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Analysis of rising sludge risk in Activated Sludge Systems: from operational strategies to clarifier design

Xavier Flores-Alsina[1], Joaquim Comas[2] and Ignasi Rodriguez-Roda[2,3]

[1] *modelEAU, Département génie civil et génie des eaux. Université Laval. Pavillon Adrien-Pouliot, 1065, avenue de la Médecine. G1V0A6. Québec, QC, Canada. e-mail:xavier.flores@gci.ulaval.ca*

[2] *Laboratory of Environmental and Chemical Engineering, Faculty of Sciences, University of Girona, Campus Montilivi s/n 17071. Girona (Spain). e-mail : {quim, ignasi}@lequia.udg.es*

[3] *ICRA, Catalan Institute for Water Research. H_2O building. Emili Grahit 17003. (Spain.) e-mail : irodriguezroda@icra.cat*

Abstract: The main objective of this paper is to evaluate the risk of suffering rising sludge problems under different modes of operation and clarifier designs using the IWA Benchmark Simulation Model no 1 (BSM1). First, as a reference case, waste flow, dissolved oxygen, external recirculation and the settling area were modified and the risk of rising sludge quantified. In a second series of simulations, the bio-kinetic parameters and the influent fractions of the Activated Sludge Model No 1 (ASM1) were considered uncertain and both Monte-Carlo and sensitivity analyses of rising sludge risk were carried out. The results of this study showed that rising sludge problems could be avoided either decreasing nitrification efficiency or reducing the biomass residence time in the bottom of the secondary clarifier. Also, the Monte Carlo simulations revealed that the uncertainty of the model predictions differed for the different evaluated scenarios. This difference was strongly related to the effect of the input uncertainty on the nitrogen removal bacteria. Finally, it was found that η_g (anoxic growth rate correction factor) was responsible for causing the majority of the rising sludge risk output uncertainty for all the evaluated scenarios. Nevertheless, when nitrification efficiency was low, the autotrophic maximum specific growth rate (μ_A) become more important having an important role on the overall model predictions. Summarizing, the study allowed a better understanding of rising sludge in wastewater treatment plants, the evaluation of different ways to overcome these problems (in both values and uncertainty), the identification of the model parameters with the strongest influence on its possible uncertainty and finally some practical implications from an operational and design perspective.

Keywords: uncertainty analysis, sensitivity analysis, microbiology-related solids separation problems, BSM1, wastewater

1. INTRODUCTION

Rising sludge is one of the most common microbiology-related suspended solids separation problems in wastewater treatment plants (WWTP) (**Ekama et al., 1997**). Rising sludge is characterized by the rise or float of the activated sludge flocs with good settling characteristics in a relatively short period of time. The main reason is undesired denitrification in the secondary settler, in which nitrites and nitrates are converted to nitrogen gas in the secondary clarifier. If enough gas is formed, the sludge mass becomes buoyant and rises or floats to the surface worsening the whole clarification efficiency.

Henze and co-workers in the early 90 (**Henze et al., 1993**) established the bases of rising sludge in secondary clarifiers experimentally investigating the role of gas solubility, hydraulic retention time, temperature and critical nitrate concentrations. Later on, **Siegrist et al., 1995** and **Gernaey et al., 2006** developed the first reactive settling models using some of the processes included in the International water Association (IWA) Activated Sludge Model No 1(ASM1) (**Henze et al., 2002**) . Nevertheless, this kind of knowledge have not been included in the computer codes widely used for benchmarking (**Copp 2002, Jeppsson et al., 2007**), design (**Flores et al., 2007**), teaching (**Hug et al., 2009**) and optimization (**Rivas et al., 2008**).

To circumvent this problem, **Comas et al., 2008** used expert knowledge a posteriori, *i.e.* once the simulation is finished, to assess the risk of occurrence of rising sludge to enable its incorporation into the interpretation of the output of quantitative WWTP models. This approach is based on a decision tree that combines the knowledge extracted from the experiments carried out by **Henze et al., 1993** and the mechanical description of a conventional activated sludge process. As a result, this risk model explores influent, effluent and operating conditions in the dynamic simulation output and gives and indication about the operational strategies or design schemes that may cause favourable conditions of rising sludge.

