Wastewater treatment modeling: discussing uncertainty

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Introduction

Uncertainty is a term that is being used often by the media to describe both the current world financial crisis and the predictions on climate change. In wastewater, however, uncertainty has been part of the job for plant designers and operators since the commissioning of the first biological treatment plant. The unpredictability of certain aspects of wastewater treatment, like the characteristics of the influent or the response of the bacterial community, has forced engineers and operators to account for uncertain variable plant responses. The recent WERF Nutrient Removal Program work on quantifying effluent variability is a perfect example of the uncertainty inherent in plant performance (*WERF, 2008*).

Uncertainty can be defined and classified as follows:

Uncertainty: Having limited knowledge about a system or process and not being able to exactly define the future outcome of a current action, because more than one outcome is possible. It can be classified as reducible or irreducible.

- ***Reducible*** – Uncertainty that can be reduced if further research or measurements are undertaken (e.g., determination of kinetic parameters).
- ***Irreducible*** – Uncertainty due to the inherent variability of a system that cannot be reduced regardless of further research/efforts (e.g., rainfall, toxic spills).

Historically, design engineers have addressed the uncertainty involved in predicting the performance of wastewater treatment plants (WWTPs) through the implementation of safety factors. In the 1993 *EPA Manual on Nitrogen Control*, as part of a design approach for a nitrifying suspended growth system, the following was mentioned: '...the anticipated variations in process conditions and the uncertainty in the kinetic coefficients warrant a safety factor of 2.0' (*US EPA, 1993*). Similarly, plant managers require redundant systems that give them the flexibility to cope with the large variability that they experience on site (*WERF, 2003a*).

These semi-arbitrary safety factors are lumped expressions of the individual sources of uncertainty underlying any treatment process. They express the collective knowledge of the industry and are applied to the parameters (maximum nitrifier growth rate, aeration system transfer efficiency, clarifier loading rates...) that, through experience, engineers know introduce most of the uncertainty in design and operation. Safety factors are a tried and tested method that reflects the requirements for robust designs and risk minimization that are the hallmark of our industry.

This lumping of uncertainty, however, often results in overly conservative solutions. In the current regulatory environment of extremely low effluent nutrient standards and increased demands for operational efficiency, a new approach that identifies the main sources of uncertainty associated with each process could help us optimize our designs. Moving away from lumped uncertainty safety factors will help us maximize existing plant capacity and avoid over-sizing new plants. The current generation of wastewater treatment plant models can assist us in this, by providing a structure which allows the identification and quantification of the sources of uncertainty. Through the incorporation into our models of knowledge from other fields that have already implemented uncertainty evaluation methodologies, we can develop a protocol for the inclusion of uncertainty evaluations in plant design, upgrade and optimization projects.

To initiate a comprehensive discussion and research aimed at incorporating uncertainty evaluations into model-based engineering projects, the International Water Association (IWA) has set-up a new task group called: Design and Operations Uncertainty Task Group (DOUTGroup) (*http://www.iwahq.org/templates/ld_templates/layout_633184.aspx?ObjectId=679607*)

Uncertainty and design – an example

The following example illustrates how engineers currently incorporate uncertainty in their designs as well as the implications that this has on the decisions utilities are faced with.

A major utility in the US has requested bids for the expansion of its nitrogen removal process to meet a final effluent total nitrogen concentration of 3 mgN/L. The new process was designed with the aid of a commercial simulator and was sized very differently, depending on the selection of key inputs into the plant model. The three independent consultants chose different process, operational, and influent parameters and proposed three different reactor volumes (X m^3, 2X m^3 or 4X m^3) during the bid stage.

