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SUSTAINABILITY RISK BASED ASSESSMENT OF THE INTEGRATED URBAN WATER SYSTEM: A CASE STUDY OF OSLO

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ABSTRACT

Sustainability studies entail the consideration of a plethora of factors including climate change, water and energy scarcity, rising energy costs, population growth, etc. All these factors put pressure on the management of water services, increasing their vulnerability and the level of risk. A risk assessment methodology to be applied at a strategic (macro) level, using an integrated approach, is presented to support the evaluation of intervention strategies in an integrated urban water system (IUWS) for a set planning horizon. Risk criteria and method for estimating risk for different circumstances were defined using a formulation consenting strategic objectives to be considered. The IUWS is modelled by "WaterMet²" which is a deterministic and quantitative IUWS simulation model, allowing quantification of the main water flows and other relevant fluxes in the IUWS. Risk assessment uses results from WaterMet² model to analyze risk in the IUWS. The developed approach is demonstrated through its application to the assessment of the intervention strategies for the water supply systems of Oslo city in Norway over a 30-year planning horizon.

Keywords: Integrated urban water system; risk analysis; WaterMet²; performance criteria; intervention strategy

INTRODUCTION

TRansitions to the Urban Water Services of Tomorrow (TRUST) (www.trust-i.net/) is a four year research project funded by the European Union. The ambition of TRUST is to deliver co-produced knowledge to enable water utilities to achieve a sustainable future without compromising service quality. The work presented in this paper is one of the products of TRUST to deliver this ambition. The research performed in TRUST builds on a common project denominator, the definition of sustainability: "*Sustainability in urban water cycle services (UWCS) is met when the quality of assets and governance of the services is sufficient to actively secure the water sector's needed contributions to urban social, environmental and economic development in a way that meets the needs of the present without compromising the ability of future generations to meet their own needs.*" (Brattebø, [1]). Hence, a set of sustainability objectives and criteria are also identified to assess the level of sustainability of a

given service. In total, this led to a predefined set of 23 sustainability criteria, according to 13 sustainability objectives, within 5 sustainability dimensions: social, environmental, economic, asset, governance.

The WaterMet² model has been developed to calculate indicators for assessment of the sustainability performance in urban water systems (UWS). WaterMet² is a conceptual, simulation type, mass-balance-based, integrated UWS model which quantifies metabolism-related key performance of UWS with focus on sustainability-related issues. Further details of WaterMet² can be found in Behzadian *et al.* (2013) [2]. Metabolism in UWS refers to the fluxes and conversion processes related to all kinds of water flows, materials and energy in the UWS, which are necessary to fulfil the necessary functions (Venkatesh and Brattebø, [3]).

The domain of analysis in TRUST is strategic: the analysis has to look at the integrated UWS and support long term decisions.

The paper presents the methodology for assessing the risk of an urban water system not reaching sustainability; the methodology essentially follows the standard steps of a risk management process (ISO, [4]). At the strategic level the usual approach of using a detailed analysis based on representative risk events (accidents or incidents) is not considered appropriate. An example of this approach is detailed in Almeida *et al.* [5], where the risk process steps are followed in the scope of the water cycle safety planning (WCSP) framework. For undertaking a similar exercise at strategic level, for a set long term planning horizon, the events should correspond to changes in circumstances (for a period of time, e.g. a year), which need to be based in plausible scenarios of change for conditions such as climate change, water and energy scarcity, rising energy costs and population growth. These conditions can affect the performance of water services, eventually increasing their vulnerability and the level of risk or decreasing reliability and resilience. Achievement of sustainability targets for water systems can be jeopardised by these changes in circumstances. Therefore, assuming established sustainability objectives defined for a specific system, risks can be identified in the context of occurrence of circumstances as events causing undesired and uncertain deviations from the objectives (risk defined as effect of uncertainty on objectives in ISO [6]), herein the sustainability objectives. In each specific application, the objectives need to be expressed by an appropriate set of criteria, supported by appropriate metrics and corresponding targets. The deviations from the expected situation in relation to the set targets, resulting from the occurrence of the undesired circumstances, are the corresponding consequences.

