Supporting Information

Cost-effective River Water Quality Management using Integrated Real-Time Control Technology

Fanlin Meng[1], Guangtao Fu[1], David Butler[1*]*

[1] Centre for Water Systems, College of Engineering, Mathematics and Physical Sciences, University of Exeter, Exeter, EX4 4QF, UK

CONTENTS

1. Definition of the case study site

1.1 System configuration and modelling

The dimensions and modelling methods of the catchment, the treatment process units and the river are provided in Table S1. The layout of the integrated UWWS is shown in Figure S1.

Table S1 Dimensions of the case study UWWS and the modelling methods

Process unit	Dimension	Hydraulic/pollutant transport model	Models for sedimentation	Models for biochemical reaction processes
Catchment	Total area of 7 sub-catchments: 7.26 km^2	Nash cascade	Not modelled	Not modelled
Sewer	--	Translation		
Storage tank	Tank 2: 2800 m^3; Tank 4: 1400 m^3; Tank 6: 2000 m^3; Tank 7: 7000 m^3;	Completely mixed reactors	Simplified model by a coefficient of settling efficiency	
Storm tank	6750 m^3			
Primary clarifier	6785 m^3		Empirical equation as a function of hydraulic retention time (HRT)	
Aerator	10,400 m^3		--	An extension of Activated Sludge Model No. 1
Secondary clarifier	6600 m^3		3-layer model, using exponential function to simulate settling velocity	Not modelled
Mechanical dewatering	--	--	Idealised solid separation	
River	45 km	SWMM5	Not modelled	Lijklema

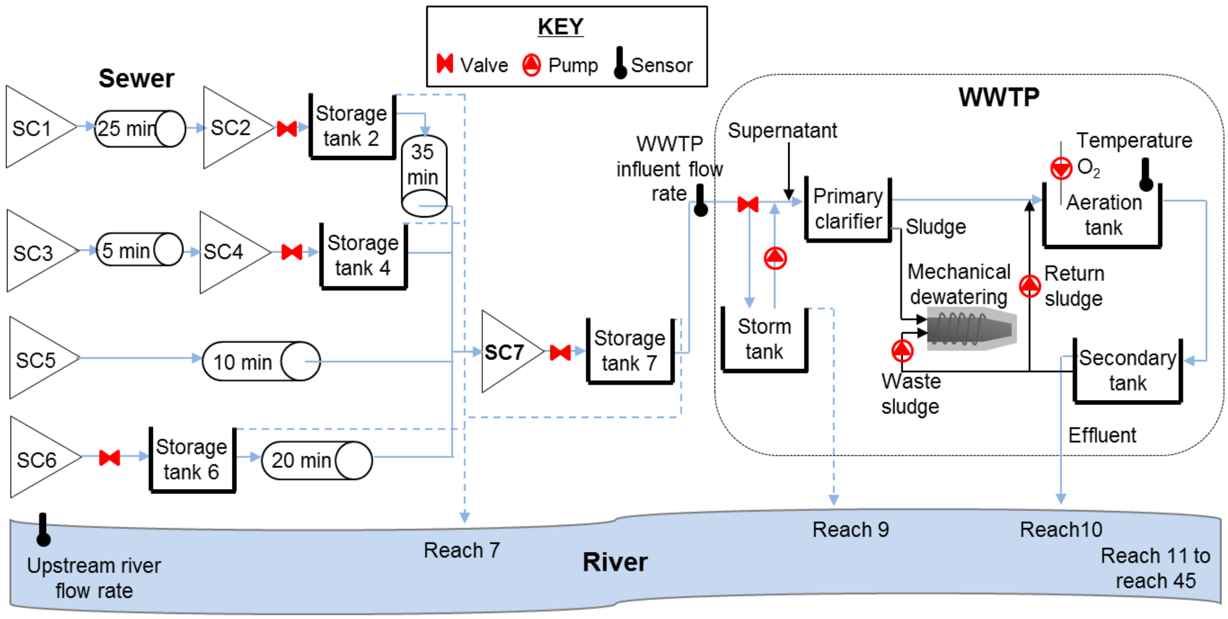

Figure S1 Schematic representation of the case study site (SC: sub-catchment)

