*International Environmental Modelling and Software Society (iEMSs)*
*7th Intl. Congress on Env. Modelling and Software, San Diego, CA, USA,*
*Daniel P. Ames, Nigel W.T. Quinn and Andrea E. Rizzoli (Eds.)*
*http://www.iemss.org/society/index.php/iemss-2014-proceedings*

# Probability-based Design of Wastewater Treatment Plants

**Mansour Talebizadeh[1], Evangelia Belia[2], and Peter A. Vanrolleghem[1]**

[1]model*EAU*, Département de génie civil et de génie des eaux, Université Laval, 1065 av. de la Médecine, Québec (QC) G1V 0A6, Canada
Email : *mansour.talebizadehsardari.1@ulaval.ca*, *Peter.Vanrolleghem@gci.ulaval.ca*
[2]Primodal Inc., 145 Aberdeen, Québec, QC G1R 2C9, Canada
Email: *belia@primodal.com*

**Abstract:** The primary goal of wastewater treatment plants (WWTPs) is to remove pollutants from wastewaters so as to reach a set of effluent standards under a set of environmental, cost, and regulatory constraints. To design a WWTP according to these criteria, design engineers usually make the initial sizing of the plant using design guidelines or a set of modeling tools under steady-state conditions. In these approaches the effect of different sources of uncertainties are taken into account in an implicit manner through the application of safety factors and/or selection of conservative design values for design inputs. In this study, the application of a set of statistical and process-based dynamic modeling tools is proposed to explicitly characterize the uncertainty/variability in the input time series and model parameters and propagate these into the uncertainty in the model outputs (i.e. effluent wastewater composition and costs). Depending on the effluent standards the probability of non-compliance (PONC) to the effluent standards can be calculated. The proposed probabilistic methodology provides the design engineers with a concerted framework to utilize and incorporate into the design of WWTPs the available and future information on the characteristics of the sewershed and the climate conditions, as well as the latest advances in dynamic modeling. Moreover, the calculated PONC can be used as an objective criterion for comparing different design alternatives and help designers avoid the application of overly-conservative safety factors.

**Keywords**: Design under uncertainty; Monte Carlo simulation; stochastic generation; Wastewater treatment plant;

## 1. INTRODUCTION

Wastewater treatment plants (WWTPs) are complex engineering systems whose failure to meet performance requirements can have detrimental effects on public health and the environment. A WWTP system should be designed such that it is capable of coping with the dynamic flow and loading conditions as well as any sources of uncertainty that could result in non-compliance events with the effluent standards set to protect human and ecosystem health. However, in practice the initial sizing of a WWTP is performed, by assuming steady-state conditions. In design methods that are based on the assumption of steady-state conditions (whether the design is based on a specific design guideline, e.g. ATV (2009) or a steady-state model (Ekama, 2009)) representative values are to be selected for design inputs (e.g. representative values for influent flow and concentrations and the required effluent standards, as well as the operational, kinetics, and stoichiometric parameters) and the dimensioning of the WWTP is done according to a set of experience-based rules or a set of empirical and/or process-based equations (Talebizadeh et al., 2012).
Despite the fact that the design guidelines do not necessarily use process-based equations for determining the size or the operating conditions of certain units of a WWTP (e.g. determining the area of a the secondary clarifier as a function of the surface overflow rate), the design guidelines are

frequently being used for the design of WWTPs and their applications might be obligatory depending on the regional regulations where the plant is to be built or upgraded (ATV, 2000).

Keeping in mind that the design guidelines are based to a great extent on the invaluable knowledge that has been gained from years of experience on design and operation of WWTPs and pilot plants, they have certain shortcomings. For example, in design guidelines the uncertainty is taken into account by applying safety factors and/or making conservative assumptions regarding the design inputs (Talebizadeh et al., 2012). One of the problems with applying safety factors to different elements of design is the double counting of a specific source of uncertainty. This could lead to an overly-conservative and possibly expensive design without necessarily providing a worthwhile benefit (Doby, 2004). Meanwhile, the inflexibility of design guidelines hinders the design engineers to better incorporate readily-available or easy-to-obtain information on climate conditions, basic sewershed characteristics, and process dynamics into their decision on the final sizing of a WWTP.

Considering the increasingly stringent effluent limits (Vanrolleghem, 2011) that are defined in terms of both value and frequency (e.g. the daily mean concentration of a pollutant in the effluent should not exceed a certain concentration more than N times in a year) and/or to be met with data averaged over a certain period (e.g. two-hour average concentration), the application of dynamic models is inevitable to gain some insight in the dynamics of the effluent and meeting the effluent standards.

