Cost benefit risk – a concept for management of integrated urban wastewater systems?

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Abstract Urban wastewater systems should be evaluated and analysed from an integrated point of view, taking all parts of the system, that is sewer system, wastewater treatment plant and receiving waters into consideration. Risk and parameter uncertainties are aspects that hardly ever have been addressed in the evaluation and design of urban wastewater systems. In this paper we present and discuss a probabilistic approach for evaluation of the performance of urban wastewater systems. Risk analysis together with the traditional cost-benefit analysis is a special variant of multi-criteria analysis that seeks to find the most feasible improvement alternative for an urban wastewater system. The most feasible alternative in this context is the alternative that has the best performance, meaning that the alternative has the lowest sum of costs, benefits and risks. The sum is expressed as the Net Present Cost (NPC). To use NPC as a decision variable has the problematic effect, that two alternatives performing completely differently when focusing on environmental cost can have the same NPC. The extreme example is one alternative with high risk and low cost and another with low risk and high cost. In this example it is up to the decision-maker to decide whether she wants to spend the budget on preventive installations or cleaning up after failures in the environment.

Keywords Cost-benefit; decision analysis; risk; systems analysis; uncertainty; urban wastewater systems

Introduction

The integrated urban runoff system consists of three main components: the sewer system, the treatment plant and the receiving waters. The different components are usually analysed by different groups of experts. When a problem is solved in one part of the system, that is by focusing only on one system component, there is the potential that this solution creates new problems elsewhere. Several papers (e.g. Durchschlag et al., 1992; Mikkelsen et al., 1996 and Rauch and Harremoës, 1997) show that the resulting water quality in a river after building large storage capacity, and thereby avoiding some overflow events, is decreased because the large storage basin causes increased flow to the treatment plant and consequently overloading.

The intention in design and operation of urban wastewater systems, with the standards of today, should be to do it in such a way that the surrounding environment is affected as little as possible. According to the principles of sustainability the surroundings should not be loaded more than they can absorb without being significantly deteriorated. The only realistic approach to achieve that is to consider and analyse the urban wastewater system and its components as an integrated system.

By analysing all components of the urban runoff system in the same framework all effects in the whole system can be taken into consideration. This may lead to solutions performing suboptimally for one specific component, but from an overall point of view the solution will perform better.

Modelling of risk requires a probabilistic modelling approach (Ang and Tang, 1984) because the desired result is, at least within water management, not whether or not a certain failure occurs, but the probability of the failure occurring within a given time period. The
modelling result—probability of failure is a result of, on the one hand variation in the input data, primarily rain, and on the other hand the uncertainty associated with the model parameters. Monte Carlo simulations are a suitable technique for including uncertainty in the calculation of these probabilities of failure.

For comparison between scenarios a cost-benefit-risk framework is used. In which the traditional cost-benefit methods are supplemented with a new element—risk. Risk analysis considers the probability of different negative effects, or failures, occurring in the system together with the expected consequence of these effects. Cost-benefit-risk is a method where the expenses of building a system, the benefits developing after execution of the project and the effect of different unwanted failures occurring can be analysed in the same framework.

Uncertainty and variation
When integrated modelling of the urban water system is carried out there are a number of phenomena that the modeller have to be aware of in order to produce good modelling results and to be able to interpret the result in a proper way. In modelling we need to distinguish between variation and uncertainty. Precipitation accounts for the largest source of variation in the urban wastewater system. It is important to include a realistic representation of this variation in the model. This can be done either by using measurements from the past as a picture of the variation that can be expected in the future, or by expressing the expected variation as a stochastic model. The stochastic model should be based on analysis of previous experiences (measurements). Precipitation however is not the only source of variation. Also water consumption (diurnal and seasonal), temperature (diurnal and seasonal) and concentration levels in wastewater (to some extend stochastic) are elements that involve significant variation. If available the variation can be described with local data series, otherwise variation must be described with a statistical model based on whatever data is available. The better the representation of the variation, the more trustworthy the model results become.

The level of uncertainty is a measure of the errors that are made when reality is simplified into a model. Model parameters are estimated based on measurements or deduced somehow from prior knowledge. The measurements provide limited information about the parameter on a single or a few spots and the value is then extrapolated to represent the whole area. This simplification of course introduces an error, but also the measurement itself is an error source because the parameter can not be determined exactly. All these errors, which under one could be called parameter uncertainty, can be taken into account by describing the parameters with a statistical distribution, for instance the normal distribution given by a mean value and a variance. Because the urban wastewater system is described by a lot of parameters, the parameter uncertainty adds up to quite a lot of variation on the output. It is therefore desirable to include the parameter uncertainty in the analysis. The model structure also introduces an error source, this type of error becomes increasingly significant when the model is simplified. Errors introduced by the model structure are not included in the discussions in this paper.

