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Assessing the equivalence of WRRF regulations using dynamic model simulations

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ABSTRACT

A wide diversity of regulatory practices for wastewater resource recovery plants exists throughout the world. This contribution aims to highlight the implications of choosing particular permitting structures and investigate the equivalence of effluent standards in terms of limit values and compliance assessment specifications. These factors heavily affect the true performance that a treatment plant has to attain and thus the required plant capacity and operation. The dynamic simulations executed in this work, based on a realistic case study and three selected permits from China, The Netherlands and the USA, show the impact of certain compliance specifications like sampling frequency, averaging and tolerable permit exceedances leading to differences in the required design capacity of more than 250% for the same wastewater to be treated. The results also reveal clear differences between permits in their capacity to handle excess variability. The latter is important to avoid overdesign, i.e., when further investment in treatment capacity would result only in marginal effluent quality gains, as well as to create a safe space for testing innovative technologies or ways of operation that might otherwise trigger compliance issues.

Key words: compliance testing, design procedure, environmental protection, permit structures, uncertainty assessment, wastewater treatment

HIGHLIGHTS

- A dynamic modelling procedure to test the equivalence of treatment plant effluent standards has been developed.
- The proposed approach allows quantifying the interactions between regulations, plant design and effluent compliance.
- Analysis of three actual permit structures covering a variety of global regulatory practices indicates the importance of compliance specifications like sampling frequency, averaging or tolerable permit exceedances.
- Strict, not-to-exceed limit values and short averaging periods for effluent parameters tend to lead to costly, overdesigned plants without guaranteeing full compliance under all circumstances.
- Permit structures that are able to handle uncertainty and variability can help foster the introduction of new innovative technologies or operational procedures.

INTRODUCTION

A wide diversity of regulatory practices for wastewater treatment and pollutant removal exists throughout the world, all pursuing the protection of environmental and human health (Vanrolleghem 2011; Maere *et al.* 2016; Vanrolleghem *et al.* 2023). This diversity not only reflects the variety of water bodies and their beneficial uses (e.g. bathing, fishing, drinking water source, transport and hydropower production) but also the many ways in which jurisdictions make regulations operational through standards, permits and compliance testing methods. When evaluating the compliance of water resource recovery facilities (WRRFs) to effluent discharge standards, this includes not only the limit values for the relevant parameters but also a specification of the methods for sampling, analysis and data treatment. Jacobsen & Warn (1999) clearly illustrated in their study evaluating six different permit structures using rigorous statistics that direct comparisons between effluent discharge standards can be very misleading due to different methods in sampling (e.g. grab vs. time or flow-proportional composites and frequency of sampling), chemical analyses and compliance assessment (e.g. all data points must comply vs. percentiles, or using daily values vs. weekly, monthly or annual averages). Differences in each of these aspects heavily affect the true performance that a treatment plant has to attain in order to be compliant. In consequence, the way a permit is written heavily affects the required plant design and operation.

Many WRRF regulations tend to be deterministic with strict, not-to-exceed effluent limits, despite the uncertainty and the stochastic nature of the processes involved (Clark *et al.* 2016, 2023). While such limits are easily understood and enforceable, they do not tell about the receiving water ecology or beneficial uses. They can lead to unsustainable and expensive investments in treatment infrastructure to comply even under extreme and rare events with only marginal additional environmental benefits. When confronted with uncertainty and variability, generally, safety factors are applied, in line with the precautionary principle. This is common practice in the design stage of WRRFs, but equally customary when translating environmental objectives into WRRF permit criteria by permit writers. An example is the worst-case assumptions made for both treatment plant loading and available river dilution when determining allowable discharge loads. Also, plant operators will apply a margin of safety in their day-to-day activities to remain well below the specified effluent limits. The accumulation of safety factors in each subsequent step is undesirable (Belia *et al.* 2021). While this approach might be valid for toxicants, it seems overly protective for other pollutants like nutrients and likely leads to cost-ineffective solutions for the environmental objectives that were set out.