Contrary to two decades ago in which the application of dynamic models was in its infancy and limited to academic and research domain, these models have become quite popular and are now being used to assess the performance of a WWTP under dynamic conditions as well as determining the optimal operating conditions of plants. Also dynamic models enable the designers and plant operators to test the performance of recent innovative treatment technologies whose applications are not as widespread as the conventional treatment systems like the activated sludge systems.

Moreover, dynamic models in conjunction with the Monte Carlo simulation procedure provide a tool to propagate uncertainties in model inputs to model output(s) and hence to provide a probabilistic evaluation of meeting the effluent standards. Several researchers have reported the application of Monte Carlo simulation along with the dynamic model of WWTP to assess the effect of different sources of uncertainty on the effluent (Rousseau et al., 2001; Bixio et al., 2002; Benedetti et al., 2006; Huo et al., 2006; Sin et al., 2009). However, in most of the studies of this kind, the main emphasis was laid on the uncertainty of model parameters and the characterization of the influent variability lacks statistical rigor (see Belia et al. (2009) for different types and sources of uncertainty).

Considering the shortcomings of the conventional design methods and lack of a rigorous approach for considering the effect of relevant sources of uncertainty in dynamic simulation of WWTPs, this paper outlines a new probabilistic method for the design of WWTPs that provides users with a quantitative criterion that measures the degree of compliance to the effluent standards in terms of probability.

## 2. PROPOSED PROBABILISTIC DESIGN METHOD

In this section the proposed design methodology along with the required data and modeling tasks are explained in detail. Figure 1 shows the various sources of information (the first column), modeling tasks and characterization of uncertainty (the second column), as well as the design method and the required simulations for evaluation of the different design alternatives that will be used in the proposed probability-based design methodology (the third column).