In the example later in this paper, 10 years of rain recordings are used to represent variations in precipitation. Uncertainty is taken into account by making 400 model calls for each scenario, where all parameters are given a new value, picked randomly, within a statistical distribution that have been chosen to represent the uncertainty for each parameter.

Risk assessment of integrated urban wastewater systems
The urban wastewater discharges cause different effects in the receiving waters, i.e. hydraulic disturbances of the riverbed, short-term effects such as oxygen depletion and
ammonia pollution, and long term effects such as eutrophication and heavy metal accumulation in lake sediments. Usually the decision-makers accept these effects in the receiving waters to some extent. But when the effects pass a given level, the acceptance level, they are no longer accepted. Even though a system has been designed according to all existing guidelines and rules, the true performance of the system is unpredictable and hence there is a probability that the design fails. This is motivating for a risk assessment of the wastewater system.

In this context the urban wastewater system is considered as a system with two purposes, one: to transport the wastewater (including stormwater runoff) out of the urban area and two: to protect the environment from the potential harmful effects that this discharge of wastewater involves. How well the environment is protected is evaluated by formulating a number of criteria for the state of the system. By definition the system fails when the different loads exceed the carrying capacity, then things are damaged to such an extent that measures have to be taken in order to restore the damage, or the magnitude of an effect reaches beyond the political defined acceptance level. The receiving part of the system has a certain capability of resisting the load that the pressuring part of the system imposes on the receiving part. An example: a lake can absorb a certain load of phosphorus before it is influenced to such a degree that conditions in the lake change significantly due to the increased phosphorus load eutrophication occurs. It has been common practice to formulate the acceptance level on the pressuring part of the system in terms of maximum allowed loads and volumes instead of effects in the receiving part of the system in terms of water quality criteria. Allowed number of overflows from a CSO structure is one example of an acceptance level on the pressuring part of the system. The acceptance level is established based on an assumption that the recipient has a carrying capacity of a certain number of CSOs. But it is unknown whether or not the recipient is actually damaged when the number of CSOs is exceeded. Damage could also happen with fewer events. When ever possible the acceptance level should be formulated on water quality criteria. It is not necessarily the overflow event that is the problem but the potential harmful results such an event might have.

A risk assessment procedure could be divided into a three-step process:
1. Identification of possible failures. The whole point of integrated analysis is to include all (or as many as possible) important effects from the whole system.
2. Determining the probability of failure. Through modelling and simulation the probability of failure can be estimated.
3. Estimating the consequence of failure. When a failure occurs, what is then the consequence? What will it cost to restore the damage? For how long will the water quality be decreased?

This paper focuses on the first two steps in the risk assessment process. But in risk assessment where risk is defined as probability times consequence, probability and consequence are equally important parts of the analysis and therefore consequences have to be given more attention in the future.

Figure 1 illustrates two different approaches to including uncertainty in the analysis. In Figure 1A uncertainty is only included in modelling of the pressure whereas the acceptance level is a deterministic value. In Figure 1B there is uncertainty associated with both the pressure and the acceptance level. Uncertainty on the acceptance level is introduced when the acceptance level is based on an environmental effect e.g. fish death due to oxygen depletion. The uncertainty in this example represents the lack of knowledge about the exact oxygen level at which fish is killed in that particular population in the stream of concern.
Evaluation of system failures

The failures can be assumed to be either independent or dependent. If the failures are independent, then the probability of each failure is equal to the probability of the load exceeding the carrying capacity. However if two failures are considered dependent, which in some cases is a reasonable assumption, then the joint probability of failure is calculated as:

\[ P(A \text{ and } B) = P(A) \cdot P(B) - P(A) \cdot P(B | A) \]

where A and B represent two different failures. The equation can also be expanded to three or more failures. Failures should be treated as independent failures when the criteria concern different parts of the system, in other words when different things are damaged. Dependency is used in order to take overlapping criteria into account. If the criteria concern the same effect or the same part of the system they should be regarded as dependent.

An example of two independent criteria could be the hydraulic stress on the riverbed as a result of overflow from an upstream CSO structure and effluent concentrations from a downstream treatment plant. The processes that lead to the two failures are interrelated, but the effects are observed in different parts of the system and therefore they are independent criteria. Yearly overflow volume and frequency of overflows from the same CSO structure should on the other hand be considered as dependent criteria, because both criteria are concerned with damage of the same part of a river.