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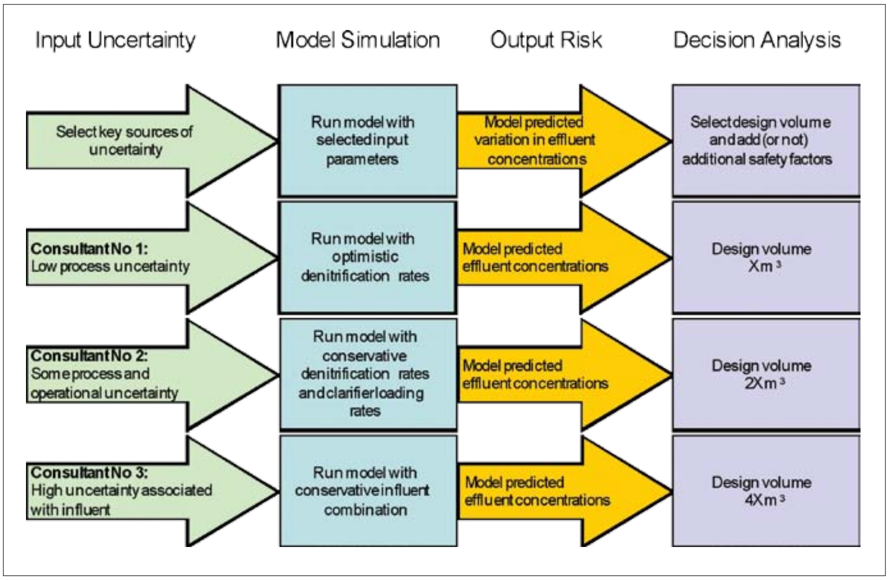

FIGURE 1 Model-based design process for the three proposed solutions.

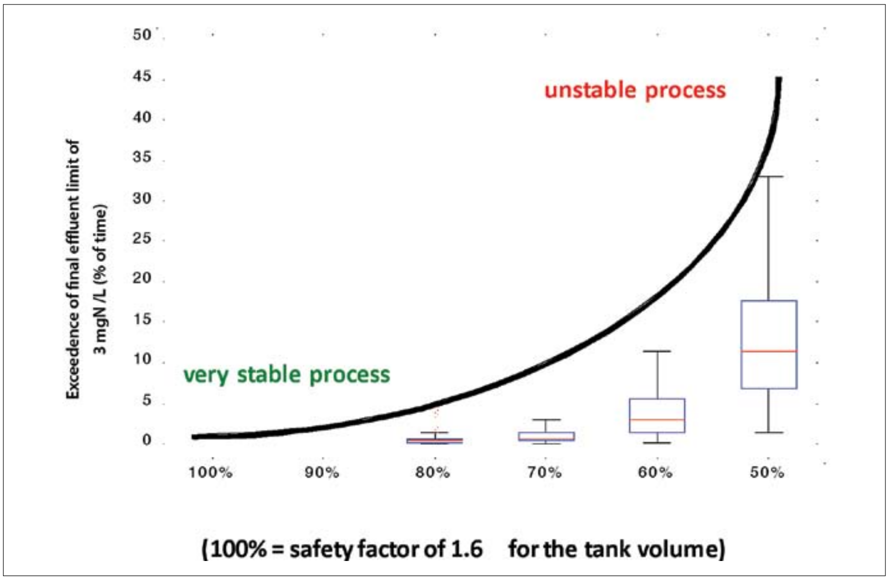

FIGURE 2 Exceedance of nitrogen effluent limit as percentage of time over a one-year evaluation period for a given process and a given time-varying influent as a function of tank size; 100% of volume refers to a design volume resulting from conservative guidelines).

The differing data inputs used by the consultants produced three widely variable outputs, which had multi-million dollar implications for the utility. One of the main parameters differentiating the three options, even though not explicitly stated, was the selection by each design engineer of the major sources of uncertainty of the new design. Figure 1 shows a simplified, pictorial representation of the model-based design process for each of the three solutions.

The first consulting firm assumed that there was very low uncertainty in the process rates and selected an optimistic value for the parameters describing denitrification rates in the model when using an external carbon source such as methanol. The second firm felt that the main sources of uncertainty were in the process and the response of the clarifiers. They decided that they wanted to lower the operational risk, because they felt that increased operator comfort was required. They selected a conservative denitrification rate and maximum clarifier loading rate. The third firm felt that most of the uncertainty was in the influent and, therefore, used conservative influent parameters for their design by combining the maximum flow and minimum temperature simultaneously.

The utility managers were faced with having to make a decision without being able to compare objectively the risk that each of the designs carried. This was due to the fact that an explicit evaluation and quantification of the sources of uncertainty was not part of the design brief. A more systematic methodology quantifying the uncertainty in each of the critical model parameters was needed to enable the utility to compare objectively the three options.