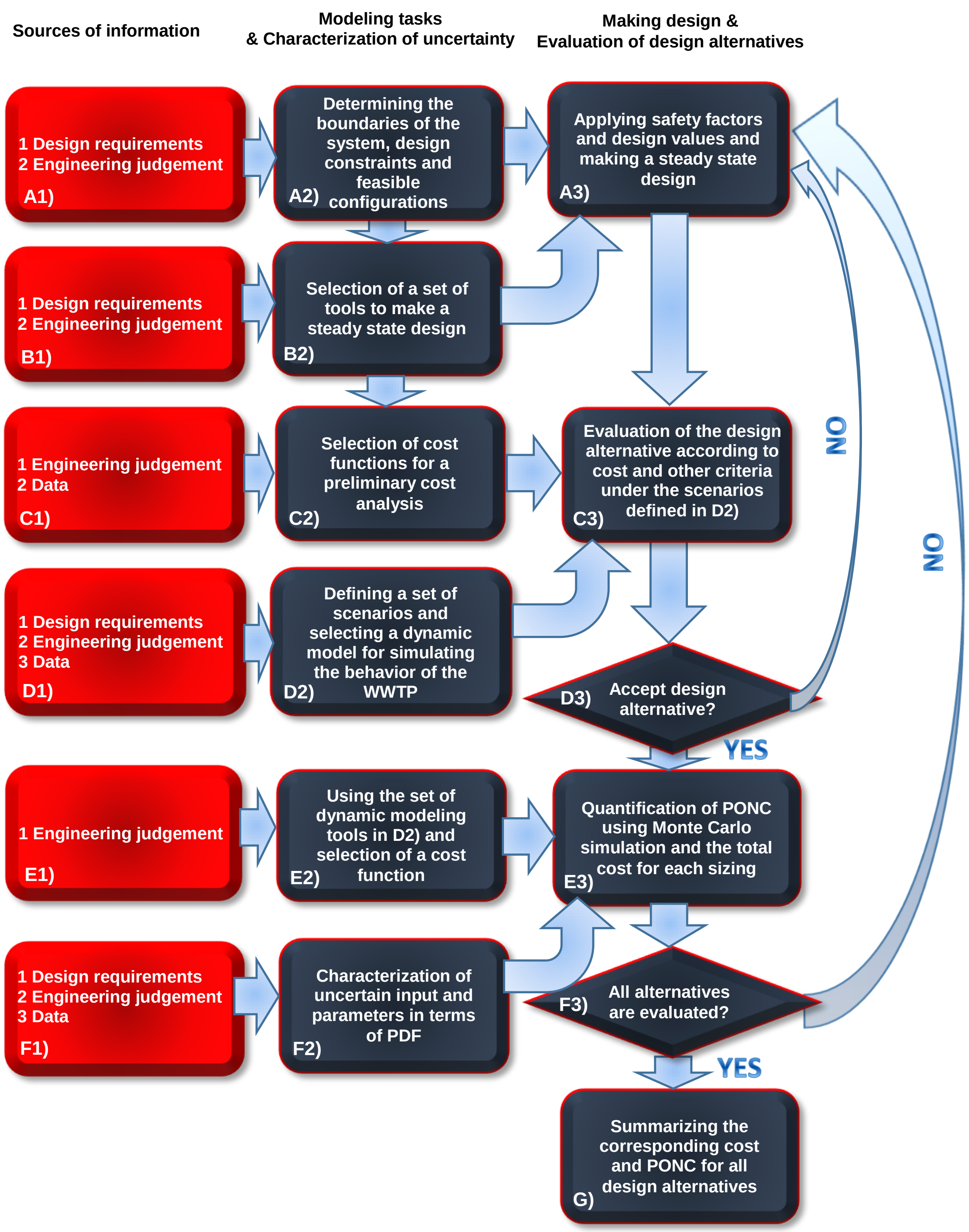


Figure 1. General methodology for probability-based design

## 2.1 Steady-state Design

Prior to making any design, the objectives of the project, design constraints and the responsibility of a design or construction firm towards its client should be clearly defined and the boundaries of the WWTP have to be determined. Demarcation of the boundaries of the WWTP system helps designers identify the required inputs and also the types of analysis required for evaluating the performance of different design alternatives.

Depending on the design requirements, site-specific conditions may make that some treatment technologies or configurations can be ruled out with little or no quantitative analysis (A2 in Figure 1). According to the proposed probabilistic design procedure, the initial sizing of a design alternative is made under steady-state conditions with a specific level of conservatism that is reflected in the selection of *design values* and safety factors (A3 in Figure 1).

Depending on the design requirements and engineering judgement a steady-state design tool should be selected (B2 in Figure 1). A common method that is based on the assumption of steady-state condition is the application of design guidelines in which the size of different treatment units is calculated using a set of equations based on the mass balance equations of the system under steady state conditions, empirical equations as well as of experience-based rules (Talebizadeh et al., 2012). However, in cases in which designers are not obliged to use a specific design guideline, the dimensioning of the different treatment units can be done using a process-based steady-state model (Ekama, 2009).

## 2.2 Preliminary Evaluation of Design Alternatives

A design alternative whose dimensions have been determined using a steady-state design method should be evaluated in terms of a preliminary cost function and its treatment performance under a limited number of dynamic hydraulic and pollutant loading conditions (C3 in Figure 1). Prior to any dynamic simulation or analysis, a preliminary cost function (Gillot et al., 1999) should be defined to obtain a rough estimate of the cost associated to each design alternative (C2 in Figure 1). Meanwhile a dynamic model should be selected to assess the performance of design alternatives under a set of typical dynamic loading scenarios (D2 in Figure 1).

The objective of this phase is to identify and eliminate those design alternatives which have huge costs or have a poor performance with respect to meeting the effluent standards. The preliminary filtering of weak design alternatives (D3 in Figure 1) has the advantage of reducing the computational load that will come with the intensive Monte Carlo simulation that is required for estimating the PONC in the next steps of the probabilistic design.

## 2.3 Quantification of PONC and Total Cost

The quantification of PONC constitutes the most innovative part of the proposed probabilistic design method. In this section the PONC will be estimated for design alternatives that have passed the preliminary filtering (i.e. due to a huge cost or a very poor performance under a set of dynamic loading scenarios defined in D2 in Figure 1). Figure 2 illustrates the different steps required for calculating the PONC for a specific design alternative.