The aim of the current study is to show the impact of uncertainty and variability on the compliance performance of WRRFs designed according to different effluent discharge permits. It is hypothesized that some permit structures, regardless of whether they come from a technology or water quality-based origin, are more appropriate to handle influent and process variability and will lead to more appropriate design sizing. At the same time, such permit structures would also leave some room for plant operators to test new strategies or technologies that appear promising and potentially reduce the overall environmental impact but that might perform less robustly. As such, choosing the right permit structure can create a safe space for experimentation and present a path forward to support innovation.

In what follows, the methodology to investigate the equivalence of effluent standards in terms of limits and compliance assessment under variable conditions will be explained and discussed based on a realistic and dynamic model-based case study.

METHODOLOGICAL APPROACH

Jacobsen & Warn (1999) studied a WRRF operating under steady-state conditions to evaluate how the true effluent quality and treatment performance to be pursued are different under different permit structures. Their methodology was adapted for this study under dynamic conditions by employing effluent quality data obtained from dynamic model simulations. Input data for the model were taken from a nitrogen-removing WRRF located in Virginia (Virginia Initiative Plant in Norfolk, VA, USA) for which a full year of influent measurements was available. This WRRF has been the subject of a modelling study before by EnviroSim Associates Ltd as part of a contract with Hampton Roads Sanitation District (EnviroSim 2011), and the results on influent fractionation were taken over in its entirety. The flow rate was downsized to attain approximately 200,000 people equivalent (PE), which translates into an average flow rate of 20 million gallons per day (MGD). More influent details can be found in Vanrolleghem *et al.* (2023). Table 1 lists the yearly flow-proportional average values for raw wastewater quality. The yearly patterns for flow, chemical oxygen demand (COD), total suspended solids (TSS), total Kjeldahl nitrogen (TKN) and temperature can be found in Supplementary Information (Figures S1–S5).

The base-case scenario for the study is a Modified Ludzack–Ettinger (MLE) configuration, which is a common type of pre-denitrifying WRRF. The layout of the plant was kept as simple as possible with only one anoxic and aerated tank in series. The design was made according to Metcalf & Eddy (Tchobanoglous *et al.* 2003) using the influent flow rate and pollutant concentrations as mentioned in Table 1 and the desired treatment performance as mentioned in Table 2. Additional assumptions had to be made for the treatment plant design regarding mixed liquor suspended solid concentrations (3,000 mg/L), anoxic tank retention time (2.5 h), dissolved oxygen concentration (2 mg/L), the clarifier hydraulic loading rate (22 m^3/m^2d) and several other design parameters. These design parameters were taken from Tchobanoglous *et al.* (2003). The resulting design volumes for the anoxic and aerobic tank and the surface for the clarifier in the base-case scenario can be found in Table 2, just as the values for the sludge retention time and the internal and return activated sludge recycle rates.

The chosen layout and obtained design were transferred into the WRRF modelling and simulation environment WEST (DHI, Denmark). ASM2d was chosen as the biochemical model with default parameter values (Henze *et al.* 2000), while, for the secondary settler, a standard Takács SVI model was chosen, again with default parameter values (Copp 2002) and

Table 1 | Yearly flow-proportional averages for influent wastewater quality

Pollutant	Mean value
BOD (biological oxygen demand)	179.8 mg/L
sBOD (soluble BOD)	110.2 mg/L
COD (chemical oxygen demand)	410.8 mg/L
sCOD (soluble COD)	220.5 mg/L
rbCOD (readily biodegradable COD)	209.5 mg/L
TSS (total suspended solids)	142.8 mg/L
VSS (volatile suspended solids)	116.1 mg/L
TKN (total Kjeldahl nitrogen)	31.7 mg/L
NH_4-N (ammonia nitrogen)	22.4 mg/L
TP (total phosphorus)	4.6 mg/L
bCOD/BOD (biodegradable COD to BOD ratio)	1.36
Alkalinity	150 mg/L
Temperature	22.1 °C
Flow rate	20 MGD

