Decision Support System for Metabolism-Based Transition to Urban Water Systems of Tomorrow

Mark Morley*, Kourosh Behzadian*, Zoran Kapelan*, Rita Ugarelli**

* Centre for Water Systems, College of Engineering, Mathematics and Physical Sciences, University of Exeter, Exeter, EX4 4QF, UK
** SINTEF Building and Infrastructure, Forskningsveien 3b, NO-0314 Oslo, Norway

Abstract: A decision support system (DSS) tool for the assessment of intervention strategies in an urban water system (UWS) with an integral simulation model called "WaterMet^2" is presented. Lists of intervention options and Performance Indicators (PI) are exposed by the DSS for the user to define intervention strategies and metrics for their comparison. The quantitative and risk-based metrics are calculated by WaterMet^2 and risk modules while the qualitative metrics may be quantified by external tools feeding into the DSS. Finally, a Multi-Criteria Decision Analysis (MCDA) approach is employed in the DSS to compare the defined intervention strategies and rank them with respect to a pre-specified weighting scheme for different scenarios. This mechanism provides a useful tool for decision makers to compare different strategies for the planning of UWS with respect to multiple scenarios. The suggested DSS is demonstrated through the application to a northern European real-life case study.

Keywords: decision support system, WaterMet^2 model, indicator, intervention strategy, risk

Introduction

Urban water systems (UWS) face the long-term perspective of constraints and challenges associated with climate change and the availability of natural resources. This prospect requires the adaptation of the operation and infrastructure of UWS to meet uncertain future scenarios through the adoption of mitigating technologies in the water industry. However, it is suggested the impact on the UWS of these technologies, prior to their practical implementation, is best evaluated by a DSS. This approach has attracted attention by practitioners and researchers in recent years, leading to the development of tools such as *AQUACYCLE* (Mitchell *et al.*, 2001), *UWOT* (Makropoulos *et al.*, 2008), *UVQ* (Mitchell and Diaper, 2010) and *City Water Balance* (Mackay and Last, 2010). Despite a plethora of DSS being developed in recent years, relating to the integrated modelling of UWS, there remain outstanding issues which need to be addressed in this framework. The principal concern relates to simultaneously covering the whole range of sustainability dimensions in the Performance Indicators (PIs), including both quantitative and risk-based indicators. Ideally, the PIs should reference all facets of sustainability including social, environment, economic, governance and assets (Alegre *et al.*, 2012).

This paper presents a DSS which implements a tool which is able to quantify the impact of different sets of interventions/technologies on the performance of the UWS, including associated risks and costs by evaluating a wide variety of sustainability PIs under different scenarios. The WaterMet^2 model (Behzadian *et al.*, 2013), which undertakes the simulation of the integrated modelling of UWS, is employed in the DSS presented. In the following section, a brief description of the DSS configuration is followed by a review of WaterMet^2. The principal stages of the DSS are mapped through four steps including 1) problem definition, 2) metric calculation/decision matrix population, 3) ranking and 4) result viewing/modification/re-evaluation. The capabilities of the developed DSS are demonstrated on a real–life UWS in northern Europe. By way of the real case study, the paper presents a walk-through for each stage, presenting a list of the scenarios, intervention strategies and metrics used. The values obtained after running the WaterMet^2 model and the risk module are shown, along with how those outputs are used in the population of the multi-criteria decision analysis decision matrices.

DSS Methodology

The Decision Support System (DSS) developed seeks to support long-term, strategic-level planning of Urban Water Systems at the city/system level. This is achieved through a novel methodology for comparison and selection of alternative solutions, within the framework of long-term transition paths, and amidst multiple decision criteria. The support offered to the decision maker takes several forms and guides the user through the description of the "Environment" the analysis takes place in, the generation and evaluation of intervention strategies and to rank and evaluate the results obtained. The user is assisted in defining the Environment configuration – i.e. the outline definition of the problem to be analysed. This assistance takes the form of:

- Defining a time horizon for the analysis, along with the intermediate times at which Interventions may take place.
- Defining Scenarios which comprise varying input parameters to the WaterMet^2 model or to custom metrics defined outside of WaterMet^2. Note that analysis of the UWS over some planning horizon in the DSS is the basis of a pre-specified scenario. Each scenario can influence a number of specific variables in WaterMet^2.
- Selecting the criteria to be used for evaluation from the list of available Metrics, along with defining any user preferences that are to be taken into consideration when ranking the proposed Intervention Strategies.

