Uncertainties in water system models – breaking down the water discipline silos

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INTRODUCTION

This paper is the result of a workshop held in November 2010 with 12 participants active in different water disciplines that had the desire to exchange on their different methods of handling uncertainties. The water systems covered included: groundwater, catchment hydrology, wastewater treatment, stormwater, (integrated) urban drainage and water distribution. The initiative of the workshop was the realization that uncertainty is increasingly being addressed in these different disciplines:

1. In the EU Water Framework Directive Guidance Documents numerous references are being made to the issue of uncertainty in river basin management. Because dealing with uncertainty is not yet operational with decision makers, major research is being conducted in this direction (Refsgaard *et al.*, 2007; van der Keur *et al.*, 2010);
2. For urban drainage systems uncertainty-related methodologies are scrutinized by the International Working Group on Data and Models that works under the Joint IWA/IAHR Committee of Urban Drainage (Deletic *et al.*, 2009);
3. Within wastewater treatment a Design and Operations Uncertainty Task Group was initiated under the IWA umbrella (Belia *et al.*, 2009). DOUT focuses on the uncertainties in model-based decision-making for wastewater treatment plant design and operation and aims to make uncertainties more explicit than is now the case in this profession, where safety factors are the current paradigm to deal with uncertainties.

In fact, the workshop taught us that 30 years ago a process was started in the urban drainage discipline in Denmark where experience-based safety factors in the dimensioning of sewer pipes were gradually abandoned for sharper dimensioning on the basis of dynamic simulation models (Figure 1). Twenty years later, however, a change in legislation that made designers accountable for problems with sewer systems changed this evolution into a re-design of safety factors that are explicitly accounting for particular uncertainties, among which are the effects of climate change.

It appears that, even today, the wastewater treatment discipline is going through a strikingly similar thinking process with the widely accepted belief that the use of so-called process models leads to more resource-effective designs (e.g. smaller volumes). However, it may be that making uncertainty and variability more explicit actually leads to the adoption of larger safety factors.

The workshop was thus very timely in ensuring that the developments regarding uncertainty methods and their practical use are shared among the different disciplines. For instance, major methodological contributions regarding uncertainty originate from the hydrology field (from the viewpoint of water disciplines), but is it possible to successfully transfer these methods to other water disciplines? The extent to which methods are around is exemplified by the fact that van der Keur *et al.* (2010) recently created a meta-guidance (a guidance on available guidances) used to navigate through the wealth of uncertainty-related tools.

FRAMEWORK

The workshop focused on creating a framework to discuss uncertainty in different water engineering fields. The first consensus among the representatives of the different disciplines was that the classification of uncertainties should be based on the three dimensions of uncertainty as proposed by Walker *et al.* (2003) but modified according to Refsgaard *et al.* (2007) and van der Keur *et al.* (2008). Uncertainty can be characterised by (i) source, i.e. where does it originate from, (ii) type, i.e. can it be described statistically, by scenarios, qualitatively or as ignorance (Figure 2) and (iii) nature, i.e. the uncertainty can be due to imperfect knowledge and is thus reducible (epistemic uncertainty) or it may be due to inherent variability, thus making it not reducible (onthological uncertainty).

Quite a discussion was held about the sources of uncertainty and how they should be represented. While the equation below seems extremely simple, its interpretation initiated a vigorous discussion among the participants, partly due to varying backgrounds, practices and terminologies in the different disciplines.

$$Y(t) = f(X(t), \theta \mid S)$$

X and Y are vectors of variables, Y being the model outputs (the variables one is interested in) and X the inputs (forcing functions). In the model structure f() the parameters are represented by θ. They do not change with time (in some water disciplines parameters can be time-varying, but we agreed that we should consider these model constituents as variables). The outcome of f is conditional on S, standing for scenarios that are fully quantifiable, e.g. a future climate scenario is one that is fully defined.

Sources of uncertainty can be found in f (model structure uncertainty), X (input uncertainty), θ (parameter uncertainty) and S (scenario uncertainty). Assessment of the impact of uncertainties in f, X, θ, S and their propagation into Y is known as the forward modelling problem. Assessment of uncertainties in θ (and/or f) by comparing Y to corresponding measurements is termed the inverse modelling problem; this was the subject of most of the discussions during the workshop.