METHODOLOGY

The adopted methodology for risk assessment is composed by the following steps:

1. Problem definition
2. Establish context for risk assessment
3. Risk identification (RI): RI.1 – Selection and characterization of scenario based events; RI.2 – For each event, calculation of metrics for each alternative and time step
4. Risk analysis (RA): RA.1 – Set likelihood for each event; RA.2 – For each event, calculation of consequences (deviation of metric result from target) for each alternative and time step; RA.3 – Estimate risk for each event and consequence metric, for each alternative and time step
5. Risk evaluation (RE): RE.1 – Comparison of risk level obtained with decision criteria; RE.2 – Ranking alternatives according to risk level
6. Final selection and implementation

In each specific case, the overall problem definition is carried out prior to risk assessment. Furthermore, the context for the risk assessment has to be established before starting the tasks of risk identification. Establishing the context is partly covered by previous tasks of problem definition and needs to be complemented by selection of appropriate risk criteria and methods to be used, the later strongly dependent of available information.

The overall structure for supporting decisions is based in the evaluation, for a given system, of the overall performance according to the selected sustainability metrics and, for each metric, how close it is from the targets set for the time horizon of the analysis. Even if for present and

expected future conditions targets were met, uncertainty derived from plausible scenarios of changes in circumstances need to be investigated and better course of action identified, considering viable alternatives.

However, the current situation for existing systems is that actions to increase sustainability are necessary and strategies for improvement should be compared. For each alternative, values of selected sustainability metrics, and corresponding deviations to targets, are calculated for each time step. Aggregation of metrics and deviations is carried out for each time step and for each alternative, using appropriate methods.

Sorting or ranking of the alternatives can be obtained using the selected MCDA method and adopted decision criteria, including metrics of risk as well as of performance and cost.

The step of risk treatment, where measures to modify the risks that need treatment are identified evaluated and selected, is already incorporated in problem definition and alternatives are analysed through the steps together with the existing situation. The alternatives represent the possible courses of action for which different levels of risk might be obtained. These actions can be further modified before proceeding to the assessment of alternatives in an MCDA, resulting in the modification of alternatives already under analysis. New alternatives may also be defined. In any of these situations, calculations need to be carried out in order to obtain the updated risk assessment.

From a methodological point of view, it is foreseen that the alternatives can change the consequences (deviation of computed values from metrics) side and not the probability side of the risk since it is considered, as a simplification, to be the same of the scenario (i.e. any alternative will not influence the probability of e.g. increase of population in a given period of time and space).

In the following section, the application of the proposed methodology to the case study of the UWS of Oslo in Norway is presented.

APPLICATION TO THE OSLO CASE STUDY

The case of the water supply system of Oslo was selected to apply the methodology proposed in TRUST. Only one scenario is presented here to illustrate the steps as described in the methodology.

Problem definition

Oslo Water and Sewerage Works (VAV in Norwegian) are responsible for the provision of water and sanitation services to the 600.000 inhabitants of Oslo. Challenges to the city include the likely population growth, increasing urbanization and deterioration of water infrastructures. Oslo main water sources are two surface water bodies, Maridalsvannet and Elvåga lakes, each connected to a water treatment works (WTW) and a service reservoir, together providing fresh water for Oslo city with 90% and 10% of total supply capacity, respectively. Both key water sources to the city are of limited capacity (120 and 13.8 million cubic metres (MCM), respectively) as well as the inflow (average of 287 and 12 MCM/year, respectively). Leakage from the sub-catchment pipelines is currently 22% of total water demand. The sewer system of Oslo city is a mix of combined and separate systems (out of total length of sewers, 37% are combined sewers, 30% sanitary sewers and 33% storm sewers). Two wastewater treatment plants (WWTW) collect 63% and 27% of the produced wastewater, respectively for WWTW1 and WWTW2. Oslo VAV has developed a water cycle safety plan (WCSP) (Røstum *et al.*, [7] Røstum, [8], Ugarelli and Røstum, [9]) and the study showed that most important challenges in the urban water system in Oslo are related to water supply, especially the lack of a robust water supply system. In the risk analysis carried out in the drinking water supply system, the higher risk associated with the most severe event identified was the lack of treated water to supply the city of Oslo due to under designed treatment plants.