The user is then helped to generate one or more Intervention Strategies by specifying a set of interventions that are undertaken at the pre-determined times defined in the Environment Configuration. An intervention strategy is defined as a combination of a number of individual intervention options organized along the defined planning horizon. The DSS supports an existing library of individual intervention options quantified by WaterMet^2 based on different components in the UWS.

Through repeated execution of the WaterMet^2 model each Intervention Strategy is evaluated to determine its effect on Urban Water Cycle Sustainability (UWCS) performance. This is achieved by, firstly, applying each Scenario defined in the Environment Configuration in turn and also applying each Intervention in the Strategy in turn – at the appropriate timestep. This process results in a series of metric values, for each timestep and scenario, representing the performance of the system – in order to populate the decision matrices to be used by the ranking process.

Having created two or more Intervention Strategies, the principal role of the DSS is to undertake an automatic ranking of the Strategies using a Multi-Criteria Decision Analysis (MCDA) technique. Two such techniques are implemented: Compromise Programming (CP) and the Analytic Hierarchy Process (AHP) although the design does not preclude other techniques to be added, including optimization. The ranking is performed according to the Metrics that have been identified in the Environment Configuration and is repeated for each combination of scenario and user preferences defined. Following ranking, the decision maker is supported in interactively modifying the intervention strategies and submitting it for the evaluation and rankings to be revised. Any number of Intervention Strategies can be created by the DSS and existing Strategies can be cloned and modified to assist in "what-if?" analysis, allowing variations of Strategies to be analysed in a straightforward fashion to investigate their influence on the overall strategy rankings.

DSS Implementation

The assessment of intervention strategies in an UWS is encapsulated in a framework expressed through a DSS. The structure of the classes in the DSS engine is split into three principle modules including Environment, Performance and MCDA. The 'Environment' part manages the specifications of the analysis including timing, intervention strategies, PIs, scenarios and customised model input. The 'Performance' part undertakes the responsibility of evaluating the indicators which are split into two categories: (1) quantitative performance and risk indicators calculated by the WaterMet^2 and Risk Modules, respectively; (2) qualitative indicators of the aforementioned types, defined within the DSS and quantified by external tools outside the immediate scope of the DSS. Finally, the MCDA module applies a user-configured ranking approach to the specified intervention strategies for the purposes of scoring and ranking them for each scenario and user preference combination.

In order to configure an evaluation of intervention strategies over a planning horizon in the DSS, the following four principal steps are required from the user: (1) an intervention strategy is defined in the 'Environment' part of the DSS based on the list of available intervention options. The intervention strategy comprises a set of individual interventions, including technologies and their operation on different parts of the UWS, each of which is assumed to occur at a specific time over a defined planning horizon. (2) The PIs of interest to the analysis, including those supported by the WaterMet^2 model and those supported by other tools outside the DSS, are also specified in the 'Environment' part of the DSS. (3) PIs including performance, risk and cost are evaluated in the 'Performance' section of the DSS. The PIs calculated or supported by the WaterMet^2 directly such as risk-based indicators are automatically populated in the DSS, whilst others evaluated outside the DSS need to be supplied manually by the user. (4) Scoring and ranking of the defined intervention strategies are conducted in the 'Strategy' part of the DSS by employing a user-defined MCDA.

As a part of the built-in simulation model in the DSS, the WaterMet^2 model is used to calculate all non risk-based performance indicators in an integrated UWS. This is handled through a simplified approach for modelling water supply, stormwater and wastewater systems based on mass-balance equations. The physical metabolism of this integrated UWS is then quantified through some performance indicators (PIs). Details of the principal flows and storages modelled in WaterMet^2 as well as descriptions of the components and their functionality can be found in Behzadian *et al.* (2013).

The risk assessment is calculated based on the likelihood of occurrence and severity of consequences. The likelihood is assumed here as the probability of the scenario under analysis and is scaled in five levels, each associated with a specified probability range (Table 1). The likelihood scale needs to be as objective as possible. Therefore, it is recommended that a range of probability values should be defined for each class. Considering that consequences are established as deviations from the sustainability objectives, with corresponding criteria, metrics and targets, the consequence scale consists of levels defined by ranges of deviations from the set targets. A deviation can be expressed as a percentage or in any other way considered appropriate for each analysis. For each scenario, only some dimensions will be of interest, but the complete consequence scale needs to be defined prior to application. Scales used should be selected or constructed to reduce subjectivity in the application by different people as much as possible. The different dimensions of consequence have to be evaluated using comparable scales. A consequence in any class should have the same impact from the decision-maker's perspective, for all the dimensions considered in the application. Consequences are also defined as five levels (A-E) of deviations of absolute value of risk event from a specified sustainability target value (Table 1). The absolute value of the consequences is estimated based on the PIs obtained from the UWS simulation in the WaterMet^2 model. Note that the level of deviations for each metric needs to be converted to the summary scale as well (i.e. from A to E). Finally, the risk level can be estimated based on the assessment of likelihood and consequence levels for each event using a selected risk matrix, as shown in Table 1.

