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ACTIVATED SLUDGE TOXICITY MITIGATION USING A RESPIROMETRIC MEASUREMENT

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Abstract: This paper presents the results of an evaluation of a toxicity mitigation control strategy using the *IWA simulation benchmark* (Copp *et al.*, 2002; Copp, 2001). The aim of the proposed strategy is to minimise the impact of a toxic influent shock load on process performance. To do this, the strategy makes use of a respiration rate measurement to detect toxic events and uses an equalisation tank to store toxic influent. A defined control algorithm specific for the benchmark plant was developed and is used to reintroduce the stored influent back into the process stream once the influent is deemed non-toxic. The results of the simulations indicate that the impact of the toxicant can be significantly mitigated through the use of off-line storage and reintroduction of suspected influent. *Copyright © 2002 IFAC*

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1. INTRODUCTION

There is a substantial amount of literature on activated sludge toxicity, and that literature varies from methods for toxicity detection to the impact of such toxicity on process performance (Spanjers *et al.*, 1998). However, to avoid a process upset caused by a toxic influent a suitable detection technique must be developed in conjunction with a suitable mitigation strategy and the literature on mitigation options is substantially less extensive as is the applied use of respirometry-based toxicity control. Several things limit the full-scale evaluation of toxicity control strategies not the least of which is the defined and regular occurrence of toxic events in a particular wastewater.

The evaluation of activated sludge control strategies through simulation is becoming increasingly popular because it is not always practical to evaluate such strategies in other ways (i.e. at full-scale). However, in order to carry out fair and unbiased simulation comparisons, it is necessary to standardise the evaluation procedure. That is, simulations provide a cost-effective means for the evaluation of control strategies, but the unlimited number of simulation permutations make the need for a standardised protocol very important if different strategies (and different simulation results) are to be compared. The term used to describe the standardised simulation procedure is '*simulation benchmark*'. The *IWA simulation benchmark* is described in detail elsewhere (Copp *et al.*, 2002).

2. CONTROL STRATEGY DESCRIPTION

The aim of the proposed strategy is to minimise the impact of a toxic influent shock load and thus avoid the occurrence of a process upset event. The proposed control strategy has two parts. The first involves the use of respirometry as a technique for the detection of a toxic influent and the subsequent diversion of the toxic influent to a non-reactive storage tank. The second part of the strategy involves reintroducing the stored influent back into the process stream after the toxic event is over. Two things are assumed with such a strategy: (i) that the material in the diverted influent (besides the toxic material) needs to be treated on site, and (ii) that the toxicant effect is related to its concentration (i.e. that the impact of the toxicant can be decreased if it is diluted).

Summary of the Proposed Toxic Control Strategy

Strategy Objectives
- to avoid a process upset (as signified by high effluent substrate and depressed microbial activity)
Control Objective
- to maintain the measured respiration rate *(OUR)* in the process respirometer as similar as possible to the *OUR* measured in the reference respirometer
Measured Variables
- respiration rate (x2)
Controlled Variables
- respiration rate difference between process and reference respirometers
Manipulated Variable
- influent diversion to an off-line non-reactive storage tank

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3. BENCHMARK APPLICATION

Because the simulation benchmark is generic and not designed for a specific control strategy, it must be applied in a step-wise manner. At each step (where necessary), assumptions are made to adjust the reported strategy to the benchmark system. As this control strategy is not directly related to any previously published literature reference, there were no *implementation* decisions to be made. However, many other benchmark-related decisions were necessary to implement the strategy.