Table 2 | Design conditions and results for the base-case scenario using a design flow of 20 MGD

Design conditions	Value
Effluent COD	<30 mg/L
Effluent BOD	<15 mg/L
Effluent TSS	<15 mg/L
Effluent NH_4-N	<0.5 mg/L
Design results	**Value**
Sludge retention time (SRT)	8.6 d
Volume aeration tank	33,280 m³
Volume anoxic tank	7,885 m³
Surface of the clarifier	3,440 m²
Internal recycle (IR)	2.62
Return-activated sludge (RAS)	0.6

a sludge volume index of 100 mL/g. The WRRF model was run for a full year (to cover temperature and weather variability) giving output data every 15 min. Basic versions of control systems and procedures that can be expected in modern-day treatment facilities were implemented to maintain the intended dissolved oxygen (DO) concentration, sludge and internal recycle rates, and sludge age during the simulations. Different sampling strategies (e.g. grab, time and flow-proportional) and averaging and aggregation methods (day, week, month and year) were applied to the model simulation results mimicking actual compliance assessment methods described in permits. Three permit structures from China (class 1B), USA (Nansemond, VA) and The Netherlands (generic permit) were chosen, covering a variety of standard permitting practices worldwide. Details for each permit are given in Table 3. The limit values are valid for a 20 MGD WRRF serving 200,000 PE, discharging in a receiving water body used for drinking water production, fishery and recreational activities. Phosphorus is not considered in this study.

The permits were evaluated for effluent limit exceedances for the base-case scenario as described before and subsequently compared for the minimal design size that actually is required to be fully compliant. For this, the design was varied only considering the anoxic and aerobic tank volumes and the settler surface area. Different designs were made according to the Metcalf & Eddy design procedure by varying the influent flow rate but keeping the same influent concentrations. In the

Table 3 | Overview of the effluent requirements for the chosen permits in this study

Permit	Pollutants	Concentration limit (mg/L)	Reduction limit (%)	Load limit (kg/d)[a]	Averaging	Allowed exceedances
China class 1B[b]	COD	60	–	–	Daily	–
	BOD_5	20	–	–	Daily	–
	TSS	20	–	–	Daily	–
	TN	20	–	–	Daily	–
	NH_4-N	8	–	–	Daily	–
The Netherlands[b,c]	COD	125	–	–	Daily	7.3%
	BOD_5	20	–	–	Daily	7.3%
	TSS	30	–	–	Daily	11.5%
	TN	10	75	–	Annually	–
USA Nansemond[d]	BOD_5	45	–	3,408	Weekly	–
	BOD_5	30	85	2,271	Monthly	–
	TSS	45	–	3,408	Weekly	–
	TSS	30	85	2,271	Monthly	–
	TN	8	–	–	Monthly	–

Sources: People's Republic of China (2002), Official Gazette of the Kingdom of The Netherlands (1996), Commonwealth of Virginia (2019).
[a]Load limits derived from concentration limits using the yearly average flow, i.e., 20 MGD.
[b]24 h flow proportional samples, 5 times per week, not the weekend.
[c]The allowed percentage of exceedances varies depending on the number of samples taken.
[d]24 h flow proportional samples, 3 times per week, influent grab samples between 9 am and 11 am are used to calculate % reduction.

Results section, the adapted design capacity or design size is expressed through the flow rate for which the design was made. 20 MGD stands for the base-case design size, and values below (e.g. 10 MGD) or above (e.g. 40 MGD), respectively, indicate a smaller or bigger design than used for the base-case scenario. The effluent results from these simulations with different design sizes but using the same standard 20 MGD influent input file are then compared to see the effect of permit structure and design capacity on compliance.