FORWARD AND INVERSE MODELLING

First, it was generally agreed in the group that forward modelling, i.e. propagating uncertainties in f, X(t) and θ into Y(t), is, for all practical purposes, a solved problem, even though its transfer into practice is still suffering from a lack of available compute power and training. The (sampling) methods have reached a maturity that is more than satisfactory for most of the applications at hand. Of course, the suitable methods should be selected on a case by case basis, but no clear gap could be identified where research is required.

Something different holds for the assessment of uncertainties. Assessing qualitative uncertainties and recognized ignorance (evidently nothing can be stated about assessing total ignorance) is a field in full development. Developments occurring in the water-related social sciences focus on novel ways for qualitatively generating uncertainty profiles through drawing out context specific understandings of risk perceptions and tacit knowledge of the system from key stakeholders. When it comes to scenario analysis, methods for scenario building have been developed and are becoming increasingly mature with contemporary approaches focusing on the relationship between the societal and biophysical systems. Ultimately however, decision makers faced with plausible scenarios producing different outcomes, will need to trade-off robustness (or insensitivity to different scenarios) against performance.

Finally, when it comes to statistical uncertainties, it is observed that many methods have been proposed. This doesn't mean that the problems for this assessment have been solved. In principle one wants to determine the values and uncertainties in θ and/or f from known X and Y. The participants of the workshop consisted both of frequentists (basically the training that most water professionals have had) and Bayesians. However, the consensus was reached that inverse modelling is probably best done according to the Bayesian paradigm for it offers the necessary statistical rigour and allows integrating models and observation systems that account for all significant sources of uncertainty. Also, the assumptions made can be scrutinized. The question remains, however, whether classical Bayesian inference methods can be employed in complex models (particularly integrated models that link hydrology, water supply, ecology, socio-economics, …). Also, quite some work is still required to understand the error models and make the approach work. From the discussions evolved the four step procedure of Figure 3. It encompasses both frequentist and Bayesian approaches.

REMAINING CHALLENGES

Key challenges we agreed upon were related (i) to the question on how to assess prediction uncertainties for situations where we don't have data for calibration/validation (e.g. ungauged sites, future scenarios), ii) to the critical importance of data sets (size, content) used for the inverse modelling, (iii) to the conclusion that model structure uncertainty probably dominates statistical uncertainties and that we are ill-equipped to actually deal with this type of uncertainty, (iv) to the fact that, despite the availability of different methods for statistical uncertainty estimation, scenario analysis is an important method to explore recognized ignorance, (v) to reducing predictive uncertainty through better consideration of the different sources of uncertainty, (vi) to how one can best utilise the quantified uncertainty in the decision making process, and (vii) how to help decision makers deal with qualitative or scenario uncertainty.

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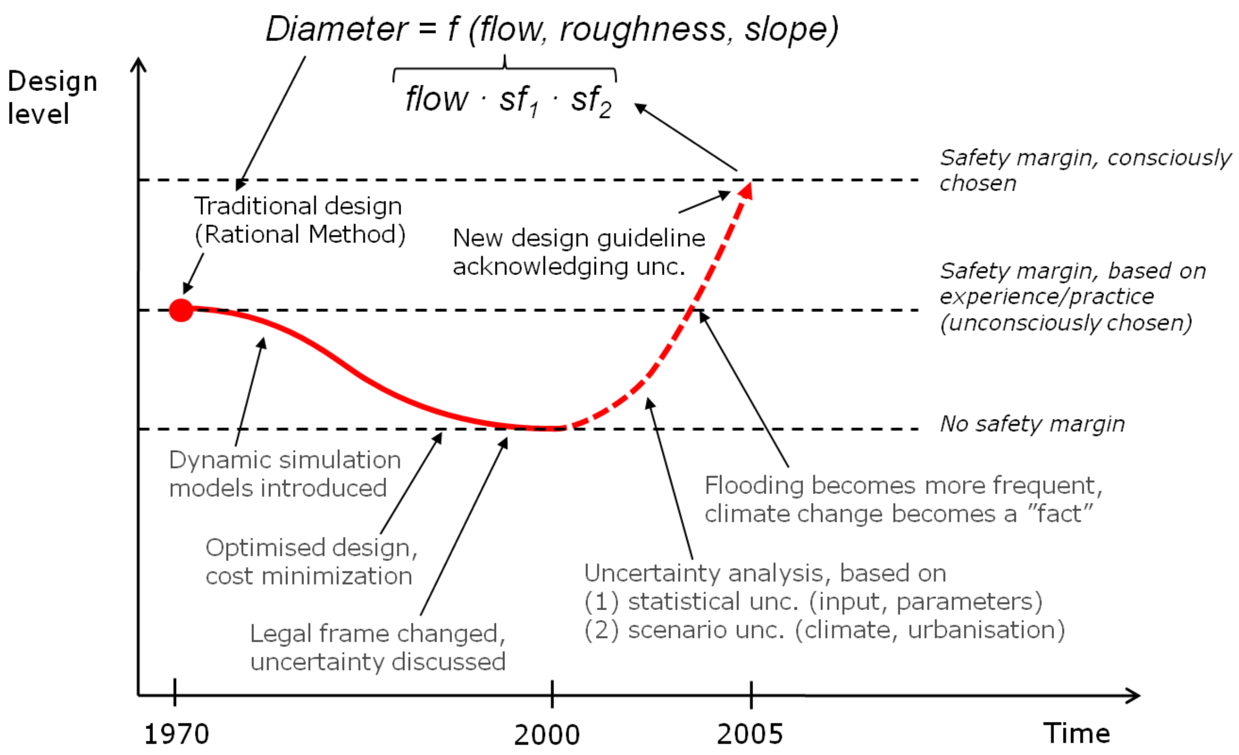