Similar as in previous literature[1,2], different levels of simplifications were adopted in the modelling as it is impractical to simulate in depth all (possibly known) processes in the context of integrated modelling. Hence, some processes are simulated in a simple manner (e.g. mixing, sedimentation in storm/storage tanks, sludge dewatering) or not included (e.g. biochemical reactions in the sewer, sedimentation in the river). Nevertheless, processes critical for wastewater treatment and its environmental impacts, namely sedimentation in the secondary clarifier and biochemical reactions in the aeration tank and the receiving river, are modelled in a relatively detailed manner.

pH and variable temperature are not included in the river water quality model. As a result, the biochemical reactions (e.g. nitrification, BOD deoxygenation) influenced by temperature change are modelled based on constant temperature (17 ^{o}C) over the simulated year. However, the effect was found to be of minor significance by changing the temperature setting from 5 ^{o}C to 30 ^{o}C. Also, the generation of un-ionized ammonia, which is toxic to fish and controlled by the UK regulation (99%ile: 0.04 NH_3-N mg/L)[3], cannot be simulated because pH and temperature are the key factors influencing the equilibrium between un-ionized ammonia and ionized ammonia. Still, its risk can be estimated from the simulation results on total ammonia given the river pH and temperature[4]. For the studied river, the risk is considered to be low as the un-ionized ammonia limit is automatically complied with if the total ammonia limit is met under conditions where the river pH is lower than 8.0 and the temperature below 25 ºC or at a higher pH below 8.5 and the temperature lower than 10 ºC.

1.2 Flow and water quality input data

The flow and water quality data of the DWF in the sewer system [2], rainfall runoff [2] and supernatant flow from the sludge dewatering unit in the WWTP[5] are presented in Table S2. The values for the runoff and supernatant are assumed to be constant in the simulation, while that for the DWF are average values and are used by multiplying pre-defined diurnal patterns[2].

Table S2 Flow and water quality data for dry weather flow, rainfall runoff and supernatant flow

	Flow rate (L/s)	Water quality (mg/L)					
		COD	$COD_{soluble}$	SS	VSS	NH_4+NH_3	NO_3
Dry weather flow	318.3	606	281	335	245	27.7	0
Rainfall runoff	--	100	46	190	139	2	0
Supernatant	20	8,221	84	7,595	6,155	12	0

A one-year simulation was set up so that long-term performance of the system can be evaluated. In the original model established for this case study site[2], the evaluation of system performance was rather short-term (e.g. one week) so wastewater temperature and upstream river flow rate and water quality were assumed to be constant. To accommodate long-term simulations, a pattern of seasonal wastewater temperature was defined and one-year input data sets (rainfall and corresponding river data) were incorporated into the model. As no monitoring data on temperature of the Norwich WWTP were available, a seasonal pattern (18 °C, 23 °C, 19 °C and 15 °C from spring to winter) was assumed by adjusting a WWTP wastewater temperature pattern reported in the literature[6] to data on the local climate of Norwich[7]. The rainfall time series is shown in Figure S2.