Table 1. Risk matrix for quantifying risk-based metrics.

		Probability Range	**Consequence level**				
			E	D	C	B	A
Likelihood level	**5** *Almost certain*	$P > 10\%$	**5E** – Med.	**5D** – Med.	**5C** - High	**5B** – High	**5A** - High
	4 *Likely*	$2\% < P \leq 10\%$	**4E** – Low	**4D** – Med.	**4C** – Med.	**4B** – High	**4A** – High
	3 *Moderate*	$1\% < P \leq 2\%$	**3E** – Low	**3D** – Med.	**3C** – Med.	**3B** – Med.	**3A** – High
	2 *Unlikely*	$0.2\% < P \leq 1\%$	**2E** – Low	**2D** – Low	**2C** – Med.	**2B** – Med.	**2A** – Med.
	1 *Rare*	$P \leq 0.2\%$	**1E** – Low	**1D** – Low	**1C** – Low	**1B** – Low	**1A** - Low

MCDA Module

Two well-known MCDA methods are implemented in the DSS for the purpose of ranking intervention strategies under different scenarios and user preferences: (a) the Compromise Programming (CP) method (Zeleny, 1973) and the Analytical Hierarchy Process (AHP) method (Saaty, 1980). The two methods were selected because of their widespread use but also because they use different ranking technologies and, also, allow users to express their preferences in a different way. In the CP method, user preferences are specified as multiple evaluation criteria weights making this method more suitable for use by less experienced users. In the AHP method, user preferences are specified via the pairwise criteria-importance comparisons. This requires more experience to configure and employ the method. The DSS will enable the user to select the method to use when solving a particular problem, including the possibility to use both methods on the same problem and then compare results (e.g. to see if there an alternative solution that is ranked highly regardless of the MCDA method used).

Case Study

Introduction

The urban water system of a northern European city is used here as a reference city for the case study combined with assumptions when necessary. The DSS is demonstrated here for conditions of likely future population growth. In the first instance, the DSS needs to have specified scenarios, intervention strategies and metrics and associated target/goals and preferences, described in the following sections.

Scenarios

In order to demonstrate the efficacy of the DSS, the following two scenarios related to high (*Scenario 1*) and low (*Scenario 2*) population growth are considered in this case study. In this instance, the WaterMet^2 parameters changed in these population growth scenarios are the different water demand categories (i.e. household/population growth, industrial/commercial growth and irrigation growth).

Intervention Strategies

Three types of intervention options are employed in this case study

(1) Addition of a new water resource along with two water treatment works (WTW);

(2) Increased annual rehabilitation rate for pipes;
(3) Addition of rainwater harvesting (RWH) and grey water recycling (GWR) schemes;

Based on the above individual intervention options, the metabolism model is analysed in this demonstration based on the following seven alternative UWS intervention strategies against a 30 year planning horizon (2011-2040). Note that the intervention strategies numbered 3 to 7 start from 2015.

(1) Business as usual;
(2) Addition of a new water resource along with two WTWs starting from 2020;
(3) 1% additional annual pipe rehabilitation starting from 2015;
(4) Addition of RWH and GWR systems at a local level by 25% of households starting from 2015;
(5) Addition of RWH and GWR systems at a local level by 25% and 50% of households, respectively, starting from 2015;
(6) Addition of RWH and GWR systems at a local level by 50% of households starting from 2015;
(7) Addition of RWH and GWR systems at a local level by 25% of households and 0.5% additional rehabilitation annually starting from 2015;

Performance Metrics

Six metrics according to the performance criteria of sustainability dimensions of water systems (Alegre *et al.*, 2012) are considered for the purposes of this case study. These metrics include three quantitative criteria (C_1-C_3), two quantitative risk-based criteria (C_4, C_5) and a single qualitative example. The quantitative metrics are directly calculated by WaterMet^2 and risk modules, respectively. The qualitative metric (C_6) is quantified by relevant experts and the quantified values incorporated in the DSS. Instead of using qualitative categories (linguistic terms) for metric C_6, these are rated as scoring on a scale of acceptance ranging from 1 to 10, being: extremely low (1-2), low (3-4), medium (5-6), high (7-8) and extremely high (9-10). Furthermore, for the risk-based metrics, failure times shorter than the time step in the simulation model (i.e. daily in the WaterMet^2 metabolism model) cannot be captured by the DSS. A brief description of these metrics is outlined below:

(1) Reliability of water supply (C_1): the ratio of water delivered to customers to the total water demand.
(2) Total cost (C_2): annual average of the discounted initial capital investment of interventions plus discounted value of the fixed and variable costs in different UWS components to the first year with a specific discount rate.
(3) GHG emissions (C_3): annual average of the aggregated greenhouse gas emissions, as Global Warming Potential (GWP100) measured in units of carbon dioxide equivalents (CO_2-eq) from all components of the UWS.
(4) Days with restrictions to water service (C_4): the risk of the annual days with restriction (water supply failure) being greater than the target value.
(5) Prolonged hydraulic failure (C_5): the risk of annual expected value for the time length of hydraulic failure being greater than a target value.
(6) Social acceptance (C_6): the extent to which an intervention strategy would be supported by society, especially water consumers; in order to fulfil the water demands with respect to a number of factors especially safety and health issues.

Results and discussion

The results are presented in the following in two parts: (1) calculation of the quantitative and risk-based metrics for each intervention strategy; (2) ranking the intervention strategies using MCDA. The expert-quantified values for the single qualitative metric are directly populated in the decision matrix.

The time-series of the quantitative metrics (C_1-C_3) over the planning horizon are calculated by the DSS by running the WaterMet^2 model with respect to each scenario and intervention strategy. The single value for each of these metrics is calculated and populated in Table 3 for each of the two scenarios.

The risk-based metrics (C_4, C_5) are calculated based on the following sequential steps (Ugarelli *et al.*, 2014): (1) likelihood of risk event; (2) consequence levels from the PIs calculated by WaterMet^2 for each scenario; (3) risk estimation. The likelihood of risk events is assumed to be correspond with the probability of scenarios, i.e. 4 'likely' and 3 'moderate' for the high and low population rate Scenarios (1 and 2), respectively. Assuming a target value of 1% and 100%, respectively, for risk events of water supply failure (C_4) and prolonged hydraulic failure (C_5), the consequence scales of deviation value in Table 1 are defined as: $E < 5\% < D < 20\% < C < 40\% < B < 60\% < A$ and $E < 20\% < D < 50\% < C < 85\% < B < 90\% < A$, respectively. Given the maximum value experienced being used to aggregate the risk-based metrics over the planning horizon, the consequence levels of risk events can be calculated as shown in Table 2. With the given likelihood and consequence levels, the risk is then estimated according to the risk matrix of Table 1 for each intervention strategy and scenario, the results of which are further illustrated in Table 2.

Table 2. Deviation values and risk estimation for risk-based metrics; H=high, M=medium, L=low

	Scenario 1								**Scenario 2**							
Strategy	C_4[%]				C_5 [%]				C_4[%]				C_5 [%]			
	Dev.	Prob.	Cons.	Risk	Dev.	Prob.	Cons.	Risk	Dev.	Prob.	Cons.	Risk	Dev.	Prob.	Cons.	Risk
1	99	4	A	H	100	4	A	H	97	3	A	H	99	3	A	H
2	6	4	D	M	83	4	C	M	1	3	E	L	80	3	C	M
3	99	4	A	H	100	4	A	H	77	3	A	H	97	3	A	H
4	73	4	A	H	88	4	B	H	9	3	D	M	80	3	C	M
5	55	4	B	H	88	4	B	H	1	3	E	L	83	3	C	M
6	25	4	C	M	84	4	C	M	1	3	E	L	83	3	C	M
7	60.4	4	A	H	88	4	B	H	4	3	E	L	90	3	B	M

Ranking results

The aforementioned metric values calculated for each intervention strategy are used to populate the corresponding MCDA decision matrix, as per Table 3, for each of the two scenarios respectively. As the qualitative risk levels reported in Table 2 cannot directly be used for a quantitative comparison between the intervention strategies, they are rated on a scale between 1 and 3 as: high (3), medium (2) and low risk (1).

Following the population of the decision matrices, the ranking of intervention strategies is undertaken by means of the Compromise Programming (CP) method (Zeleny 1973). The outputs of this ranking can be seen in the two right-most columns of Table 3. In this table, equal metric weights have been used to rank the strategies.

To further analyse the sensitivity of the ranking to the metric weights of the metrics, two further weighting schemes, including Water Company and Consumer perspectives, have been ranked by the MCDA (Table 4).