3.1 Model Changes

The most important decisions involved the modelling of the toxicant and its affect on the process. The biological conversion processes of the simulation benchmark are described by ASM1, which does not included a toxic variable, so one had to be defined. In this instance, to simplify the analysis, the toxicant was assumed to be a soluble, unbiodegradable substance devoid of COD [For illustrative purposes we might consider it to be the soluble form of a heavy metal, but it should be noted that the constants used in this study do not reflect a particular compound.]. This compound was given the symbol S_T, and its toxic affect was modelled in two ways. The first impact was modelled using a Monod-type 'switching function', where the toxic compound effect was to decrease the observed heterotrophic growth rate. The second toxic effect was on the observed decay rate. In this instance the toxic compound served to increase the rate at which the heterotrophic biomass decayed. Expressions 1, 2 and 3 were used to model the impacts.

$$\hat{\mu}_H \left(\frac{S_S}{K_S + S_S}\right)\left(\frac{S_O}{K_{OH} + S_O}\right)\left(\frac{K_I}{K_I + S_T}\right) X_{BH} \qquad (1)$$

$$\hat{\mu}_H \left(\frac{S_S}{K_S + S_S}\right)\left(\frac{K_{OH}}{K_{OH} + S_O}\right)\left(\frac{S_{NO}}{K_{NO} + S_{NO}}\right)\left(\frac{K_I}{K_I + S_T}\right) \eta_g X_{BH} \qquad (2)$$

$$b_H \left(1 + \frac{M_{TD} \bullet S_T}{K_{BH} + S_T}\right) X_{BH} \qquad (3)$$

where:

S_T = toxicant concentration (g m^{-3})
K_I = toxic half-saturation constant (g m^{-3})
M_{TD} = relative maximum increase in decay
K_{BH} = toxic decay half-saturation constant (g m^{-3})

The toxic impact was modelled in this way to be consistent with observations at an industrial treatment plant that has to deal with periodic toxic events. Observations at the industrial installation suggest that the toxicant(s) in that wastewater has a two-fold effect. During toxic events at that facility, a decrease in biological activity in the plant is noted, which is consistent with Expressions 1 and 2 above. However, it also is observed during these events that less sludge is produced (i.e. an apparent decrease in observed yield) and the observed recovery from the toxic event is not immediate. This is consistent with an increase in the rate of decay. The additional decay (and subsequent decrease in active heterotrophic biomass) modelled by Expression 3, should cause a delay in the modelled recovery of the plant. The parameter values used in this study are shown in Table 1.

Table 1. Model parameters used in the toxic model.

Parameter	Value	Units
K_I	2	g m^{-3}
M_{TD}	1	d^{-1}
K_{BH}	2	g m^{-3}

3.2 Toxic Influent

In this instance two toxic files were developed. The first 'shock-type' toxic load is depicted by a very high concentration (max 90g m^{-3}), short (1.5 hours) duration toxic spike. The second toxic file depicts a much lower concentration of toxicant, but the duration is much longer (12 hours). The second file was engineered specifically so that it would NOT trigger a toxic alarm. In both instances the mass of toxicant depicted is similar (~85.5 and 86.5 kg).

3.3 Process Layout

A 5 tanks-in-series design was used where all tank volumes and influent flows remained as defined in the benchmark description (IWA, 2001). The GPS-X layout used to evaluate this strategy is shown in Figure 1. To facilitate influent storage a non-reactive storage vessel was needed, and for the detection algorithm two respirometers were added.

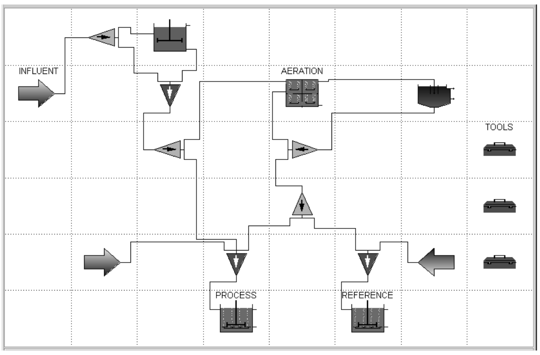

Figure 1. GPS-X™ layout used in this study.