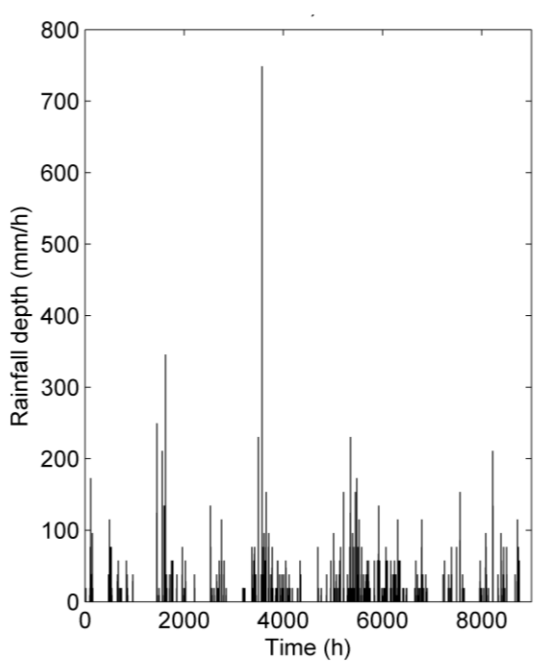

Figure S2 Rainfall data (Oct 2012 to Oct 2013) for the case study

2. Formulation of operational cost

Energy cost refers to the expenditure incurred in pumping, aeration and sludge treatment as calculated using Equations (S1)-(S4):

$$\text{Operational cost} = C_{pump} + C_{aeration} + C_{sludge} \quad \text{(S1)}$$

$$C_{pump} = 0.16 \times E_{pump} \quad \text{(S2)}$$

$$C_{aeration} = 0.16 \times E_{aeration} \quad \text{(S3)}$$

$$C_{sludge} = 1.24 \times 10^{-4} \times V_{ts} \times C_{ts} \quad \text{(S4)}$$

where C_{pump} ($) is the cost for pumping, E_{pump} (kWh) is the total electricity consumption from pumping within the simulation period, $C_{aeration}$ ($) is the cost for aeration, $E_{aeration}$ (kWh) is the total electricity consumption from aeration, C_{sludge} ($) is the cost for sludge treatment, V_{ts} (m^3) is the total volume of thickened waste sludge, and C_{ts} (mg/L) is the concentration of the thickened waste sludge. The constant 0.16 is the electricity tariff rate ($/kWh) defined for pumping and aeration in this study. The constant 1.24×10^{-4} is the mechanical dewatering cost ($) per gram of dry waste sludge[8].

3. Value ranges for operational variables

Table S3 Baseline values and ranges of the operational variables (unit: m^3/d)

Operational variable	Baseline value	Lower bound value	Higher bound value
Tank 2 overflow threshold	24,900	15,000	40,000

Tank 4 overflow threshold	11,300	6,800	18,000
Tank 6 overflow threshold	23,000	14,000	37,000
CSO (tank 7)	137,500 (i.e. 5DWF)	82,500 (i.e. 3DWF)	220,000 (i.e. 8DWF)
Storm tank overflow threshold	82,500 (i.e. 3DWF)	55,000 (i.e. 2DWF)	137,500 (i.e. 5DWF)
Storm tank emptying threshold	24,000	16,800	31,200
Storm tank emptying rate	12,000	7,200	24,000
Return sludge pumping rate	14,400	7,200	24,000
Waste sludge pumping rate	660	240	960
Aeration rate	720,000	240,000	1,200,000

4. If-Then control rules for the case study

Table S4 RTC rules for aeration rate control in accordance to wastewater inflow rate, temperature and upstream river flow rate

Scenario	Wastewater inflow rate to the WWTP (m^3/d)	Temperature (°C)	Upstream (reach 2) river flow rate (m^3/d)	Aeration rate tier (m^3/h)
S1	> 41,250	> 15	> 300,000	Y_1
S2	<= 41,250	> 15	> 300,000	Y_1
S3	> 41,250	<= 15	> 300,000	Y_2
S4	> 41,250	> 15	<= 300,000	Y_2

S5	<= 41,250	<= 15	> 300,000	Y_1
S6	<= 41,250	> 15	<= 300,000	Y_1
S7	> 41,250	<= 15	<= 300,000	Y_2
S8	<= 41,250	<= 15	<= 300,000	Y_1