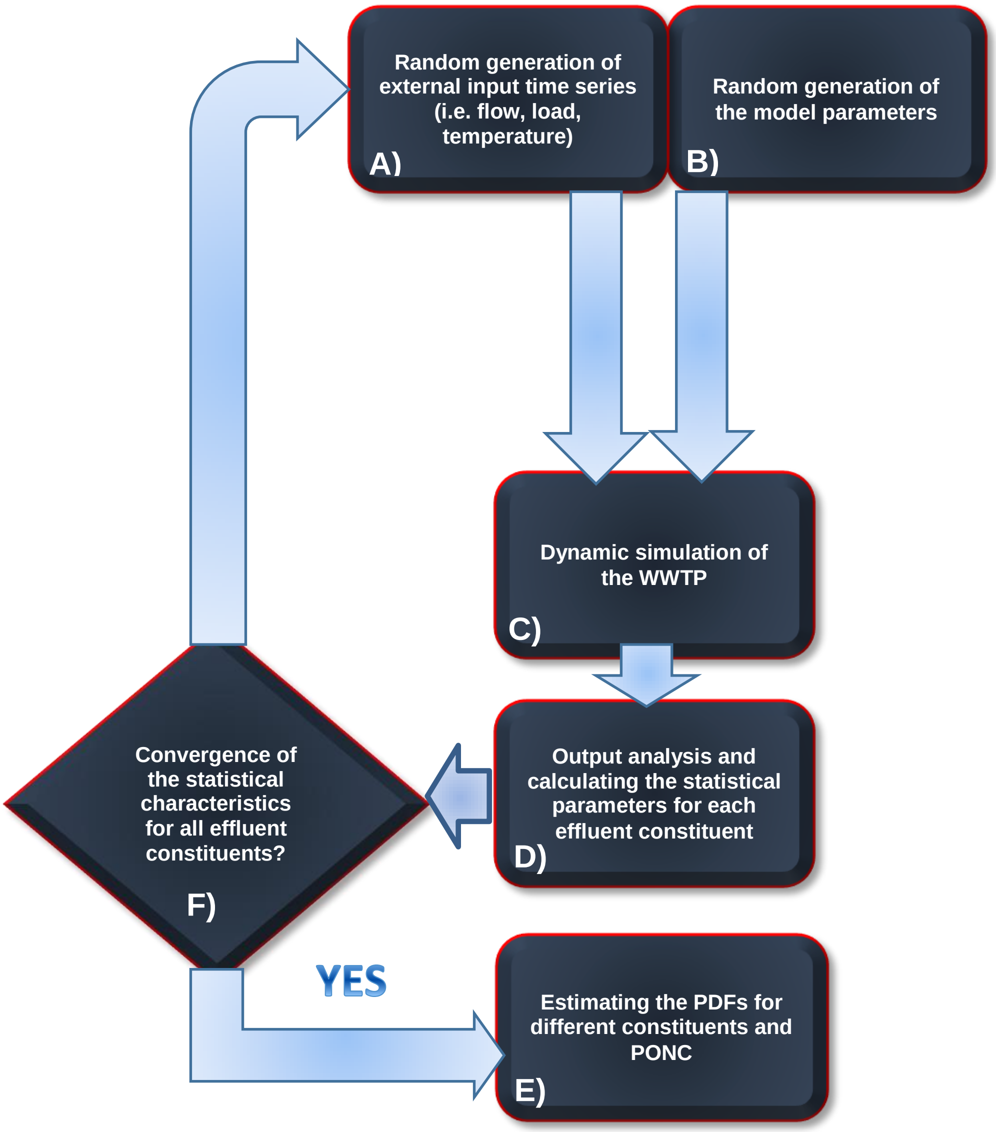


Figure 2. Calculating PONC for a design alternative

### *2.3.1 Random Generation of the External Inputs*

The performance of a WWTP system concerning the treatment of wastewater depends to a great extent on the amount and time variation of the influent. Therefore, it is of great importance to generate different realizations of the influent time series with similar stochastic properties as real influent time series. To this end, an influent generator was developed using a set of statistical and conceptual models for stochastic generation of the influent time series (Talebizadeh et al., 2014). In the developed influent generator the time series of rainfall and influent in dry weather flow (DWF) conditions are generated by two statistical models (i.e. a Markov chain-gamma distribution for rainfall time series and a multivariate autoregressive model with periodic terms for the generation of influent time series in DWF conditions). The rainfall and influent time series in DWF conditions are then input to a conceptual model of the sewer system to generate the time series of influent in WWF conditions.

### *2.3.2 Random Generation of Model Parameters*

As mentioned in a previous section dynamic simulation of a design alternative is indispensable for calculating its PONC. To simulate the effluent time series the dynamic model should be provided with influent time series and proper values should be set for the model parameters. The uncertainty in model parameters was characterized (i.e. F2 in Figure 1) by assigning uniform distributions to the model parameters. To consider the effect of model parameter uncertainty and the variability of the influent time series on model outputs, for each simulation run a vector of model parameters is sampled from the joint distribution of parameters and inputs to the model along with a realization of a year-long influent time series (generated using the developed influent generator).