In order to evaluate the potential of developing rising sludge problems, several operational strategies and clarifier designs are evaluated by dynamic simulation. Specifically, we suggest the modification of dissolved oxygen, sludge retention time, external recirculation and settling area. Thus, it is possible to investigate using mathematical modelling the process insights that promotes the development of the undesirable rising sludge problems. The analysis is carried out assuming certain and uncertain model parameters.

It is important to highlight that uncertainty is an important concept when dealing with activated sludge models (**Belia *et al.* 2008**) since these models are in general based on quite a number of assumptions. However, the traditional modelling approaches assume constant rather than variable model parameters. An evaluation procedure assuming constant parameters arguably is not realistic because the possible variation in some of these assumptions is ignored e.g. model parameters describing the COD fractionation or the effect of toxics and temperature on the model kinetics.

The Monte Carlo procedure is an engineering standard, which is commonly used for evaluating uncertainty in the predictions of simulation models. Monte Carlo simulations are based on a probabilistic sampling of input uncertainties followed by determination and analysis of the propagation of input uncertainty to model outputs (**Helton & Davis 2003**). This practice can be complemented with sensitivity analysis involving the identification of the input uncertain parameters that contributes in the output uncertainty the most (**Cariboni et al., 2007**). The use of these techniques has started to be successfully applied in field of water/ wastewater engineering field (**Benedetti et al., 2006; Neumann et al., 2007; Flores et al., 2008 and Sin et al. 2009**)

The paper is structured in the following way. Firstly, it is detailed how the risk of rising sludge can be taken into account in WWTP simulation studies. The performance of the IWA Benchmark Simulation Model No 1 (BSM1) is then evaluated assuming certain and uncertain bio-kinetic and influent fractions ASM parameters via Monte Carlo simulations making special attention to rising sludge problems. Afterwards, the simulations results are analysed identifying operational strategies and clarifier design schemes that reduces the risk of suffering rising sludge risk in both value and uncertainty. In the final section of the manuscript sensitivity analysis is performed using Standard Regression Coefficients, which allow to draw conclusions on the effect of the different model parameters in the rising sludge model predictions variability.

2. METHODS

2. 1. Plant layout, implemented control strategies and evaluation criterion

The BSM1 plant layout using the dry weather influent is the activated sludge system under study (**Copp 2002**). The plant has a modified Ludzack-Ettinger configuration (see **Metcalf & Eddy, 2003**) and two PI control loops. The first loop controls the dissolved oxygen concentration (S_O) in the aerobic zone through the manipulation of the aeration flow (K_La)

and the second control loop the nitrate concentration (S_{NO}) in anoxic zone by manipulating the internal recycle flow-rate (Q_{intr}). Further details about the sensor and actuator dynamics can be found in **Rieger et al., 2003.**

Several operational strategies and clarifier design are simulated using the closed loop BSM1 and then compared to the base case conditions. The default (D) operational settings (S_O = 2 g (-COD) m^{-3}, external reciculation or Q_r = 18336 m^3 day^{-1} and Q_w = 385 m^3 day^{-1}) are modified decreasing (S_O^- = 0.5 g (-COD) m^{-3}, Q_r^- = 13834 m^3 day^{-1} and Q_w^- = 300 m^3 day^{-1}) and increasing (S_O^+ = 3 g (-COD) m^{-3}, Q_r^+ = 23057 m^3 day^{-1} and Q_w^+ = 500 m^3 day^{-1}) their value. The same kind of analysis was done for the secondary clarifier, where the default settling area (A = 1500 m^2) was increased (A^+ = 2000 m^2) and decreased (A^- = 1000 m^2) maintaining the same height (h = 4 m). The values above and below the defaults (D) are indicated with either positive (+) or negative (-) super-index symbol. Thus, a total number of 12 (4 * 3) simulations are analysed and interpreted.