The suitability of the assignment of the aeration tier for each scenario is tested. As it is certain to assign Y_2 to the 'worst' environmental condition and to assign air flow Y_1 to the 'best', S2 and S7 need not to be examined. For the rest of the scenarios, the assignment of aeration tier is tested by changing it to the alternative option (i.e. from Y_1 to Y_2, or Y_2 to Y_1) and checking if great improvement in system performance can be achieved. The changes in the two objectives are presented in Figure S3. By altering the aeration tier from Y_2 to Y_1 for S3 and S4, cost reduction can be achieved but with a disproportionate increase in risk. Similarly, disproportional cost is increased if the aeration tier Y_1 is changed to Y_2 for S5, S6 and S8. It is uncertain however of whether the aeration tier for S1 needs to be changed from the produced results. The slope of the curve suggests more percentage of risk can be reduced by a lower percentage of cost increase. Nevertheless, the rule is not changed because a) the amount of change is marginal and b) the reduction in operational cost is harder to achieve for this case compared to the environmental risk. Note that if the aeration tier of S1 is changed, the framework of the RTC strategies will be altered, as the condition of river flow rate will be redundant for the "If-Then" rules. Therefore, the suitability of parameters selected for the RTC rule conditions can be checked through the optimization of the controlled variable values.

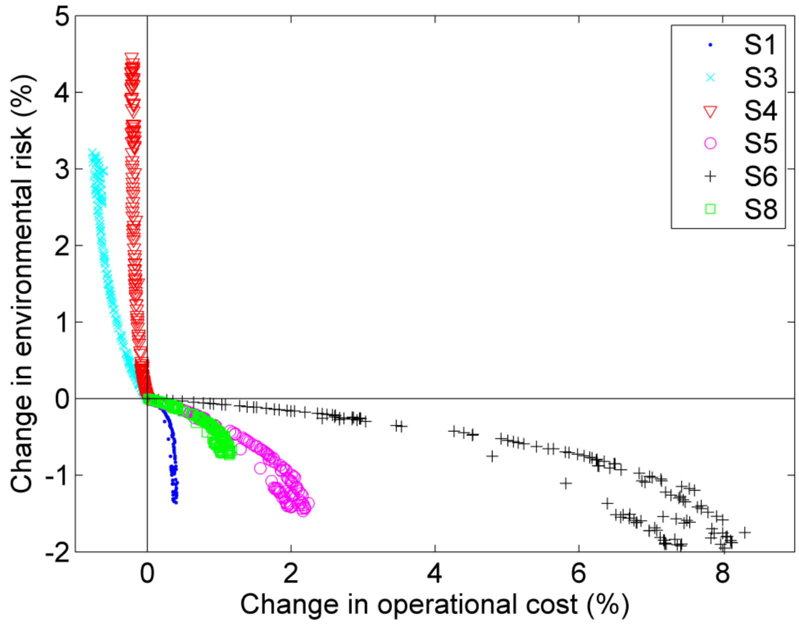

Figure S3 Changes in operational cost and environmental risk by varying aeration tiers from Y1 to Y2 or Y2 to Y1 of S1, S2-6 and S8

5. OAT analysis results

In the OAT analysis, the setting of one operational variable is changed at a time (to the lower or higher bound value), while keeping others at their baseline values. Then the variable is returned to its baseline value, and the process is repeated for each of the other variables in the same way. The baseline and lower and higher bound values of the operational variables are listed in Table S3. Sensitivity is measured by running a one year wet weather simulation and recording the value changes in the output parameters (i.e. cost and environmental objectives as defined in Equations (1) to (3)).