The effluent results come with an intrinsic variability that depends on the sampling and aggregation methodology as well as the intrinsic dynamic nature of the WRRF's treatment performance. By adding random noise to the effluent time series, one can further increase the coefficient of variation (i.e., the standard deviation divided by the mean) of a set of effluent results and in this way assess the effect of added variability to compliance performance. This added noise can be perceived in several ways, e.g. uncertainty related to influent dynamics and process performance or variability related to sampling, laboratory analyses and sensor readings. It can also give an idea of what happens when employing an innovative treatment technology that operates equally on average but with more variation in its performance. To this end, the noise was sampled randomly from a normal distribution and added to the effluent results (after sampling) for the smallest WRRF design compliant with each of the studied permits. Each time, the analysis was limited to the three most stringent effluent parameters. The noise addition was truncated to an interval between zero and twice the original effluent value to ensure symmetry and keep the same yearly mean effluent values. In the Results section, the level of noise addition is expressed as the coefficient of variation (CV) added to the original effluent series. Added noise ranges between 0 and 40% of added CV with increments of 5%. 0% added CV represents the original effluent series. An example of a 40% CV increase in effluent variability for a yearly series of TSS results is given in Figure 1. The noise addition procedure was repeated 500 times per 5% CV increment.

RESULTS AND DISCUSSION

The effect of compliance specifications on WRRF design

Simulations were run for the base-case scenario WRRF with a design flow of 20 MGD using the 20 MGD influent file, as described before. Subsequently, the same 20 MGD influent flow was sent through plants with smaller or bigger designs obtained by gradually varying the design flow between 10 and 40 MGD. The resulting anoxic, aerobic and settler volumes for these different designs are given in the Supplementary Material (Table S1). The average, 90th and 99th percentile values for various effluent quality parameters at 10 and 40 MGD are given in Table 4, giving an indication of the obtainable

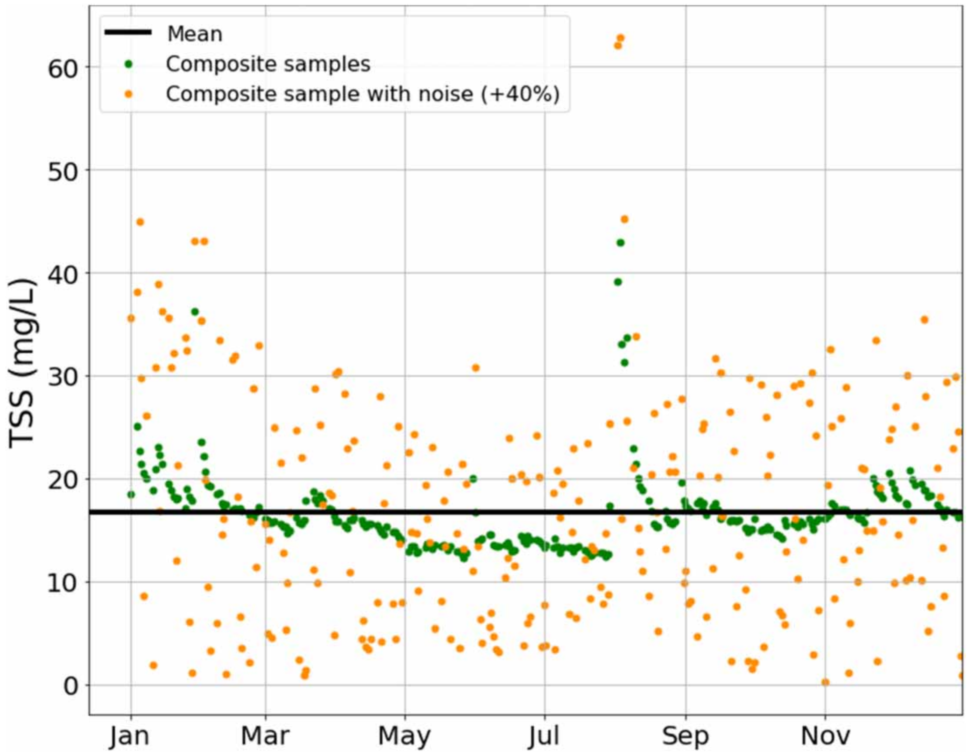

Figure 1 | Noise addition to sampled TSS data for evaluating permit compliance, expressed as a % increase in the coefficient of variation (e.g. +40% CV).