2. 2. Analysis of rising sludge in activated sludge systems

Risk of rising sludge has been estimated using the decision tree suggested by **Comas et al., 2008**. Rising sludge becomes a problem when the nitrate concentration in the secondary clarifier influent is higher than the critical nitrate concentration (8 g N m^{-3} at 15ºC). In this situation, the time required for nitrogen gas production is calculated (based on the denitrification rate and the time delay caused by removal of the remaining oxygen in the bottom of the clarifier), and compared to the sludge residence time in the clarifier (estimated as the amount of sludge in the sludge blanket divided by the Q_r flow rate). Whenever the nitrate concentration is higher than the critical level, and nitrogen gas production time is lower than or equal to sludge residence time in the secondary settler, then favourable conditions for denitrification are inferred, and consequently the risk of solids separation problems due to rising sludge increases.

2.3. Uncertainty analysis of rising sludge in activated sludge systems

To carry out this analysis, the uncertainty associated to the ASM1 parameters was characterized by a set of probability distributions. These distributions were assumed to characterize a degree of belief with respect to possible values of the considered parameters **(Helton and Davis, 2003**). Three uncertainty classes are distinguished to allow the representation of the parameter uncertainty in a structured way, and each uncertainty parameter was assigned to a certain class depending on the extent of knowledge available in the literature about this specific parameter value (see for example **Omlin *et al*., 2001**). The first class corresponded to low uncertainty and included mostly stoichiometric parameters. In this class (C_1), the parameters were assumed to have a 5 % upper and lower bound around their default values. The second class (C_2) corresponded to medium uncertainty and involves kinetic parameters such as the maximum specific growth rate and the affinity constants. In this class, 25 % upper and lower bounds around the default values were assumed. For simplification, all the kinetic and stoichiometric parameters were supposed to be independent although the authors are aware of possible correlations amongst several parameters e.g. the maximum specific growth rate and the half saturation constants. The third class of uncertainty (C_3) corresponded to high uncertainty and included the influent fraction related parameters, assuming upper and lower bounds equal to 50 % of the default parameter values. In this case study, to comply with the different mass balances the following restriction was imposed $\alpha\_X_S = 1 - \alpha\_S_S - \alpha\_S_I - \alpha\_X_I - \alpha\_X_S - \alpha\_X_{BH}$ and $\alpha\_S_{NH} = 1 - \alpha\_S_{ND} - \alpha\_X_{ND}$. It is important to mention that the uncertainty analysis presented in this paper focuses on the studying the how the biodegradation properties affect the rising sludge problems. Other sources of uncertainty such model structure or other parameter values, e.g. settling characteristics, may have also an important role on the overall rising sludge risk predictions. However, in the framework of this study are not taken into account.

2.4. Sensitivity Analysis

The sensitivity analysis involves performing a linear regression on the output of the Monte Carlo simulation (1000 shots for 28 uncertain parameters), revealing the (linear) relationships between the inputs i.e. bio-kinetic model parameters and influent fractions, and the outputs i.e. rising sludge risk. The regression model is represented in the following equation (**Eq 1**)

$$X_j = b_0 + \sum_{k=1}^{nS} b_k U_k \qquad \text{Eq1}$$

Where X is the vector of the regression model predictions, b_0 is the offset and b_k are the slopes of the regression model. The standardized regression coefficients (SRC) are obtained by multiplying the slopes b_k by the quotient of the standard deviation of the input and the output. According to **Saltelli et al. (2004)** the SRC are a valid measure of sensitivity if the coefficient of determination $R^2 > 0.7$.The higher the absolute values of the SRC, the stronger the influence of the corresponding input [A] on determining the output [X]. The absolute values of the regression coefficients are then ranked and categorized in strong, medium and weak influence by k-means clustering (**Hair et al. 1998**).