Establish context for risk assessment

The WCSP analysis concluded that the water supply system of Oslo requires further investigation to estimate risk and identify reduction strategies. Therefore, also the application of the sustainability based methodology, here presented, focused on the water supply side of system. The establishment of the context for risk assessment included the following steps for

the case study of Oslo: (a) selection of scenarios and alternatives; (b) determination of the sustainability dimensions, objectives, assessment criteria and metrics to express the assessment criteria and the variables for defining the metrics that are relevant for the scenario; (c) definition of scales for expressing the likelihood and the consequence levels for the scenario based events, for the selected dimensions / criteria / metrics; (d) selection of the aggregation method.

(a) Selection of scenarios and alternatives

The changes in circumstances identified as relevant for the risk analysis, presented as sets of scenarios are: population growth, asset deterioration and climate change. Dialogue with the personnel of VAV allowed selecting the type of alternative interventions that should be prioritized at strategic level of planning, in case of occurrence of the above mentioned scenarios of change. Looking at the upper side of the system, as was the understanding from the Oslo VAV personnel, and for the utility to be better prepared for temporary failures in the existing supply system, they would like to increase the capacity of the water sources, as well as the WTP hydraulic capacity, due to the pressing concern about the predictions of population growth recently published by the Norwegian Statistics Institute (Statistics Norway, [10]). For the sake of this demonstration, 2 scenarios have been considered:

1. Scenario of population growth (HIGH Scenario) without interventions;
2. Scenario of population growth (HIGH Scenario) with an intervention (A1).

The alternative intervention considered (A1) can be briefly described as follows: the raw water is sourced from a source (Holsfjorden) located to the west of the city and that requires the setting up of a facility close to it and associated piping and pumping. Data for the capital investments required for this purpose are sourced from Paus & Hem [11]. For this alternative, the new source would provide 20% of the raw water, with the lake Maridalsvannet (in the north) providing 71.9% and the lake Elvåga (in the east) 8.1% (Figure 1).

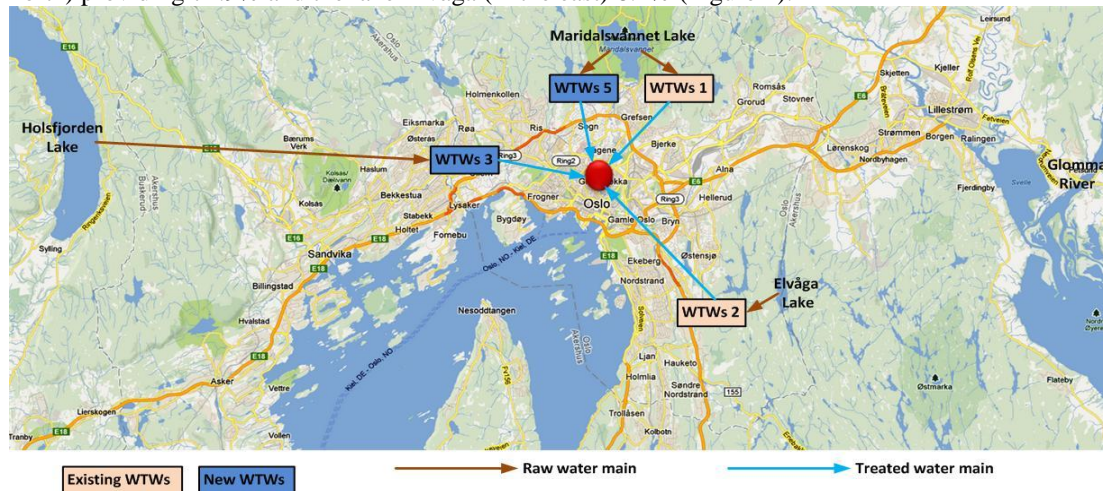


Figure 1: Layout of Oslo water supply system for intervention alternative A1

(b) Sustainability dimensions, objectives, assessment criteria and metrics

Table 1 summarizes the selected sustainability dimension, objective, assessment criteria, metrics and set targets selected in this case.