Decision analysis

In a decision analysis a number of different alternatives are compared. All the alternatives aim at improving the urban wastewater system. The alternatives are designed on the basis of a prior decision about which technologies to choose among and a set of design criteria. Basically the evaluation will be some sort of multi-criteria analysis that makes it possible to compare alternatives by combining integrated analysis and probabilistic modelling approaches. The analyses usually include the same elements, normalisation and weighting. Normalisation means bringing the criteria to the same scale so further analysis and comparison is possible. In weighting the relative importance of the criteria are defined. The more different the criteria in the analysis the more difficult it becomes to bring all criteria to the same scale. The weighting can be based on for instance economics, things are given weight according to the economical importance of the criteria. Another weighting method is ranking of importance of the criteria among the users. The users are asked to rank the criteria by for instance distributing 100 points among the criteria. A third way of weighting is according to political consensus. This approach is widely used in life cycle assessment. A criterion that is given a lot of attention and has strict requirements in the laws and international treaties is given a high weight and vice versa.

There are numerous ways to make a multi-criteria-analysis, this paper concerns a special
variant of multi-criteria analysis, the cost-benefit-risk analysis. Here the defined environmental criteria (the risks) are supplemented with economic criteria such as construction cost, operation and maintenance, and benefits of the alternative, like resource savings and changes in land values etc. Cost-benefit-risk has the great advantage that the normalisation and weighting procedure is something that everybody can relate to, economic terms. The disadvantage is that everything cannot be converted into monetary terms. This problem with normalisation and weighting is not unique for methods that use economics as a scale.

**Cost-benefit-risk: NPC as a decision variable**

The different alternatives are analysed by comparing Net Present Cost (NPC) for each alternative. NPC is as the back discounted value of cost benefit and risk for the defined lifetime of the alternative. NPC represents the cash it is necessary to possess in year \( t = 0 \) in order to be able to pay all expected expenses (i.e. costs, benefits and risks) in the lifetime of the alternative. NPC is calculated with the following formula:

\[
NPC = \sum_{t=0}^{T} (C_t - B_t + R_t) \left( \frac{1}{1 + r} \right)^t
\]

where \( C_t, B_t, \) and \( R_t \) are Cost, Benefit and Risk in year \( t \), \( T \) is the total lifetime of the alternative and \( r \) the interest rate. This means that all effects in the whole lifetime of the scenario are taken into consideration in the analysis. Costs are normally concentrated in the first few years of a project, whereas benefits and risks are more evenly distributed over the lifetime. The lifetime has a significant influence on the result of the analysis. The longer the lifetime, the more weight is given to benefits and risk and the lesser weight is given to cost.

NPC is used as a decision variable in the search for the most feasible solution. The most feasible alternative is the alternative with the lowest NPC, meaning that this alternative requires the lowest amount of cash when the constructions are initiated. To use only NPC as a decision variable has disadvantages, since two alternatives with very different performance can get the same NPC. The extreme example is one alternative with high cost and low risk and another alternative with low cost and high risk. In these cases the decision makers have to decide whether they want to spend the budget on building preventive installations or clean up after failures in the environment.

**Estimation of costs, benefits and risks**

Of the three elements in cost-benefit-risk analysis, cost is the most easily calculated, it includes cost associated with construction, operation and maintenance of the system. The problems and the uncertainty in estimating the cost is relatively small compared to the two other elements, risk and benefit.

Benefits theoretically include all changes in resource use and service level, that the future users of the system will experience as a consequence of the execution of the project. Benefits are calculated by comparing the alternative with a reference alternative which could be a “do nothing” or “business as usual” alternative. Estimating benefits is a complicated matter mainly because it is difficult to decide which benefits to include in the analysis, and because some benefits are very intangible and difficult, if not impossible, to convert into monetary terms. There are a large variety of different benefits, ranging from very easily assessable benefits such as energy savings and reduction in discharge taxes to the intangible benefits such as the benefit of maintaining a lake with a high biodiversity. The choice of benefits and how they are changed into monetary terms can influence the final result significantly. A thorough discussion about the benefits is therefore a necessary preliminary step before the actual decision analysis starts.
Risk is calculated as the probability of a failure multiplied by the expected cost associated with failure. This way of calculating the risk corresponds well to the common place definition of risk as: probability times consequence. With this way of estimating the risk it can be implemented directly in the Cost-Risk-Benefit concept. If the failure is calculated through a probabilistic simulation, the risk will represent the price society will have to pay on average as a consequence of failures in the urban wastewater system. Assessing the cost associated with failure is not a trivial task. The problem is the same as with benefits i.e. what should be included in the price and what is the value of the different parts that are included. Even a simple definition such as, “the cost associated with failure is equal to the price of restoring the damage” is difficult because it is hard to know in advance what the price of cleaning up will be. If other elements such as compensation to affected people, loss of image, loss of earnings etc. is included it becomes even more complicated.