3.RESULTS

3. 1. Analysis of rising sludge without uncertainty

The simulation study revealed that the default rising sludge risk [57.14 % of the total simulation time the plant under risk of suffering rising sludge problems] may be overcome by **(1)** decreasing the oxygen set-point (S_O) in the aeration section [53.56 % of the simulation time], **(2)** increasing the return activated sludge withdrawal [43.01 %] i.e. increase Q_r, **(3)** decreasing the solids retention time [49.10 %] i.e. increase Q_w and finally **(4)** decreasing the settling area (A) [43.30 %]. The objective of actions **(1)** and **(3)** was to decrease nitrification efficiency as shows the dynamic effluent ammonium profiles in **Figure 1a** and **b.** As a consequence there is a reduction of the quantity of nitrate which is sent to the secondary clarifier. On the other hand, actions **(2)** and **(4)** reduced the detention time of the sludge in the clarifier decreasing the quantity of biomass in the lower layer of the secondary clarifier (see dynamic profiles in **Figure 1c** and **d**). Thus, there is a lower biomass that potentially can denitrify the nitrate arriving from the reactor.

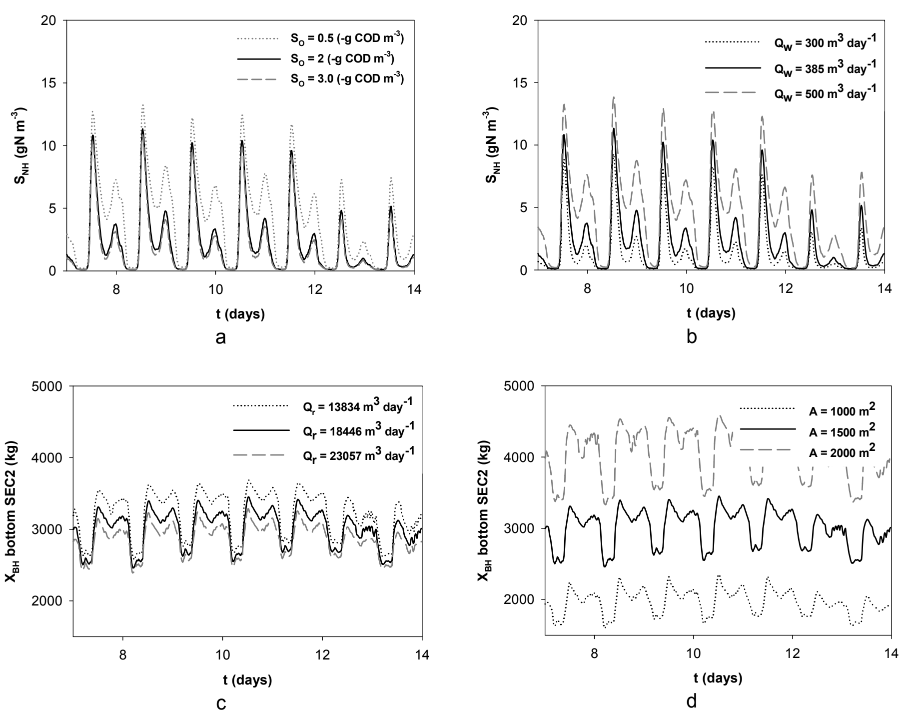


Figure 1. Effect on the effluent ammonium (S_{NH}) and heterotrophic biomass in the bottom of the secondary carifier (SEC2) of the S_O - action **(1)** - a), Qr - action **(2)** - , c), Q_w - action **(3)** - , b) and Area -action **(4)** - d)

3.2. Uncertainty Analysis

The results of the Monte-Carlo analysis showed that the values of output uncertainty, *i.e.* rising uncertainty, differs in the control actions which intends to avoid nitrification in the bio-reactor - actions **(1), (3) -** or reduce denitrifiers residence time in the secondary settler - actions **(2), (4)** - (see the results in **Figure 2**). This difference is strongly related to the effect of the input uncertainty on the BSM1 nitrogen removal microorganisms. In order to illustrate these differences two examples are shown.