Results of the OAT analysis are represented in tornado graphs from Figure S4 to Figure S6, where the operational variables are ranked by the greatest range of percentage change for any model output. For example, as shown in Figures S4, the waste sludge rate produces a 318% increase in the 90%ile river total ammonia concentration compared to the base scenario when the waste sludge rate is at the high bound (960m^3/d), and a 54% decrease at the high bound (240 m^3/d). The difference between 318% and -54% is the largest among all operational variables. Results suggest that waste sludge pumping rate, return sludge pumping rate, overflow threshold of the storm tank in WWTP and aeration rate are the most essential factors influencing environmental total ammonia concentration; aeration is the major source of operational cost, followed by waste sludge pumping rate and return sludge pumping rate.

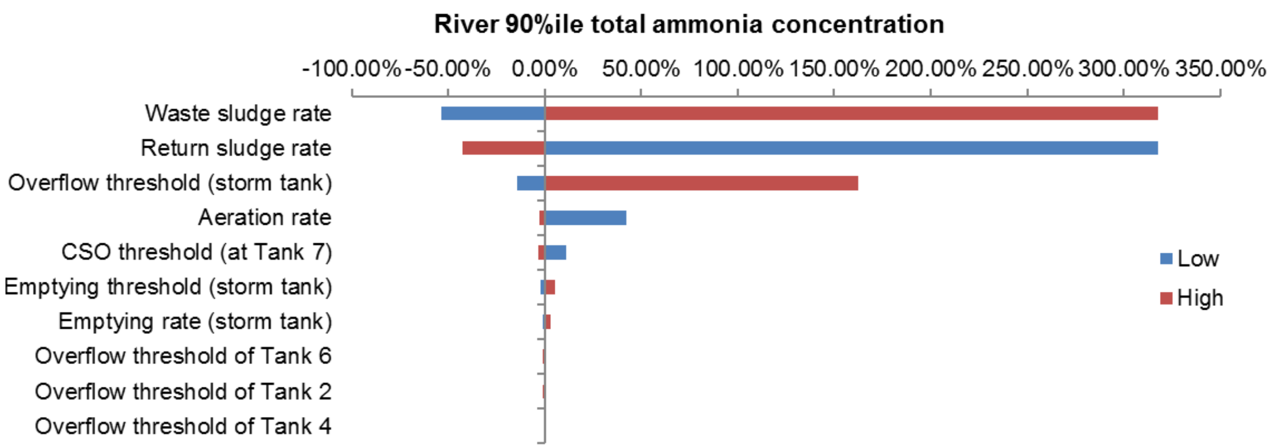

Figure S4 Percentage changes in river ammonium 90% values in reach 11 from the base case when operational variable values are varied to low bound and high bound values