The respirometers were designed to operate in batch mode, taking a sample once every 30 minutes. The reference respirometer (right) has two input streams, (i) a sludge input from the sludge recycle stream (1L), and (ii) an external input stream consisting of readily biodegradable substrate (S_S) only (9L). The process respirometer (left) has three input streams, (i) a sludge input from the sludge recycle stream (1L), (ii) an external input stream consisting of readily biodegradable substrate (S_S) only (4.5L), and (iii) a input stream from the influent line to the biological treatment process (4.5L). During the 30-minute cycle, the ideal respiration rates (no noise or time delay) were monitored and the maximum observed respiration rate in each vessel during that period were saved.

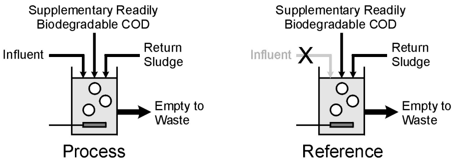

Figure 2. Illustration of batch respirometers.

Figure 1 shows that influent to the process respirometer is diverted after the storage tank. This was done because it is conceivable that a secondary toxic event could upset the process if the flow from the storage tank is too high.

The storage tank was modelled as a non-limiting, non-reactive vessel. Being non-reactive, no biological conversions occurred in the tank, and hence no added treatment was added to the default process layout. The volume of the storage tank was set sufficiently large enough so that it never limited the amount of influent that could be stored.

4. CONTROL LOOP SPECIFICS

If the activity in the process respirometer was <50% of the activity in the reference respirometer, the detection algorithm was triggered. Note that this trigger level seems quite low, but an investigation revealed a toxic concentration of 8 g m^{-3} (4x K_I) was sufficient to trigger the detection algorithm (data not shown). Following the detection of a toxic event, all flow from the storage tank was stopped and 90% of the influent flow was diverted to the storage tank. The diversion of influent continued until the process respirometer activity returned to the level observed in the reference respirometer. Once this activity returned to an acceptable level, the diversion of influent to the storage tank was stopped and the pumped flow from the storage tank was triggered. The rate at which the storage material was reintroduced into the process is discussed below.

4.1 Reintroduction of Diverted Influent

The reintroduction rate must be as fast as possible, so that the storage tank is ready to except another diversion stream if necessary, while at the same time it must not be so fast that it causes a process upset or triggers another detection event. Therefore, the rate of reintroduction was determined as a function of two respiration rate fractions calculated from the two respirometers and calculated as follows:

$$Q_{pump} = \left(ff \cdot rf_{trigger} \cdot rf_{current}\right) Q_{in} \tag{4}$$

where:

Q_{pump} = pumped flow from the storage tank (m^3 d^{-1})
Q_{in} = raw influent flow rate (m^3 d^{-1})
ff = flow factor
$rf_{trigger}$ = rate fraction that triggered the event
$rf_{current}$ = rate fraction currently measured

5. RESULTS COMPARISON

To fully appreciate the impact of a control strategy, a number of simulations have to be performed. However, due to space limitations, only a selection of those results will be presented here.

The first step in the evaluation procedure is to simulate the to which the control results can be compared. Table 2 presents a selection of base case results. In this instance, the first column refers to the uncontrolled benchmark plant simulated using the *dry weather* influent file without any toxicant. The second column presents the results generated by the toxic layout (i.e. with functioning respirometers) using the toxic influent file #1 (i.e. the 'shock-type' spike of toxicant), but without the controllers active (i.e. no diversion of influent). The last column presents the results generated by the toxic layout, using the toxic influent file #1, with the controllers active.

Table 2. Summary of selected performance data from a series of dynamic *dry weather* simulations.