### *2.3.3 Dynamic Simulation and Output Analysis*

Different realizations of effluent time series can be generated by inputting the model with influent time series and random samples from the joint distribution of model parameters. The required number of simulations depends on the statistical properties of the effluent time series. As a rule, simulation runs must be continued until the statistical properties of the different effluent constituents like average, standard deviation or a certain percentile become stable (Benedetti et al., 2011) (e.g. the statistical properties of effluent ammonia distribution become stable).

### *2.3.4 Estimating the Probability Distribution of Different Effluent Constituents*

Once the statistical properties of the effluent time series have converged, the cumulative distribution function (CDF) corresponding to each effluent constituent can be estimated. Beside the distribution of the effluent time series, the value of PONC depends on the effluent standards which could be very different depending on the legislative settings of the region in which a plant is to be built (Vanrolleghem, 2011). Depending on the effluent standards, the dynamic effluent time series must be aggregated to a time series with a lower temporal resolution by which the compliance to the effluent standards is measured. For example, if the daily average values of effluent concentration should be less than a certain limit, the simulated effluent time series must be aggregated to a time series with daily temporal resolution and the corresponding CDF is calculated using the daily average values (Figure 3).
By comparing the CDF of each wastewater constituent with the effluent standards, the PONC can be calculated for each design alternative.

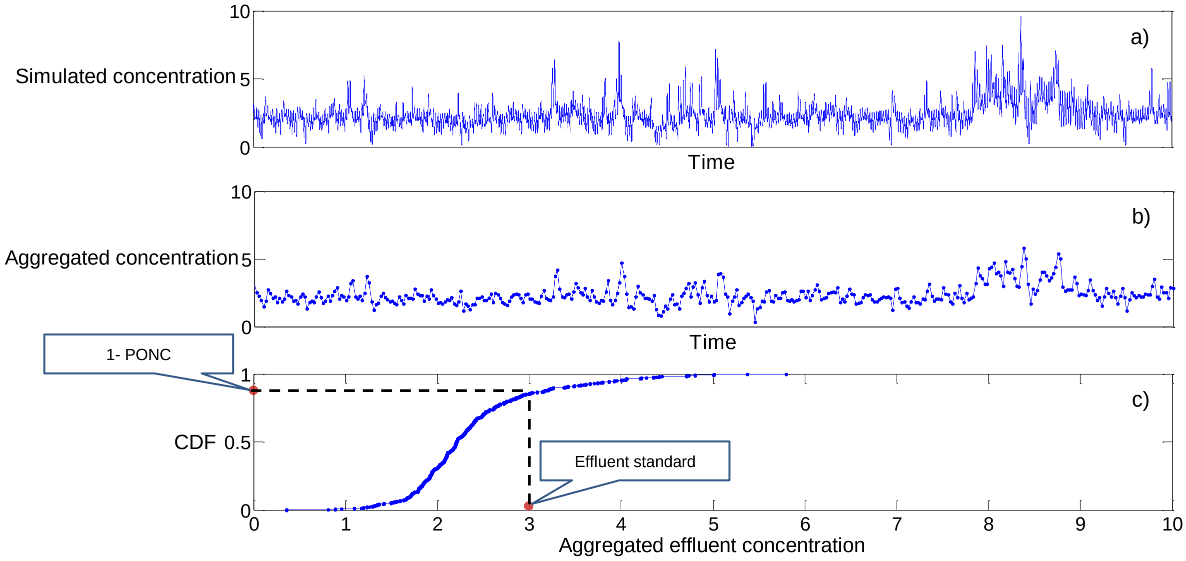


Figure 3. Estimating the PONC using the empirical CDF

### 2.4 Summarizing the PONC and Cost for Each Design Alternative

The PONC and the total cost (i.e. calculated using the cost function defined in E2)-Figure 2) will be calculated for each design alternative. These two quantitative criteria will be used among other quantitative and qualitative criteria for selecting the optimum design alternative (G in Figure 1).

## 3. CONCLUSION AND RECOMMENDATIONS

In this study the outline of a probabilistic design method for the design of WWTPs was presented. The relevant sources of uncertainties were identified and characterized by probability distribution functions (PDFs), and the probability of non-compliance (PONC) was calculated using a dynamic model of the plant and Monte Carlo simulation. Calculating PONC as a quantitative measure of safety for each design alternative helps designers better understand and compare the performance of different design alternatives. Even in projects in which the sizing of a WWTP should be consistent with a specific design guideline, the proposed probabilistic design can be used as a tool for selecting proper values for safety factors and other inputs that are required for dimensioning the different units of a WWTP. It should be noted that any calculated PONC depends on the validity of some assumptions. For example, in this study it is assumed that there is no interruption or failure in the performance of the technical components of the WWTP (e.g. pumps or sensors). Considering the impact of failure in technical components on PONC requires explaining their performance in terms of probability and doing a comprehensive reliability analysis. This could be the subject of future studies.