Figure 1. Temporal evolution of safety margin in sewer pipe design, Denmark (Mikkelsen, personal communication)

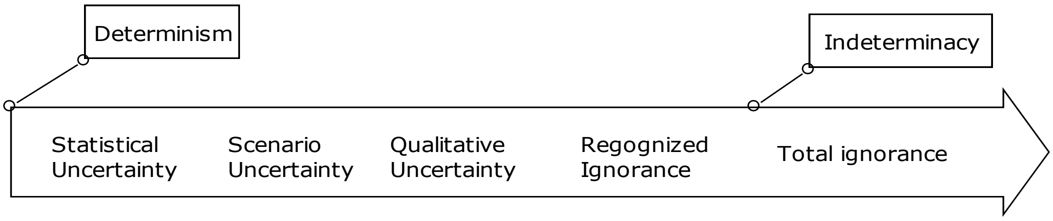

Figure 2. Types of uncertainty according to van der Keur et al. (2008)

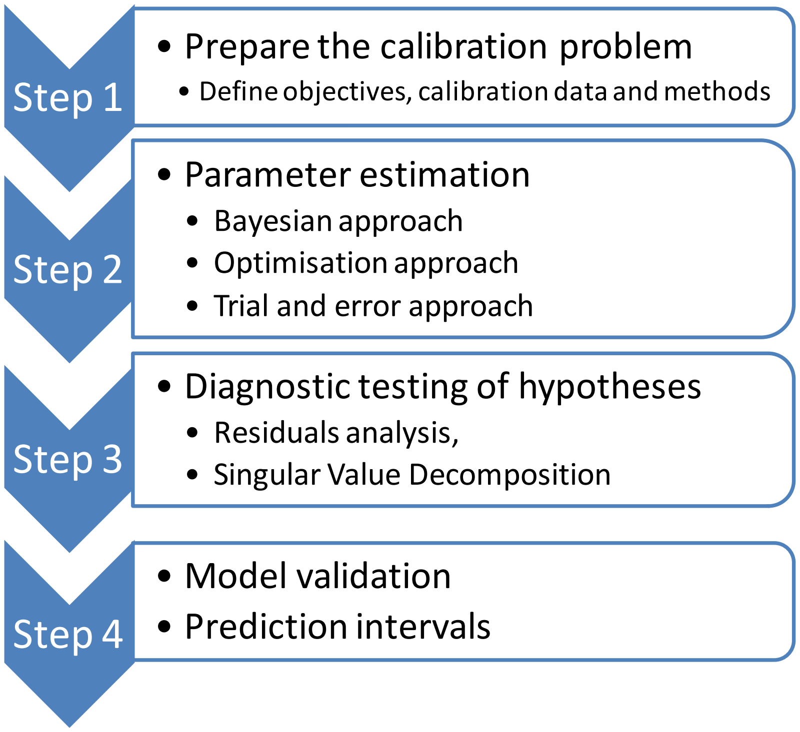

Figure 3. Step-wise procedure for inverse modelling (statistical uncertainty assessment)