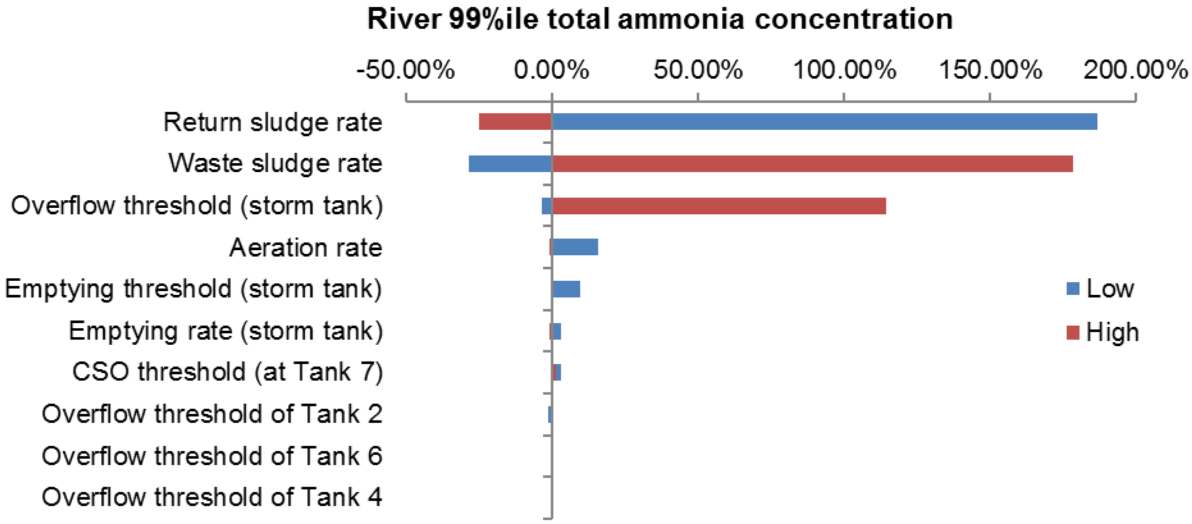

Figure S5 Percentage changes in river ammonium 99% values in reach 11 from the base case when operational variable values are varied to low bound and high bound values

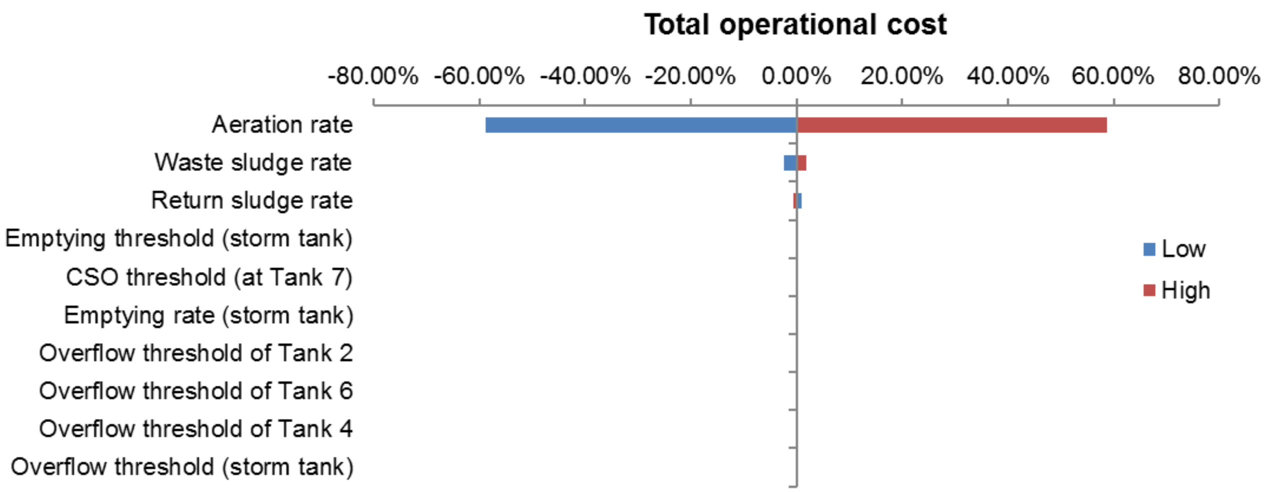

Figure S6 Percentage changes in total operational cost from the base case when operational variable values are varied to low bound and high bound values

6. Optimization results with three aeration tiers

Figure S7 shows the variable values of the optimal solutions when three aeration tiers are used and optimised by NSGA-II. Each solution corresponds with one set of X, Y and Z values. As shown in the figure, the values of Y and Z for most solutions are close, suggesting only two aeration tiers could be sufficiently enough.