	Uncontrolled Benchmark	Toxic Influent, Control Inactive	Toxic Influent, Control Active	Units
EQ index	1720	1770	1750	kg d^{-1}
Sludge Production	2683	2601	2592	kg SS d^{-1}
Aeration Energy	12175	12175	12175	kWh d^{-1}
Pumping Energy	753	753	764	kWh d^{-1}
Effluent TSS	13.0	12.9	13.0	gSS m^{-3}
Effluent TKN	2.2	2.4	2.4	gN m^{-3}
Effluent N	36.3	36.4	36.4	gN m^{-3}
Effluent COD	48.0	49.4	48.7	gCOD m^{-3}
Effluent BOD_5	2.7	3.0	2.8	gO m^{-3}

The results show that the toxicant had an impact both on effluent quality and sludge production as expected. As compared to the non-toxic influent the toxicant seemed to have about a 3% adverse affect on the effluent quality. As expected, the 'benchmark' and 'control inactive' columns (Table 3) show no trigger events and as designed, the 'control active' column shows only one event. That is, the measuring technique does not seem to produce false positives and the reintroduction algorithm (using a flow factor of 1.0) does not seem to result in secondary toxic events being triggered as a result of the toxic flow from the storage tank.

Table 3. Summary of selected control data from a series of dynamic *dry weather* simulations.

	Uncontrolled Benchmark	Toxic Influent, Control Inactive	Toxic Influent, Control Active	Units
trigger events	0	0	1	
triggered time	0.00	0.00	1.19	% of 7 days
maximum Ss	0.8	31.9	7.2	gCOD m^{-3}

Figure 3 shows the impact of the toxicant on the effluent readily biodegradable substrate (S_S). From the figure it can be seen that the control strategy significantly dampens the toxicant impact and decreases the maximum observed effluent S_S from approximately 32 g m^{-3} to just over 7 g m^{-3}. However, as can also be seen, the control strategy tends to lengthen the time that the effluent S_S remains 'higher' than the benchmark case. Nevertheless, these results suggest that this strategy may be useful for plants that discharge into concentration sensitive receiving waters.

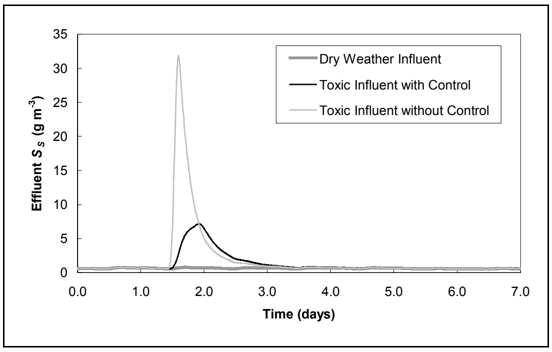

Figure 3. Benchmark simulation results showing the variation in effluent S_S as a result of the toxic influent with and without control.

The behaviour in the detection respirometers around the toxic period is also of interest (data not shown). In the control case, the process rate is clearly lower than the reference rate for the entire period that the stored influent is being reintroduced, but that lower rate is not sufficiently low that it triggers another toxic sequence. From a series of supplemental simulations, it was determined that the reintroduction rate has an impact on process performance.

Figure 4 shows the impact of the reintroduction flow factor on effluent S_S. Clearly, as the flow factor is increased, more toxicant is pumped from the storage tank resulting in more inhibition and a higher short-term effluent S_S concentration. In contrast, when the flow factor is decreased to 0.1, the effluent S_S is significantly reduced (to ~2 g m^{-3}), but the duration of the increased effluent S_S is longer.

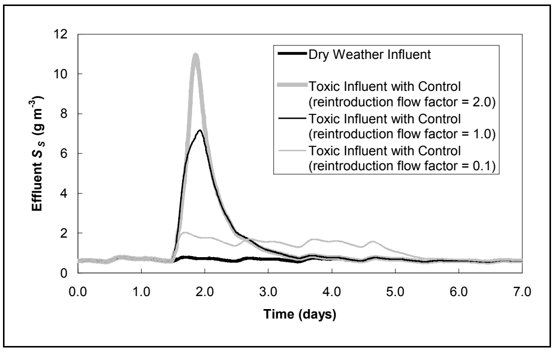

Figure 4. Benchmark simulation results showing the variation in effluent S_S as a result of the toxic influent with different flow factors.