As mentioned above, all elements in cost-benefit-risk analysis are associated with large uncertainties for many different reasons. It is therefore important to make a sensitivity analysis of the results as a part of the analysis. This sensitivity should as a minimum include sensitivity to changes in unit prices for cost, risk and benefits. Other important elements to include in the sensitivity analysis are changes in lifetime, interest level and level of parameter uncertainty.

An application example
In this example cost-benefit-risk analysis is applied as a decision tool on a hypothetical system. The analysis concerns a performance improvement of an existing urban wastewater system, which includes one combined sewer catchment, one basin with overflow to a small stream and a wastewater treatment plant discharging to a lake located at the downstream end of the stream (see Figure 2).

The inspiration to this example comes from a trend in Danish urban water management, where the counties require very large storage volumes in combined sewer systems as a solution to all kinds of urban drainage problems. Volumes up to 25 mm have been mentioned in some cases (DVPC, 1998). Storage volume of this magnitude is very expensive. This example seeks to investigate whether or not this large investment could be placed more efficiently, either by using the budget for building decentralised rainwater infiltration trenches or by combining a smaller basin with construction of infiltration trenches.

The following three alternatives are compared:
- 25 mm storage volume
- Disconnection of 60% of the reduced area into infiltration trenches
- 10 mm of storage volume and disconnection of 30% of the area

Simplified model
The model of the system is built by combining simplified models of the different parts of the system into one integrated model. Simple models are necessary in this type of calculations, in order to bring down the computation time to a realistic level. The failures are assumed to be independent, and all parameters describing the wastewater system are assumed constant but uncertain. The uncertainty is taken into account by making Monte Carlo simulations, where a normal distribution with standard deviation 10% of the mean value describes the uncertainty of the model parameters. The parameters are assigned with a new value for each model call. One model call simulates a 10-year period with data from a Danish rain gauge as precipitation input. All values for water consumption, concentration levels etc. are chosen according to average values for Danish conditions (Hauger and Nielsen, 1999). The Monte Carlo simulation of each alternative consists of 400 model calls.
Failures formulated on five different criteria are included in the analysis, three concerning the physical structures and two concerning the water quality of the receiving waters. The five criteria are:

- Number of overflows per year
- Effluent from WWTP, maximum N_{tot} concentration
- Effluent from WWTP, maximum P_{tot} concentration
- Minimum DO in stream
- Maximum steady state P concentration in lake

Minimum dissolved oxygen concentration is modelled with an event based Streeter Phelps model, assuming a 0’ order oxygen consumption in the bottom and a first order consumption in the waterphase. Flow is assumed uniform, no dispersion takes place and discharge is stationary and fully mixed during the event (Harremøes and Malmgren-Hansen, 1990). Failure is calculated as the fraction of one-year events (one event per model call) where the minimum dissolved oxygen concentration is below the acceptance level. The carrying capacity is based on the oxygen level necessary for trout survival. The acceptance level is defined as a normal distribution with mean value 4 mg/l and standard deviation 0.4 mg/l.

The phosphorus concentration in the lake is modelled with an empirical model, which has been found to fit conditions in Danish lakes well (Danish EPA, 1990). A lake is significantly influenced with phosphorus when the concentration in the waterphase exceeds 80–150 µg/l. The load is calculated as the yearly mean value of phosphorus in the lake and the carrying capacity is calculated as a normal distributed value with mean 115 µg/l and standard deviation 11.5 µg/l. Probability of failure is the fraction of years where the lake is significantly influenced.

The effluent water quality from the wastewater treatment plant is evaluated by simulating the control procedure that the local county is performing on all large treatment plants in Denmark. At a random day each month a 24 h flow weighted sample is taken. If the result of the samples over the whole year is above the acceptance levels it is counted as a failure year. Probability of failure is calculated as the fraction of years where the acceptance levels are exceeded.