Table 1 Sustainability dimension, objective, assessment criteria, metrics and set targets for Oslo case

Dimension	Objectives	Criteria	Metrics	Target
S - social	S ₁ Access to water services	S ₁₁ Water demand coverage	S _{11,1} : Coverage %	100%
	S ₂ Effectively satisfy the current users' needs and expectations	S ₂₁ Quality of service	S _{21,1} : Annual interruptions to supply	≤ 6 hours / person / year
			S _{21,2} : Annual resilience	≥ 100%

The main water supply system components were modelled by the WaterMet², which comprises the water sources, trunk mains, WTW and pipelines (Behzadian and Kapelan [12]).

A brief description of the selected three metrics in WaterMet² is as follows:

S_{11,1}: The *coverage* is calculated as the ratio of the total daily water delivered to customers (S_i) to the total daily water demand (D_i) during a year.

$$coverage = \frac{\sum_{i=1}^{365} S_i}{\sum_{i=1}^{365} D_i} \quad (1)$$

S_{21,1}: *Annual interruptions to supply* is calculated with daily water supply (S_i) and demand (D_i) and population (pop_i) and average population (\overline{pop}) over a year, based on equation 2.

$$Interruptions\ to\ supply = \sum_{i=1}^{365} (1 - S_i/D_i) \times pop_i \left/ \left(4 \times \overline{pop} \right) \right. \quad \text{if } (S_{i-1}/D_{i-1} < 1 \text{ and } S_i/D_i < 1) \quad (2)$$

S_{21,2}: *Annual resilience* is calculated as the ratio between total amount of any improvement following a water deficit and total amount of water deficits ($F_i = D_i - S_i$ if $S_i \leq D_i$). This calculation is given below:

$$Annual\ resilience = \left(\sum_{i=1}^{365} (F_{i+1} - F_i) \text{ if } F_{i+1} < F_i \text{ and } S_i < D_i \right) \left/ \left(\sum_{i=1}^{365} F_i \text{ if } S_i < D_i \right) \right. \quad (3)$$

(c) *Definition of scales for expressing the likelihood and the consequence levels*

The estimation of the likelihood for the full development of an event, from the risk source to the ultimate consequences, is not usually viable and a common simplification is to focus on estimating the probability of the hazardous event (Almeida *et al.*, [5]), seen as possible occurrences associated with each hazard or possible ways the hazard can occur. For this specific application at strategic level, the likelihood of a scenario based event will be assumed as the probability of the scenario under analysis. For scenarios of population growth, events are defined for each relevant change in the population; the likelihood of these events is assumed as the one associated with the corresponding scenario of population growth. Definitions of the set of scenarios of change and related probabilities must be based on existing studies to support the analysis and a number of simplifications need to be assumed. Table 2 presents the scale at present proposed to classify the level of probability for the Oslo case.

Table 2 Likelihood scale selected for the Oslo case

Levels	Likelihood description	Probability range
1	Rare	≤ 0.2 %
2	Unlikely	> 0.2 % and ≤ 1 %
3	Moderate	> 1 % and ≤ 2 %
4	Likely	> 2 % and ≤ 10 %
5	Almost certain	> 10 %

Considering that consequences are established as deviations from the aforementioned sustainability objectives, with corresponding criteria, metrics and targets, the consequence scale consists of levels defined by ranges of deviations from the set targets (Table 3). A consequence scale with five levels (A-E) and three dimensions of consequence was defined in this case.