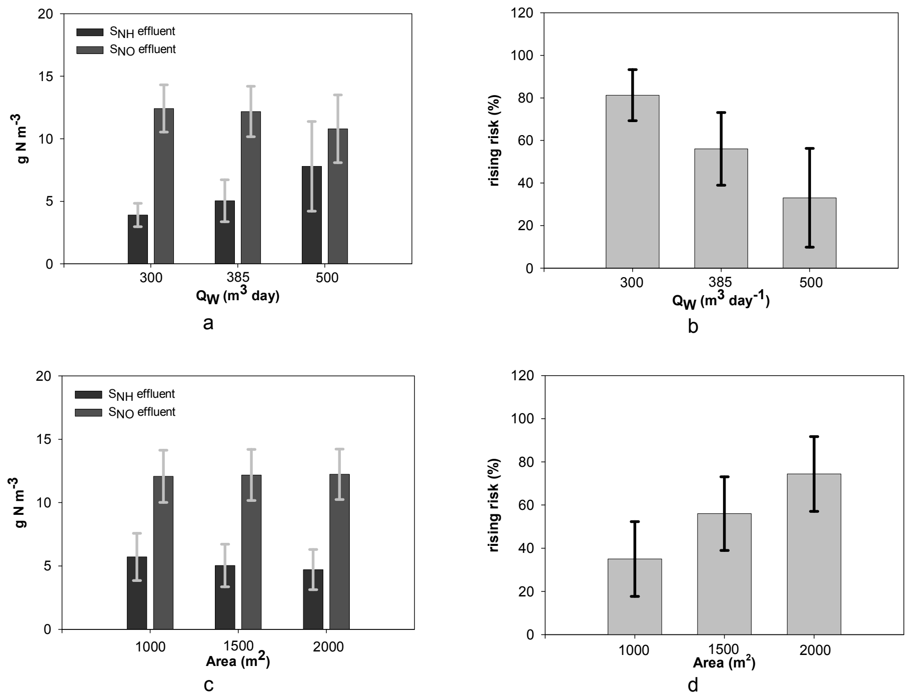


Figure 2. Results of the Monte Carlo simulation for effluent nitrogen ammonium (a,c), nitrate (a,c) and risk of rising sludge (b,d) when the waste flow (a,b) - action **(3)** - and the settling area –action **(4)** - (c,d) are changed.

The first example shows the effects of modifying the waste flow –action **(3)** - on rising sludge risk. Uncertainty in effluent S_{NH}, effluent S_{NO} and the rising sludge risk is increased when the waste flow (Q_W) is increased (see the error bars on the bars of **Figure 2a** and **b**). These differences are attributed to the changes in the quantity of autotrophic biomass in the reactor having strong impact on the propagation of the input uncertainty. As mentioned before when the SRT is decreased, the quantity of S_{NO} that is sent to the secondary clarifier is reduced and therefore the risk of rising sludge decreased (see the height of the bars in **Figure 2a** and **b**).

The second example shows the influence of the clarifier design (Area) – action **(4)** – on rising sludge risk. In this case there is not a clear effect on the effluent nitrogen compounds and rising sludge uncertainty (see the error bar on the bars of **Figure 2c** and **d)**. This is mainly due to there is no impact on the autotrophic bacteria population. The reduction of residence time of heterotrophic biomass in the bottom of the clarifier has an impact on the formation of gas bubbles, the rise of the activated sludge flocs and finally the potential decrease of the whole clarification efficiency (see the height of the bars in **Figure 2c** and **d**). However, the propagation of the input uncertainty is always the way.