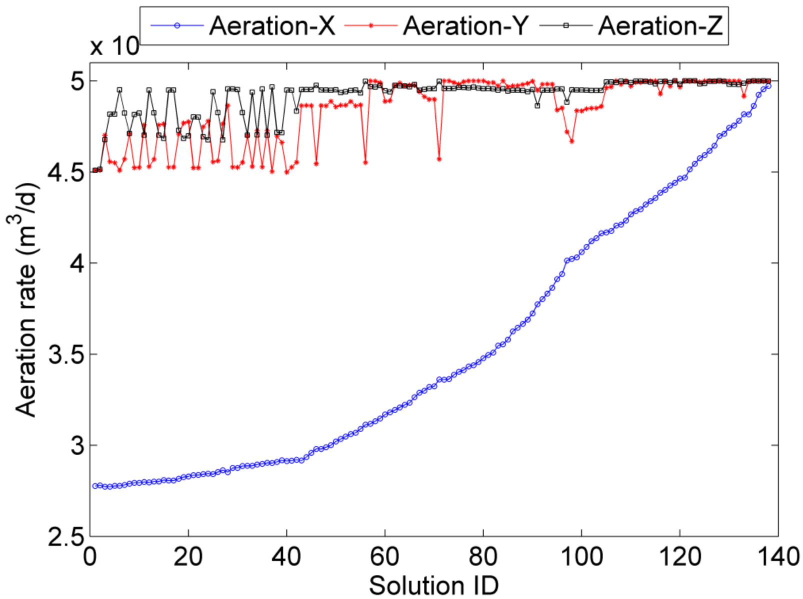

Figure S7 Operational variable values of the optimal RTC solutions with three aeration tiers

7. Uncertainty analysis against rainfall input

The uncertainty of system performance against rainfall changes are presented by results of two typical solutions, i.e. *GoodSol (OO)* and *GoodSol (RTC)* as shown in Figure S8. Dynamic simulation is run for each rainfall input data series and the resulting environmental quality values are shown in the figure as compared with those by the original rainfall data (shown in red dots). It can be seen from Figures S8b and S8d that the 99%ile limits can be easily violated even under less intensive (measured in total depth) rainfall inputs. This is expected as the 99%ile total ammonia concentration is highly influenced by sewer overflows thus cannot be effectively addressed by control measures in the WWTP. The effluent water quality is less affected by rainfall variations, which in turn results in satisfactory 90%ile total ammonia concentration in the river. Though the control solution has 19% less headroom to the 90%ile standard limit than the fixed operational solution, it is shown to withstand 30% more intensive rainfall without violating the standard limit. This suggests a high robustness of the strategy to precipitation changes, as a 10% rainfall increase (in total depth) until 2050 is what used by regulators in the UK for the preparation of climate change[9].