Table 4 presents more performance data related to different flow factors. These results indicate that the smaller the flow factor the better the performance, but optimising the rate of reintroduction will involve balancing the need for the best treatment against the need to empty the storage tank so that it is ready to accept another flow of toxic influent.

Table 4. Summary of selected performance data from a series of dynamic dry weather simulations.

	Toxic Influent, *ff* = 1.0	Toxic Influent, *ff* = 2.0	Toxic Influent, *ff* = 0.1	Units
EQ index	1750	1760	1740	kg d^{-1}
Sludge Production	2592	2597	2537	kgSS d^{-1}
Aeration Energy	12175	12175	12175	kWh d^{-1}
Pumping Energy	764	769	764	kWh d^{-1}
Effluent TSS	13.0	13.1	12.9	gSS m^{-3}
Effluent TKN	2.4	2.4	2.4	gN m^{-3}
Effluent N	36.4	36.4	36.6	gN m^{-3}
Effluent COD	48.7	48.9	48.4	gCOD m^{-3}
Effluent BOD$_5$	2.8	2.9	2.8	gO_2 m^{-3}
trigger events	1	3	1	
triggered time	1.19	1.79	1.19	% of 7 days
maximum Ss	7.2	10.9	2.0	gCOD m^{-3}

Two further things are worth mentioning. Figure 5 shows the volume of stored influent in the storage tank as a function of time. From the figure, it can be seen that if the flow factor is increased to too high a level, secondary toxic triggers can occur. Secondary toxic triggers are caused by the flow of toxicant from the storage tank and hence are not indicative of the influent toxicity.

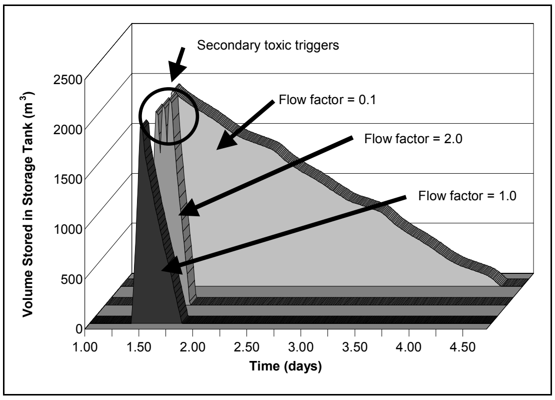

Figure 5. Benchmark simulation results showing the volume of stored influent in the storage tank using the toxic influent file and active control.

Because of the position of the process respirometer, the algorithm is unable to distinguish the source of the toxicant and so, if the flow from the storage tank is too high, a toxic condition may be detected. In this case with a flow factor of 2.0, two secondary triggers occurred. Further, it can also be seen in this figure that because of these secondary triggers, increasing the reintroduction rate does not necessarily decrease the time that the storage tank contains influent. In this instance, with the flow factor set to 1.0 and 2.0, the tank contained influent for 0.45 and 0.38 days respectively, so very little was gained by trying to increase the reintroduction rate. Also, because of these secondary triggers, more influent than necessary was diverted and hence more pumping energy was required to empty the tank.

To this point the results have focused on simulations performed with the first toxic influent file, but it was of interest to examine the impact of the second file as well. Table 5 lists the results of a simulation with the second toxic influent file next to the uncontrolled benchmark results (without toxic influent) and the controlled case (*ff* = 1.0) with the first toxic influent file.

Table 5. Summary of selected performance data from a series of dynamic *dry weather* simulations.