## 4. ACKNOWLEDGEMENT

This research work was funded by the Natural Sciences and Engineering Research Council of Canada (NSERC) and Primodal Inc. Peter Vanrolleghem holds the Canada Research Chair in Water Quality Modeling.

## 5. REFERENCES

ATV, 2000. Standard ATV-DVWK-A 131E, Dimensioning of Single-Stage Activated Sludge Plants. German Association for Water, Wastewater and Waste, Hennef, Germany.

Belia, E., Amerlinck, Y., Benedetti, L., Johnson, B., Sin, G., Vanrolleghem, P.A., Gernaey, K.V., Gillot, S., Neumann, M.B., Rieger, L., Shaw, A., Villez, K., 2009. Wastewater treatment modelling: dealing with uncertainties. Wat. Sci. Tech. 60(8), 1929-1941.

Benedetti, L., 2006. Probabilistic Design and Upgrade of Wastewater Treatment Plants in the EU Water Framework Directive Context. PhD Thesis, Ghent University, Belgium.

Benedetti, L., Claeys, F., Nopens, I., Vanrolleghem, P.A., 2011. Assessing the convergence of LHS Monte Carlo simulations of wastewater treatment models. Wat. Sci. Tech. 63(10), 2219-2224.

Bixio, D., Parmentier, G., Rousseau, D., Verdonck, F., Meirlaen, J., Vanrolleghem, P.A., Thoeye, C., 2002. A quantitative risk analysis tool for design/simulation of wastewater treatment plants. Wat. Sci. Tech. 46(4), 301-307.

Doby, T., 2004. Optimization of Wastewater Treatment Design under Uncertainty and Variability. PhD Thesis, North Carolina State University, USA.

Ekama, G.A., 2009. Using bioprocess stoichiometry to build a plant-wide mass balance based steady-state WWTP model. Water Res. 43(8), 2101-2120.

Gillot, S., De Clercq, B., Defour, D., Simoens, F., Gernaey, K.V., Vanrolleghem, P.A., 1999. Optimisation of wastewater treatment plant design and operation using simulation and cost analysis. In: Proceedings 72nd WEFTEC Conference. New Orleans, USA, October 9–13, 1999.

Huo, J., Jiang, Y., Seaver, W.L., Robinson, R.B., Cox, C.D., 2006. Statistically based design of wastewater treatment plants (WWTPs) using Monte Carlo simulation of Activated Sludge Model

No.1 (ASM1). In: Proceedings of the 2006 World Environmental and Water Resources Congress. Omaha, Nebraska, USA, May 21-25, 2006.

Rousseau, D., Verdonck, F., Moerman, O., Carrette, R., Thoeye, C., Meirlaen, J., Vanrolleghem, P.A., 2001. Development of a risk assessment based technique for design/retrofitting of WWTPs. Wat. Sci. Tech. 43(7), 287-294.

Sin, G., Gernaey, K.V., Neumann, M.B., van Loosdrecht, M., Gujer, W., 2009. Uncertainty analysis in WWTP model applications: a critical discussion using an example from design. Water Res. 43(11), 2894-2906.

Talebizadeh, M., Belia, E., Vanrolleghem, P.A., 2014. Influent generator for probabilistic modelling of nutrient removal wastewater treatment plant In: Proceedings 4th IWA/WEF Wastewater Treatment Modelling Seminar (WWTmod2014). Spa, Belgium, March 30 - April 2, 2014.

Talebizadeh, M., Martin, C., Neumann, M.B., Vanrolleghem, P.A., 2012. Global sensitivity analysis of the ATV design guideline: Which are the most important inputs for a WWTP design? In: Proceedings 85th Annual WEF Technical Exhibition and Conference (WEFTEC2012). New Orleans, USA, September 29 - October 3, 2012.

Vanrolleghem, P.A., 2011. Resolving the tensions over the treatment plant's fence: Diverse approaches around the world. Lecture held at the WEF/IWA Nutrient Recovery and Management Conference 2011. Miami, FL, USA, January 9-12, 2011. (Invited lecture).