Identifying and analyzing uncertainty

Figure 2 shows an example of how the quantification of uncertainty could be used to clarify the decisions of each consultant to the utility manager (*Benedetti, 2006*). By running multiple simulations with different process parameter values (e.g., denitrification rates) and tank volumes, each consultant could generate process profiles like the one shown in Figure 2. The graph presents a quantification of the probability that a given process will exceed the final effluent nitrogen limit depending on the size of the reactor. Using this information, the consultant can choose his or her preferred tank volume and justify that decision to the client based on the level of risk he or she is willing to take. The risk in the design is now expressed as the probability that the plant will be non-compliant for a given percentage of time. For example, by choosing the 70% volume, they will have a risk of under-designing the tank (90% sure that TN is exceeded less than 3% of the time), or, with 100% volume, that risk is much lower (90% sure that TN is exceeded less than 0.3% of the time), but the cost of the design increases and the bid could be lost.

In the case where the consultant feels that an important source of risk lies in the final clarifier operation, statistical distributions of the clarifier loading rates for different operational conditions can be generated by the model. From these, summary graphs can be created showing the probability that the clarifiers will be operating at their limiting flux for

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different flow rates, as shown in Figure 3 (*Leaf and Johnson, 2008*).

Figure 3 shows that, if the design engineer decides that the clarifiers should operate at 90% of their maximum flux once every five years, then the monthly average plant flow that the plant can treat is approximately 35.2 ML/d. If the design target is once per year, then the design capacity of the plant is approximately 40.1 ML/d.

These examples show that models can be used to quantify the uncertainty in a specific area of the treatment process and can provide the stakeholders with realistic information. It is then possible to make an objective decision and provide the owner with an objective criterion for evaluating the engineer's design choice.

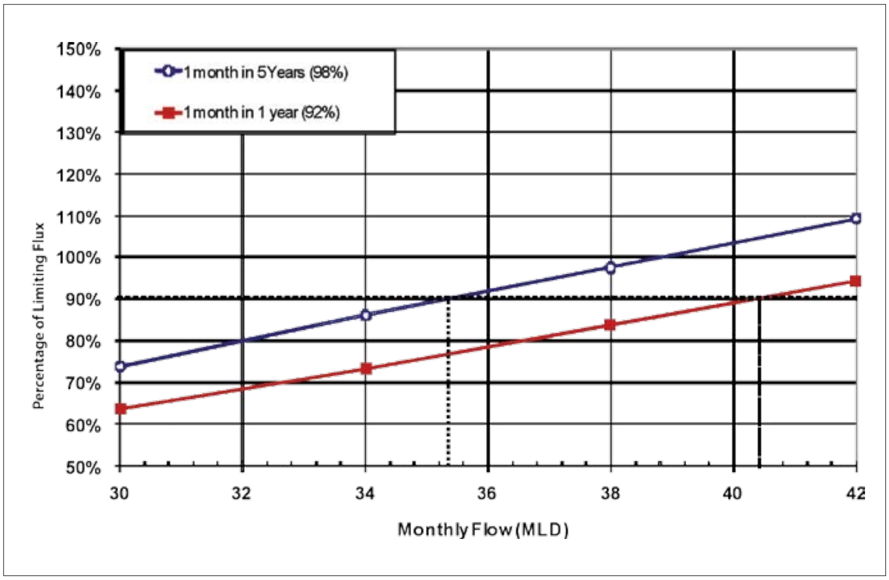

FIGURE 3 Percent of limiting flux that the clarifiers will be operating at for various plant flows.

Summary and future direction

Current regulatory demands require plant owners to design and operate processes close to their limits, while at the same time increasing energy efficiency. Conventional design approaches can often lead to conservative designs and do not provide objective ways of quantifying the risk involved in the decisions utilities and engineers make. Process models can be used as tools for the quantification of risk and uncertainty, thus providing stakeholders with the ability to explicitly quantify uncertainties and include risk evaluations in their decision-making process. To initiate the discussion of uncertainty evaluation in the wider wastewater engineering community, the research work of academics and the practical knowledge of process designers need to be combined with the needs of the engineers implementing modeling for various applications. To this end, the authors of this article are proposing a number of items that need to be discussed:

1) What are the concepts and definitions that need to be discussed so that a common language is established?
2) What are the important sources of uncertainty?
3) What are the available methods, quantitative or qualitative, that can be used to evaluate model prediction uncertainty?
4) How much effort should be put into the assessment of uncertainty?
5) Do all model applications require the same degree of detail of uncertainty evaluation?
6) What confidence levels are required for different modeling objectives?
7) How do we quantify risk?
8) What is the added benefit of including uncertainty evaluations in modeling projects?
9)How can uncertainty evaluations be incorporated into design and communicated to non-technical stakeholders?