Table 3 Consequence scale for dimensions derived for the selected metrics

Metric	Deviation calculation	Consequence scale
S _{11,1} target= 100%	$\frac{target - metric}{target} \times 100$	E<1%<D<5%<C<20%<B<50%<A
S _{21,1} target: ≤ 6 hours /person/year	$\frac{metric - target}{target} \times 100$	E<200%<D<400%<C<1200%<B<14000%<A
S _{21,2} target: ≥ 100%	$\frac{target - metric}{target} \times 100$	E<1%<D<5%<C<20%<B<50%<A

In the consequence assessment deviations are first evaluated separately: metrics are of different nature, hence the ranges of values used to define the scales of deviations vary from metric to metric (as in Table 3); however, in order to be comparable to calculate risk, the level of deviations need to be converted to the same summary scale (from A to E in this example).

Following the assessment of likelihood and consequence levels for each event, risk can then be estimated using the selected risk matrix (Table 4).

Table 4 Risk matrix for qualitative risk estimation

		Consequence level				
		E	D	C	B	A
Likelihood level	5	5E - Medium	5D - Medium	5C - High	5B - High	5A - High
	4	4E - Medium	4D - Medium	4C - Medium	4B - High	4A - High
	3	3E - Low	3D - Medium	3C - Medium	3B - Medium	3A - High
	2	2E - Low	2D - Low	2C - Medium	2B - Medium	2A - Medium
	1	1E - Low	1D - Low	1C - Low	1B - Low	1A - Low

(d) Aggregation method selected

Aggregation of deviations has been carried out for each time step and for each alternative. The results are time-series of values for the deviations of the metrics from the targets. According to the procedure and level of aggregation adopted, which will depend on the decision problem formulation, deviations can be aggregated up to one value per dimension, one value per objective, one value per criteria or one value per metric. Regarding aggregation in time, a similar procedure can be adopted. Additionally, aggregation of results for each scenario (when more than one event has been identified for the scenario) can be also produced.

In the example proposed, the maximum function was used as decision rule for aggregation.

Risk identification

RI.1 Selection and characterisation of scenario based events

The scenario based events were selected from the scenarios considered in problem definition. For the same scenario, more than one event can be characterised if relevant conditions (risk factors or risk sources) are not constant. For the case of Oslo, considering the metabolism model and the scope of TRUST, the following 2 events were selected, in agreement with problem definition:

Risk event 1 – Risk to the sustainability of Oslo's long-term water supply service related to the high scenario of population growth in absence of alternative interventions.

Risk event 2 – Risk to the sustainability of Oslo's long-term water supply service related to the high scenario of population growth AND with the implementation of the alternative A1.

RI.2 Calculation of metrics for each alternative and time step for each event

In order to obtain the necessary information for risk analysis, for each event, calculation of the values of the metrics, for each alternative and time step, was carried out, using WaterMet² model used (Behzadian *et al.* [13]). Table 5 summarizes the minimum values of the time series of metrics obtained for each event.

Table 5 Minimum values calculated results for the selected metrics for each event

Event	S _{11,1} [%]	S _{21,1} [minutes/person/year]	S _{21,2} [%]
Risk event 1	86	66564	6.7
Risk event 2	100	1498	18.2

Risk analysis

RA.1 – Likelihood of each event

As already mentioned, in the absence of better information, the probability of risk event is assumed as similar to that of the corresponding scenario. Therefore, the probability of a risk event related to the population growth is simplified as equivalent to the probability of the scenario of population growth under analysis. The scenario of highest population growth was selected to illustrate the methodology. The deterministic scenarios of population growth have

been provided by the Statistics of Norway (Statistics Norway, [10]). Foss [14] produced stochastic projections from this deterministic data to include uncertainty around this forecast. For the purpose of this paper, it is assumed that the probability of exceeding the upper limit of the 90% confidence interval is equal to 5 % ($[100 \% - 90 \%]/2$). So there is a 5 % probability that the population will follow the strong growth or higher. Therefore, and for the purpose of illustrating the methodology, assuming Table 2 as reference scale, the probability level is set to 4 'likely.