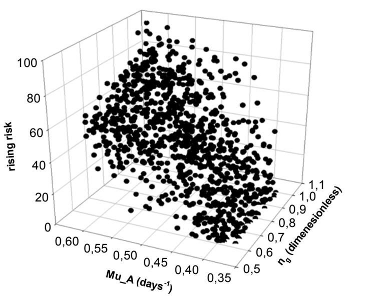
The same kind of pattern (results not shown) is observed for action **(1)** (modify S_O) and action **(2)** (modify Q_r) respectively. When S_O is decreased, the uncertainty in both effluent nitrogen and rising sludge risk is increased, while when Q_r is changed, the uncertainty values remains always the same. Thus, it can be said that there is a difference in terms of propagation of input uncertainty amongst the actions hinders nitrification (actions **(1)** and

(3)) and the actions that reduces the residence time of heterotrophic bacteria in the settler (actions **(2)** and **(4)**). The results reported in this section reveals that it is possible to achieve good nitrification rates without increasing the risk of rising as long as there is good clarifier design/external recirculation control to avoid the formation of bubbles.

3. 3. Sensitivity Analysis

Using the Monte Carlo results for the rising sludge risk, a regression model was fitted using **Eq1** (for all the different evaluated actions, the R^2 of the regression models were higher than 0.9). Since a regression approach is used for the sensitivity analysis, it is assumed there is neither interaction amongst the different nor important nonlinearities. The standard regression coefficient (SRC) for each input parameters were calculated and classified using K-means (**Table 1)**. Thus, it was possible to label the different parameters with strong (gray), medium (light grey) and weak (white) effect. From these results, it could be observed that the parameter with a strongest influence in all the cases was η_g (anoxic growth rate correction factor). This is understandable since η_g is used to calculate the time required for nitrogen gas production. Moreover, it is generally known that the BSM1 plant is highly loaded in nitrogen and has a deficit on soluble organic matter, meaning that any change on the denitrification-related parameters will be noticed in the rising sludge risk. Interestingly, for the actions that decreased nitrification efficiency, the parameters that regulate the growth of autotrophic bacteria (μ_A) become influential i.e. black coloured. This is not the case for the actions that reduced the detention time of the sludge in the clarifier, where μ_A was classified as medium influential or weak.

This type of behaviour is illustrated in **Figure 3,** which shows the correlations between η_g (X-AXIS), μ_A (Y AXIS) and rising sludge risk (Z AXIS) for the Monte Carlo simulation generated for action 1 (modification of the S_O). When the S_O is low (**Figure 3a)** can be seen the direct strong correlation between μ_A and the risk of rising sludge. On the other hand **Figure 3b**, clearly demonstrate that the rising sludge risk values are ruled by η_g, having μ_A a marginal effect.



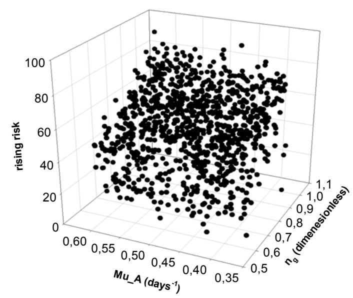


Figure 3 Correlation between the output (rising sludge risk) and some of the uncertain parameter: η_g (anoxic growth rate correction factor) and autotrophic maximum specific growth rate (μ_A) for two S_O = 0.5 (left) and 3.5 (right) g (-COD m^{-3}).respectively

This fact is understandable and could be expected to a certain extent from the results generated in the previous section. Low S_O and high Q_w - action **(1), (3) -** reduced the overall nitrogen removal and increased the uncertainty in S_{NH}, S_{NO} and rising sludge risk. For this reason, nitrification related parameters turned out to be important and made the input uncertainty propagate differently through the BSM1. On other hand, when there is no longer nitrification problems, *e.g*. actions **(2)**,**(4)** , the process is less dependent of μ_A.

4. GENERAL DISCUSSION

The results of this analysis open the door to several points of discussion. First from an operational and design and point of view, the study revealed some synergies and trade-offs within the process performance. For example, it is possible to achieve good nitrification rates without increasing the risk of suffering rising sludge if the residence time of heterotrophic bacteria on the secondary clarifier is minimized. Thus, it is highlighted the need to find a compromise solution between nitrification potential, TSS removal (*i.e.* settling area) and risk of microbiology-related TSS separation problems (*i.e*. heterotrophic bacteria residence time in the clarifier).