Table 3. MCDA decision matrix and rankings for Scenarios 1 & 2

Criteria/ metrics	*Reliability of water supply*	*Total cost*	*GHG emissions*	*Risk of restriction to service*	*Risk of hydraulic failure*	*Social acceptance*	
Units	%	M Euros/ year	10^3 Tons/ year	-	-	-	**Rank**
Weights	1.00	1.00	1.00	1.00	1.00	1.00	
Goal	Maximize	Minimize	Minimize	Minimize	Maximize	Maximize	

Scenario	**1**	**2**	**1**	**2**	**1**	**2**	**1**	**2**	**1**	**2**	**1**	**2**	**1**	**2**
Strategy 1	94	99	53	52	95	89	3	3	3	3	5	5	**7**	**7**
Strategy 2	100	100	74	72	99	90	2	1	2	2	8	8	**1**	**1**
Strategy 3	96	100	58	57	96	89	3	3	3	3	7	7	**3**	**6**
Strategy 4	98	100	62	61	90	83	3	2	3	2	3	3	**5**	**4**
Strategy 5	98	100	63	62	89	82	3	1	3	2	2	2	**6**	**3**
Strategy 6	99	100	71	69	89	81	2	1	2	2	1	1	**2**	**5**
Strategy 7	98	100	64	63	90	83	3	1	3	2	3	3	**4**	**2**

Table 4. Weights of the metrics from different perspectives

	Reliability of Supply	*Total Costs*	*GHG emissions*	*Risk of restriction to service*	*Risk of hydraulic failure*	*Social acceptance*
Equal weight	1	1	1	1	1	1
Consumer	2	1	1	3	2	3
Water company	3	3	2	2	3	1

Given the three weighting schemes and two scenarios, a total of six groups of ranking for the intervention strategies are obtained, illustrated in Table 5. Naturally, there are several ways that these rankings can be merged together to achieve a final ranking for each intervention strategy. In this instance, the sum of the ranks of each strategy is used for determining final ranking, as shown in the last column for each scenario in Table 5.

Table 5. Summary of rankings of intervention strategies and final ranking

Strategy	**Scenario 1**					**Scenario 2**				
	Equal weight	*Consumer*	*Water Company*	*Sum of rankings*	***Final ranking***	*Equal weight*	*Consumer*	*Water Company*	*Sum of rankings*	***Final ranking***
1	7	4	7	18	**7**	7	7	6	20	**7**
2	1	1	2	4	**1**	1	1	5	7	**2**
3	3	2	6	11	**3**	6	6	7	19	**6**
4	5	6	5	16	**5**	4	4	3	11	**4**
5	6	7	3	16	**5**	3	3	1	7	**2**
6	2	3	1	6	**2**	5	5	4	14	**5**
7	4	5	4	13	**4**	2	2	2	6	**1**

As can be seen, Strategy 2, which has been consistently ranked highly, is selected in the top Strategy for both scenarios. However, it is further seen that if there is low population growth (Scenario 2), Strategy 7 is ranked first owing to its consistent high rank when seen from all perspectives. Strategy 1 has the lowest final rank because it has been identified as the worst strategy for several scenario/weighting combinations. Therefore, while Strategies 2 and 7 are recommended as the best strategies to adopt in this simple example, Strategy 1is clearly not to be recommended. However, further analysis will be required to fully cover and test different criteria for these strategies.

Conclusion

A new DSS was developed to facilitate decision-making for the long-term city metabolism planning problem. This represents a novel methodology for comparison and selection of alternative intervention strategies, within the framework of long-term transition paths, accommodating multiple decision criteria and able to deal with uncertain future scenarios and differing stakeholder perspectives. The results obtained on the northern European city case study demonstrate the effectiveness of the DSS developed and presented here. The case study involved the assessment of seven intervention strategies in an UWS over a 30 year planning horizon. The DSS employed the WaterMet^2 model and risk modules to calculate three qualitative and 2 risk-based metrics for two scenarios of population growth. A further, qualitative, metric quantified by experts outside the DSS and was also included in the decision matrix to represent social acceptability for each intervention strategy. The DSS ranked the intervention strategies using the Compromise Programming MCDA method operating over different weighting schemes allowing the consideration of the case study from different stakeholder perspectives. Two of the strategies which were consistently ranked highly were identified as being the likely appropriate strategies to be implemented although further analysis for inclusion of other metrics should be conducted. The results demonstrate how the DSS, integrated with an UWS modelling approach, can be used to assist planners in supporting making better decisions with respect to meeting their long-term, strategic level sustainability objectives.

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