate Sustainable Drainage Designs, Procedia Eng. 70 (2014) 343–352. doi:10.1016/j.proeng.2014.02.039.
[8] I.M. Voskamp, F.H.M. Van de Ven, Planning support system for climate adaptation: Composing effective sets of blue-green measures to reduce urban vulnerability to extreme weather events, Build. Environ. 83 (2015) 159–167. doi:10.1016/j.buildenv.2014.07.018.
[9] L. Hoang, R. a. Fenner, System interactions of stormwater management using sustainable urban drainage systems and green infrastructure, Urban Water J. (2015) 1–20. doi:10.1080/1573062X.2015.1036083.
[10] B. Gersonius, R. Ashley, A. Pathirana, C. Zevenbergen, Climate change uncertainty: building flexibility into water and flood risk infrastructure, Clim. Change. 116 (2013) 411–423. doi:10.1007/s10584-012-0494-5.
[11] R.K. Price, Z. Vojinovic, Urban Hydroinformatics: Data, Models and Decision Support for Integrated Urban Water Management., 1st ed., IWA Publishing, London, 2011.
[12] Z. Vojinovic, D. Solomatine, R.K. Price, Dynamic least-cost optimisation of wastewater system remedial works requirements, Water Sci. Technol. 54 (2006) 467–475. doi:10.2166/wst.2006.574.
[13] W. Barreto, Z. Vojinovic, R. Price, D. Solomatine, Multiobjective Evolutionary Approach to Rehabilitation of Urban Drainage Systems, J. Water Resour. Plan. Manag. 136 (2010) 547–554. doi:10.1061/(ASCE)WR.1943-5452.0000070.
[14] S.B. Sahlu, Robust Optimization of urban drainage systems under uncertainties., UNESCO-IHE Institute for Water Education., 2012.
[15] K. Deb, A. Pratap, S. Agarwal, T. Meyarivan, A Fast and Elitist Multiobjective Genetic Algorithm: NSGA-II, IEEE Trans. Evol. Comput. 6 (2002) 182–197.
[16] S.W. Delelegn, A. Pathirana, B. Gersonius, A.G. Adeogun, K. Vairavamoorthy, Multi-Objective Optimization of Cost-Benefit of Urban Flood Management using a 1D2D Coupled Model, Water Sci. Technol. 63 (2011) 1054.
[17] Z. Vojinovic, S. Sahlu, A.S. Torres, S.D. Seyoum, F. Anvarifar, H. Matungulu, et al., Multi-objective rehabilitation of urban drainage systems under uncertainties, J. Hydroinformatics |. (2014) 1–18. doi:10.2166/hydro.2014.223.
[18] M. Woodward, B. Gouldby, Z. Kapelan, D. Hames, Multiobjective Optimization for Improved Management of Flood Risk, J. Water Resour. Plan. Manag. (2014) 201–215. doi:10.1061/(ASCE)WR.1943-5452.0000295.

[19] H. Srinivas, The Ecosystems Approach to Urban Environmental Management: Operationalizing the Cities as Sustainable Ecosystems(CASE) Initiative, 2003.
[20] L. Kleerekoper, M. van Esch, T.B. Salcedo, How to make a city climate-proof, addressing the urban heat island effect, Resour. Conserv. Recycl. 64 (2012) 30–38. doi:10.1016/j.resconrec.2011.06.004.
[21] European Commission, Green Infrastructure (GI) — Enhancing Europe's Natural Capital, 2013.
[22] M. Everard, Why does "good ecological status" matter?, Water Environ. J. 26 (2012) 165–174. doi:10.1111/j.1747-6593.2011.00273.x.
[23] CIRIA, Demonstrating the multiple benefits of SuDS - a business case, (2013) 45. http://www.susdrain.org/resources/ciria-guidance.html (accessed February 10, 2016).
[24] Stratus Consulting, A Triple Bottom Line Assessment of Traditional and Green Infrastructure Options for Controlling CSO Events in Philadelphia's Watersheds, Final Report, 2009. http://www.sbnphiladelphia.org/initiatives/green_economy_task_force/resources/.
[25] T. Slaper, T. Hall, The Triple Bottom Line : What Is It and How Does It Work?, Indiana Univ. Kelley Sch. Bus. (2011) 4–8. http://www.ibrc.indiana.edu/ibr/2011/spring/article2.html.
[26] K. Tzoulas, K. Korpela, S. Venn, V. Yli-Pelkonen, A. Ka??mierczak, J. Niemela, et al., Promoting ecosystem and human health in urban areas using Green Infrastructure: A literature review, Landsc. Urban Plan. 81 (2007) 167–178. doi:10.1016/j.landurbplan.2007.02.001.
[27] R.M. Ashley, R. Nowell, B. Gersonius, L. Walker, Surface Water Management and Urban Green Infrastructure, 44 (2011) 1–76.
[28] T. Bergier, J. Kronenberg, Sustainable Development Applications: Nature in the City, Sendzimir Foundation, 2012.
[29] USEPA, Case Studies Analyzing the Economic Benefits of Low Impact Development and Green Infrastructure Programs, Washington, DC, 2013.
[30] S.T. Lovell, J.R. Taylor, Supplying urban ecosystem services through multifunctional green infrastructure in the United States, Landsc. Ecol. 28 (2013) 1447–1463. doi:10.1007/s10980-013-9912-y.
[31] R. Haines-Young, M. Potschin, Common International Classification of Ecosystem Goods and Services (CICES): Consultation on Version 4, 2013. doi:10.1038/nature10650.
[32] R.S. de Groot, R. Alkemade, L. Braat, L. Hein, L. Willemen, Challenges in integrating the concept of ecosystem services and values in landscape planning, management and decision making, Ecol. Complex. 7 (2010) 260–272. doi:10.1016/j.ecocom.2009.10.006.
[33] B. Gersonius, T. Morselt, L. van Nieuwenhuijzen, R. Ashley, C. Zevenbergen, How the Failure to Account for Flexibility in the Economic Analysis of Flood Risk and Coastal Management Strategies Can Result in Maladaptive Decisions, J. Waterw. Port, Coastal, Ocean Eng. 138 (2012) 386–393. doi:10.1061/(ASCE)WW.1943-5460.0000142.