A number of these items will be addressed as part of the work of the IWA DOUTGroup. It is the intent of the group to build on the knowledge already acquired by certain key efforts in the field of wastewater (*WERF, 2003b and 2008*), as well as the work done in related fields such as the Harmoni-QuA project (*Refsgaard et al., 2004*) from the field of water resources management. ♦

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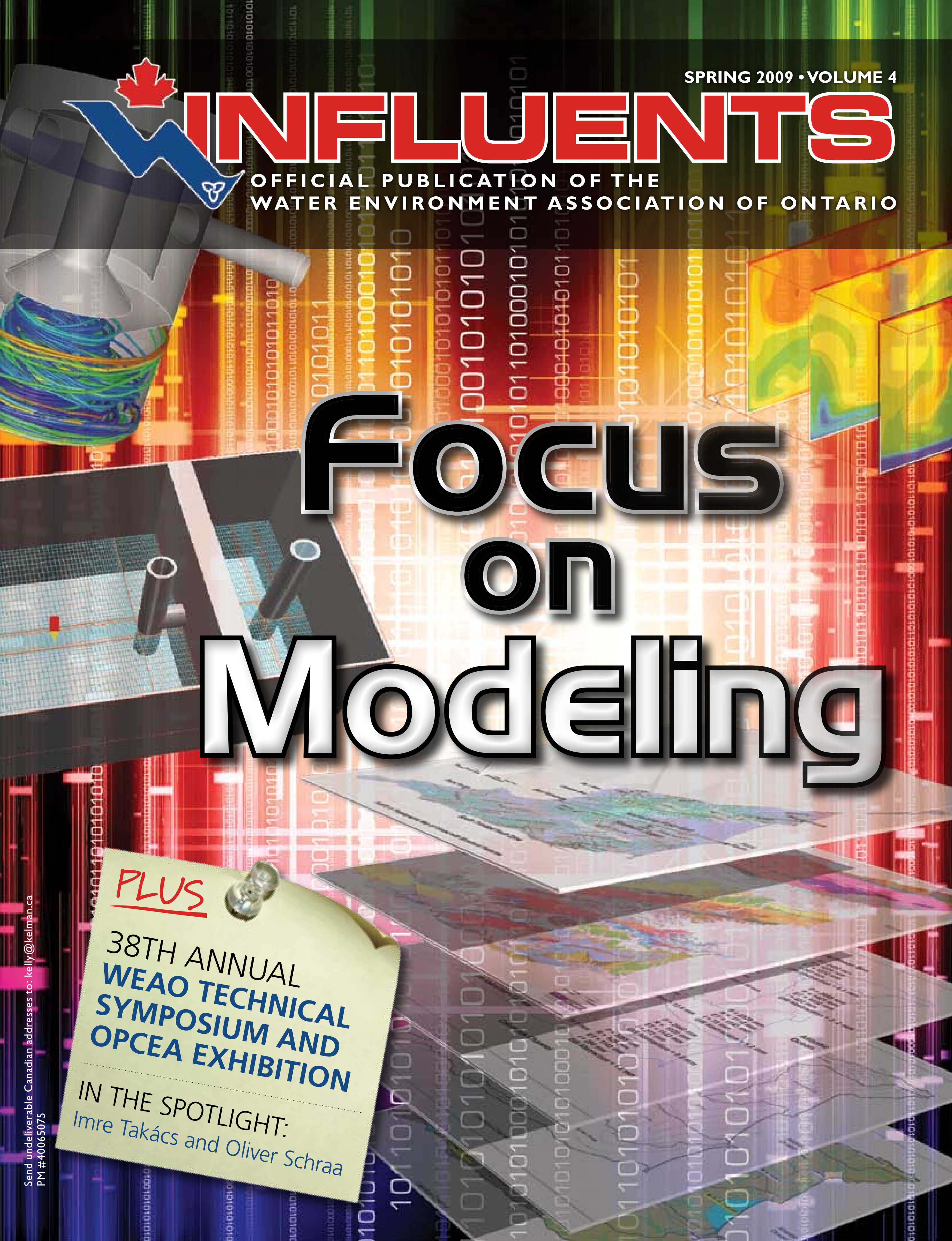

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