RA.2 Consequence levels as per computed deviations for selected metrics

For each event, calculation of the consequences is done for each alternative and time step using the results from RI.2. At this step, the deviation between the calculated relevant metrics and the target is computed. Table 6 presents the maximum computed deviation from the set targets for each metric.

Table 6 Maximum computed consequence over the period of simulation.

Event	$S_{11,1}$ [%]	$S_{21,1}$ [%]	$S_{21,2}$ [%]
Risk event 1	14	18140	93.3
Risk event 2	0	316	81.8

Table 7 shows the level of consequence obtained by comparing the computed maximum deviations from the target set for the selected metrics, with the set consequence scale.

Table 7 Consequence levels with respect to the selected metrics for each event.

Event	$S_{11,1}$ [%]	$S_{21,1}$ [%]	$S_{21,2}$ [%]
Risk event 1	C	A	A
Risk event 2	E	D	A

RA.3 Results of risk estimation

Table 8 shows the levels of probability (P), consequence (C) and estimated risk (R) for each event and metric.

Table 8 Levels of probability (P), consequence (C) and estimated risk (R) for each event and metric. H=high, M=medium

Event	$S_{11,1}$ [%]			$S_{21,1}$ [minutes/person/year]			$S_{21,2}$ [%]		
	P	C	R	P	C	R	P	C	R
Risk event 1	4	C	M	4	A	H	4	A	H
Risk event 2	4	E	M	4	D	M	4	A	H

In a more comprehensive analysis, the risk can be found for each event and consequence dimension and after the maximum risk value obtained for each event. If required one could aggregate the computed levels at criterion, objective and dimension level by using the selected aggregation functions. In the example, for instance for event 1, one could conclude, using the maximum function, that:

Aggregate metrics at the criterion level:

$$\text{Risk of below target demand coverage: } R(S_{11}) = \text{MAX} [R(S_{11,1})] = M$$

$$\text{Risk of below target quality of service: } R(S_{21}) = \text{MAX} [R(S_{21,1}), R(S_{21,2})] = H$$

Aggregate criteria at the objective level:

$$\text{Risk of below target access to water services: } R(S_1) = \text{MAX} [R(S_{11})] = M$$

$$\text{Risk of below target satisfaction of users' needs } R(S_2) = \text{MAX} [R(S_{21}), R(S_{22})] = H$$

Aggregate objectives at the dimension level:

$$\text{Risk of below target social dimension } R(S) = \text{MAX} [R(S_1), R(S_2)] = H$$

Risk evaluation

The results of the analysis show that for Risk event 1, the existing situation, there is a high risk for the sustainability of the system for two criteria while being medium for the third, which is not acceptable for all criteria. The alternative allows reducing slightly this situation, but still it is not in the acceptable risk level. Other or additional alternatives should then be sought for this

problem. Additional alternatives should target resilience. The model provides insights in what causes the poor performance on resilience index and can provide hints towards more effective alternatives. In addition, the performance of a mix of alternatives can be more efficient with respect to different metrics and the relevant risks.

CONCLUSIONS

This methodology allows evaluating risks related to sustainability of existing urban water systems and possible intervention options hence improves understanding on how decisions can contribute to meeting sustainability targets. Furthermore, adopting a comprehensive approach to the urban water systems requires the adoption of a number of simplifications for carrying out the risk assessment and risk management steps. The case study of Oslo, despite being simple, shows the importance in any application of risk analysis of the preparatory dialogue with the water utility, e.g. in steps of "Problem definition" and "Establish context for risk assessment" prior to starting the risk assessment phase.

Work is proceeding to incorporate the proposed methodology into a comprehensive Multi Criteria Decision Analysis (MCDA), to improve the comparison of the impact of scenarios of change on more dimensions of sustainability, more objectives, criteria and metrics than the few included in this example. MCDA will also help to identify the causes of risk and to analyze the impact of different alternative on the risk levels.

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