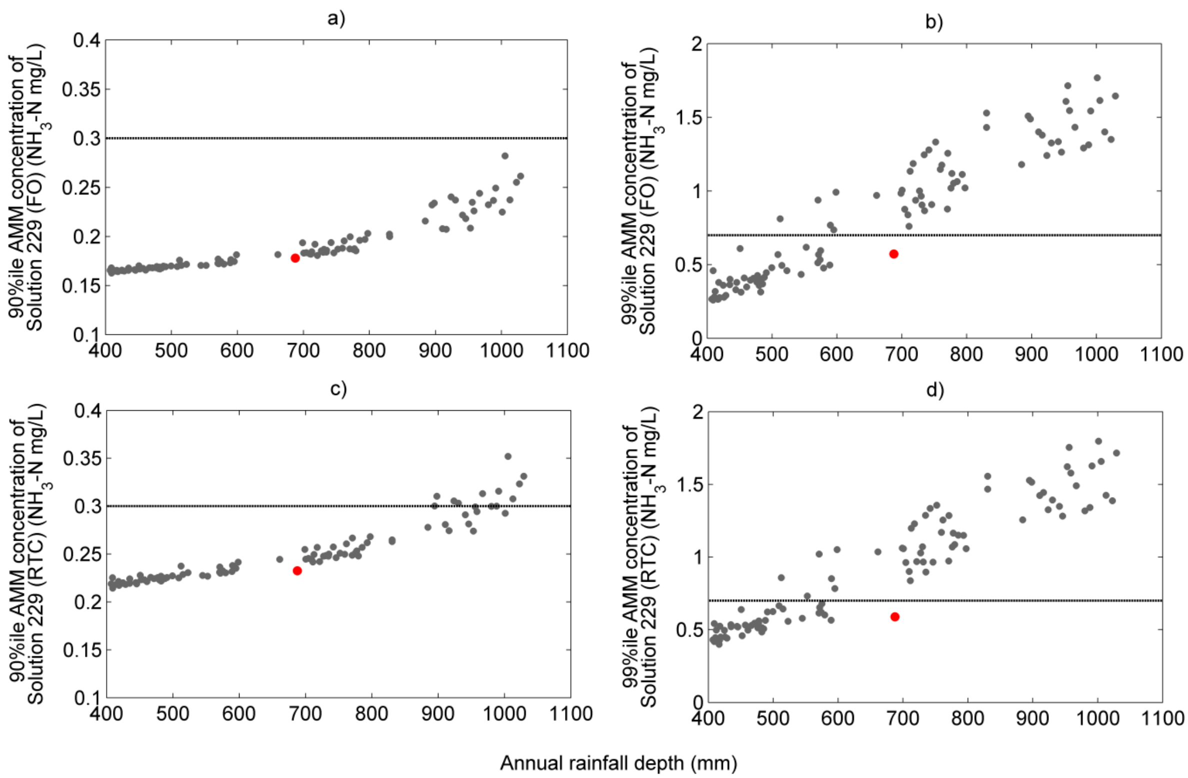

Figure S8 Comparison of performance of GoodSol (OO) (a and b) and GoodSol (RTC) (c and d) under 100 one-year rainfall input data series

As the headroom decreases such as stressed by a higher environmental target or in pursuit of a lower cost solution, the robustness of the strategy reduces. For example, the RTC solution in Figure 8 could only cope with 7% more intensive rainfall if the 90%ile limit is changed to 0.25 NH_3-N mg/L (i.e. headroom diminishing from 22% to 6%). As such, the trade-offs between cost savings and confidence level of regulatory compliance should be appraised and understood to choose a balanced solution.

References

(1) Vanrolleghem, P.; Benedetti, L.; Meirlaen, J. Modelling and real-time control of the integrated urban wastewater system. *Env. Model Softw.* **2005**, *20*, 427–442.

(2) Schütze, M.; Butler, D.; Beck, B. *Modelling, simulation and control of urban wastewater systems*; Springer: London, UK, 2002.

(3) *Urban Pollution Management Manual*; 3rd ed.; Foundation for Water Research, Marlow, UK,: Foundation for Water Research: Marlow, UK, 2012; [viewed 24 July 2017] http://www.fwr.org/UPM3/.

(4) Emerson, K.; Lund, R. E.; Thurston, R. V.; Russo, R. C. Aqueous ammonia equilibrium calculations: Effect of pH and temperature. *J. Fish. Res. Board Can.* **1975**, *32*, 2379–2383.

(5) Lessard, P.; Beck, B. Dynamic modelling of the activated sludge process: A case study. *Water Res.* **1993**, *27*, 963–978.

(6) Shatat, M.; Al-najar, H. The impacts of temperature variation on wastewater treatment in the Gaza Strip: Gaza wastewater treatment plant as case study. In *Conference of Water and Climate Change in the MENA-Region: Adaptation, Mitigation, and Best Practices*; Berlin, Germany, 2011.

(7) Hughes, K. The impact of urban areas on climate in the UK: A spatial and temporal analysis, with an emphasis on temperature and precipitation effects. *Earth & E-nvironment.* **2006**, *2*, 54–83.

(8) Mamais, D.; Tzimas, A.; Efthimiadou, A.; Kissandrakis, J.; Andreadakis, A. Evaluation of different sludge mechanical dewatering technologies. *J Residuals Sci Tech.* **2009**, *6*, 27–34.

(9) Casal-Campos, A.; Fu, G.; Butler, D.; Moore, A. An integrated environmental assessment of green and gray infrastructure strategies for robust decision making. *Environ. Sci. Technol.* **2015**, *49*, 8307–8314.