**Costs, benefits and risks**

Construction cost for infiltration trenches is set to 200 Euro per m$^3$ trench. The prize is based on unit prices on excavation, piping, transport of materials etc. The trenches are designed with overflow to the sewer system, meaning that stormwater that can not be stored in the trench will be directed to the sewer system under extreme events. Construction cost for basins is estimated on the basis of information from Danish consultant engineering.
companies. Construction cost depends on the size of the basin according to the following relation:

\[
\text{Basin cost (m}^3\text{)} = 65,000 \cdot \text{Volume}^{-0.7} \text{(Euro)}
\]

The expected cost of failure is set to 100,000 Euro for all failure types. This price is a hypothetical value and there is no correlation to the actual price of restoring the damage after a failure. The only benefit included is the reduction of discharge tax from the WWTP and CSO structure compared to the initial system. According to Danish law municipalities have to pay a tax for every kilo of N, P and BOD discharged from the wastewater system (Danish Ministry of Environment, 1998). The lifetime and interest rate has been set to 50 years and 4%.

Results

Probability of failure for the three scenarios and the initial system are displayed in Table 1. For the two alternatives involving detention basins, the tendency is the same. Oxygen problems and number of overflows is reduced but the WWTP fails more often. This is a clear example showing that solving some problems (number of CSOs and oxygen problems in the stream by building storage basins) creates other problems (increased discharge of nutrient from the WWTP and eutrophication). None of the alternatives reduce failures to a level where the contribution to NPC becomes insignificant. In fact risk accounts for more than 50% of the NPC for all three alternatives (Table 2).

The NPC for the three alternatives can be seen in table 2. The most feasible solution is clearly the combination alternative, having 25% lower NPC than the other two alternatives. For alternative 1 and 2 the total benefit is negative, because the discharge from the WWTP is larger than in the initial situation (before any improvements were built). This is because the higher loading of the WWTP causes longer periods with increased effluent concentrations and thus increased discharge taxes.

Discussion and conclusions

The intention with this example was to show the application of cost-benefit-risk analysis, and not to give a general recommendation of how to design urban wastewater systems. It is most likely that other systems with a different set of parameters will show other results.

Risk analysis together with the traditional cost-benefit analysis is a method for finding the most feasible improvement alternative. NPC as decision variable, as well as other

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Probability of failure (in %)</th>
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<tbody>
<tr>
<td>Criteria</td>
<td>Acceptance level</td>
</tr>
<tr>
<td>No of CSO</td>
<td>&lt;= 5/year</td>
</tr>
<tr>
<td>WWTP N\text{tot}</td>
<td>&lt;= 8 mg/l</td>
</tr>
<tr>
<td>WWTP P\text{tot}</td>
<td>&lt;= 1.5 mg/l</td>
</tr>
<tr>
<td>DO in stream</td>
<td>&gt;= 4 mg/l</td>
</tr>
<tr>
<td>P\text{tot in lake}</td>
<td>&lt;= 115 mg/l</td>
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<table>
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<tr>
<th>Table 2</th>
<th>The results of the simulations. Values in mill Euro</th>
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<tr>
<td>Alternative</td>
<td>Cost</td>
</tr>
<tr>
<td>1: Basin V = 25 mm</td>
<td>0.57</td>
</tr>
<tr>
<td>2: Basin V = 10 mm. Infiltration di = 30%</td>
<td>0.57</td>
</tr>
<tr>
<td>3: Infiltration di = 60%</td>
<td>0.57</td>
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</table>
multi-criteria methods that use economics as scale have disadvantages. One alternative
with high risk and low cost and another with low risk and high cost can have the same NPC.
In these cases the decision maker has to decide whether the budget should be spent on build-
ing preventive installations or cleaning up after failures. This paper explains how the cost-
benefit-risk concept can be applied to urban drainage problems. The concept is illustrated
with a simple application example.

Cost-benefit-risk is a useful method for integrated analysis of urban wastewater sys-
tems. It opens up the opportunity to take into account risk and uncertainty, two elements
that have not normally been part of integrated modelling efforts up till now. There are on
the other hand also disadvantages. The major disadvantage is the problem with converting
intangible benefits into monetary terms. In this example all problematic benefits are left out
because attempts to assign a value to the benefit failed. Another disadvantage is that conse-
quences of failure are difficult to predict or estimate. One way to work around some of the
problems is to skip NPC and thereby economics as decision variables and make a regular
multi-criteria analysis instead. This makes normalisation and weighting easier but it also
makes the result of the analysis more difficult to relate to.

The appropriateness of the framework in which the system can be analysed is open for
discussion, but the fact that uncertainty and variation play an important role in the perform-
ance evaluation of wastewater systems is evidential and should be given attention.

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