	Uncontrolled Benchmark	Toxic #2, Control Active	Toxic #1, Control Active	Units
EQ index	1720	1740	1750	kg d^{-1}
Sludge Production	2683	2590	2592	kgSS d^{-1}
Aeration Energy	12175	12175	12175	kWh d^{-1}
Pumping Energy	753	753	764	kWh d^{-1}
Effluent TSS	13.0	12.9	13.0	gSS m^{-3}
Effluent TKN	2.2	2.3	2.4	gN m^{-3}
Effluent N	36.3	36.5	36.4	gN m^{-3}
Effluent COD	48.0	48.5	48.7	gCOD m^{-3}
Effluent BOD$_5$	2.7	2.8	2.8	gO_2 m^{-3}
trigger events	0	0	1	
triggered time	0.00	0.00	1.19	% of 7 days
maximum Ss	0.8	6.5	7.2	gCOD m^{-3}

These results indicate that even though approximately the same mass of toxicant was introduced to the process with both files, there were distinct differences in the process behaviour. In particular, the lower concentration of toxicant seemed to have less impact on the effluent quality (as compared to the non-toxic case), but seemed to result in approximately the same benefit in terms of sludge production. These results also tend to support the premise on which the mitigation strategy is based; namely that the reintroduction of the toxicant at a reduced concentration is a feasible option and should reduce the toxicant impact on the process. However, of course, this conclusion should be viewed in the context of this study and the method used to model the toxic effect.

As the choice of modelling parameters (K_I, M_{TD} & K_{BH}) has an impact on the process behaviour a number of additions simulations were performed to investigate their impact. A factorial design for the parameters was devised based on two levels for each parameter (Table 6).

Table 6. Parameter values used in factorial simulations.

Parameter	Parameter Value '0'	Parameter Value '1'
K_I	2	0.2
M_{TD}	1	3
K_{BH}	2	0.2

Rather than include a series of tables with all these results, only effluent quality and the maximum S_S will be presented as an indication of the parameter impacts (Table 7). Controllers were active for all simulations, using the first toxic influent file and a flow factor of 1.0.

From the results it can be seen that K_I had the greatest influence on effluent quality, which is consistent with what would be expected, though the magnitude of the influence was somewhat surprising. Also, the results indicate that the reintroduction algorithm did not mitigate the problem sufficiently in these cases. That is, although the reintroduction rate did not produce secondary triggers, the concentration of toxicant in the biological reactors was still sufficient to disrupt the process as indicated by the high effluent numbers. This suggests that much lower flow rates (and hence a lower S_T concentration) were required to completely mitigate the toxic event when the toxic impact was modelled with these new parameter values. A lower flow rate would, of course, increase the length of time required to empty the storage tank, but this may be a justifiable consequence if the toxicant impact is as significant as it is above (Table 7).

Table 7. Toxic parameter impact on effluent quality and maximum S_S using the first toxic influent file.

Parameter Level			Effluent Quality	Maximum S_S
K_I	M_{TD}	K_{BH}	(EQ)	
0	0	0	1750	7.2
1	0	0	3190	336.2
0	1	0	1870	43.7
1	1	0	4100	478.8
0	0	1	1780	10.8
1	0	1	3510	374.7
0	1	1	2030	84.9
1	1	1	4920	550.9

6. CONCLUSION

The development of a standardised protocol for the evaluation of control strategies through simulation (i.e. a *simulation benchmark*) has been on-going for some time. This report outlines the results of an evaluation of a new toxicity control strategy using this simulation tool.

For this evaluation, several changes to the *IWA simulation benchmark* were required including three model changes, the addition of a toxic state variable and the development of two toxic influent files. Care was taken to implement a minimum number of changes.

The aim of the proposed strategy is to minimise the impact of a toxic influent shock load and avoid the occurrence of a process upset event. To do this, the strategy uses respirometry as a technique for the detection of a toxic influent and diverts the suspected influent to a non-reactive storage tank. Once the influent is deemed non-toxic again, the stored influent is reintroduced into the process stream at a significantly reduced rate. The assumption being made is that the toxicant effect is related to its concentration (i.e. that the impact of the toxicant can be decreased if it is diluted). The simulation results presented in this report indicate that the impact of the toxicant can be significantly mitigated through the use of off-line storage and reintroduction of suspected influent. The results show that the rate of reintroduction is a critical parameter in such a strategy because if the rate is too great secondary toxic triggers can occur. The results also indicate that respirometry can be used as a suitable toxicity detection technique.

7. ACKNOWLEDGEMENTS

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