Table 1. Identification of strong (gray) medium (light grey) and weak (white) parameter s for the different evaluated operational conditions and clarifier designs

	D	S_o^-	S_o^+	Q_r^-	Q_r^-	Q_W^-	Q_W^+	A^-	A^+
Kinetic and stochiometric paramters (C_1 and C_2)									
maximum specific heterotrophic growth rate (μ_H)									
half saturation (hetero. growth) (K_S)									
half saturation (hetero. oxygen) (K_{OH})									
half saturation (nitrate) (K_{NO})									
heterotrophic specific decay rate (b_H)									
maximum specific autotrophic growth rate (μ_A)									
half saturation (auto. growth) (K_{NH})									
half saturation (auto. oxygen) (K_{OA})									
autotrophic specific decay rate (b_A)									
anoxic growth rate correction factor (η_g)									
amonification rate (k_a)									
maximum specific hydrolysis rate (k_h)									
half saturation (hydrolysis) (K_X)									
anoxic hydrolysis rate correction factor (η_h)									
autotrophic yield (Y_H)									
heterotrophic yield (Y_A)									
fraction of biomass to particulate products (f_P)									
fraction of nitrogen in biomass (i_{XB})									
fraction of nitrogen in particulate products (i_{XP})									
conversion from COD to particulates (X_{2TSS})									
Influent fractions (C_3)									
Fraction of soluble inorganic (α_S_I)									
Fraction of particulate inorganic (α_X_I)									
Fraction of soluble organics (α_S_S)									
Fraction of heterotrophic biomass (α_X_{BH})									
Fraction of particulate organics (α_X_S)									
Fraction of organic soluble nitrogen (α_S_{ND})									
Fraction of organic particulate nitrogen (α_XND)									
Fraction of ammonia (α_S_{NH})									

The results of the uncertainty and sensitivity analysis can also guide process engineers in future calibration studies pointing out what parameters should be first determined experimentally. For example, the standard deviation of rising sludge risk after running 1000 Monte Carlo shots is 17.8 (default conditions). However, when η_g *i.e.* most sensitive parameter, is set to its default value and the experiment is re-run again the standard deviation is 12.43

The reader should be aware that results of this study strongly depend on the model selection. For example the clarifier model (**Takacs *et al*., 1991**) is extremely simplified and it could not describe accurately the hydrodynamics of some of the studied clarifiers. Thus, general assumptions regarding settling cam be dangerous and it would be necessary using 2-D and 3-D models. In the same way, results of uncertainty analysis will to a large extent depend on the studied uncertain parameters, characteristics the defined uncertainty classes and the assumed probability distributions. The results of this simulation study are deemed interesting and useful but they should be treated with caution and certainly not generalized

CONCLUSIONS

This paper has evaluated the role that certain operational strategies and clarifier designs have as promoters of rising sludge in wastewater treatment plants: The key finding of this research can be summarized in the following points:

- The risk of suffering rising sludge problems in wastewater treatment plants can be minimized by: decreasing oxygen in the aerated zone, increasing activated sludge withdrawal from the secondary settler, reducing the sludge retention time and without over-sizing clarifier designs. It is possible to achieve good nitrification rates without increasing the risk of rising if there is a good design/control on the secondary clarifier.

- The uncertainty in the rising sludge risk predictions is strongly related to the autotrophic bacteria. Thus, the operational strategies that decreased nitrification efficiency increased the uncertainty of the model predictions. On the other hand, operational strategies or design schemes that reduced the denitrifying biomass time in the secondary settler did not have an important effect on the propagation of the input uncertainty.
- The parameter that causes the highest variation in the rising sludge risk predictions is η_g (anoxic growth rate correction factor) unless nitrification problems occur. In that case, the role of μ_A becomes really important. The uncertainty of rising sludge could be reduced by the experimental determination of these parameters.

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