Table 4 | The average, 90th and 99th percentile values for several effluent quality parameters for the 10 MGD and 40 MGD WRRF designs

Design size	Effluent variable	Mean concentration (mg/L)	90th percentile (mg/L)	99th percentile (mg/L)
10 MGD	BOD_5	11.3	15	33.2
	COD	79.7	88.1	135.3
	NH_4	1.1	1.82	8.4
	TN	7.8	8.9	14.8
	TSS	35.6	42.4	79.3
40 MGD	BOD_5	2.5	3.3	4.6
	COD	45.3	52.3	56.7
	NH_4	0.6	1.0	2.1
	TN	6.0	7.0	7.9
	TSS	7.7	9.3	14.3
Ratio of obtained values: 10 MGD/40 MGD	BOD_5	4.5	4.5	7.2
	COD	1.8	1.7	2.4
	NH_4	1.8	1.8	4.0
	TN	1.3	1.3	1.9
	TSS	4.6	4.6	5.5

treatment performance for a certain wastewater flow when varying the design size. When taking the ratio between the obtained results for 10 and 40 MGD, it is observed that the effect of design size on treatment performance is more pronounced for BOD_5 and TSS and also for NH_4 for the more extreme values.

Compliance with the selected permits of China, The Netherlands and the USA (see Table 3 for details) was verified for each simulated design size. The permit exceedance results for the different effluent parameters are shown in Figures 2–4. The minimum design flow rate that is needed to have a compliant WRRF under the Chinese permit is about 37.5 MGD and is

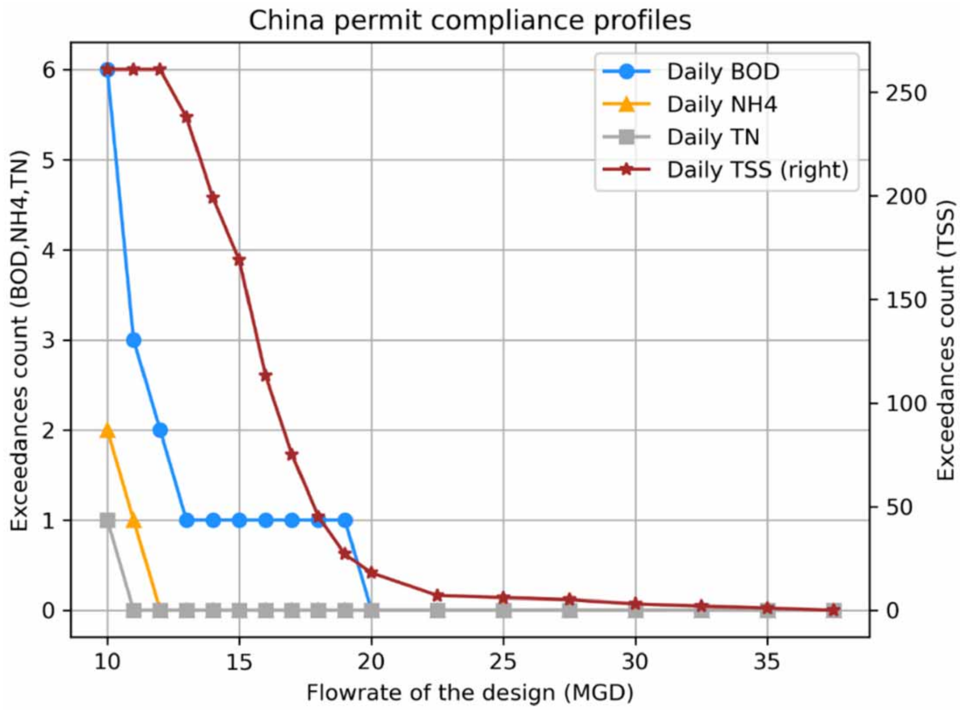

Figure 2 | Number of limit exceedances for the most stringent effluent parameters according to the China permit. Simulations and compliance verification were executed for design sizes ranging from 10 to 40 MGD.

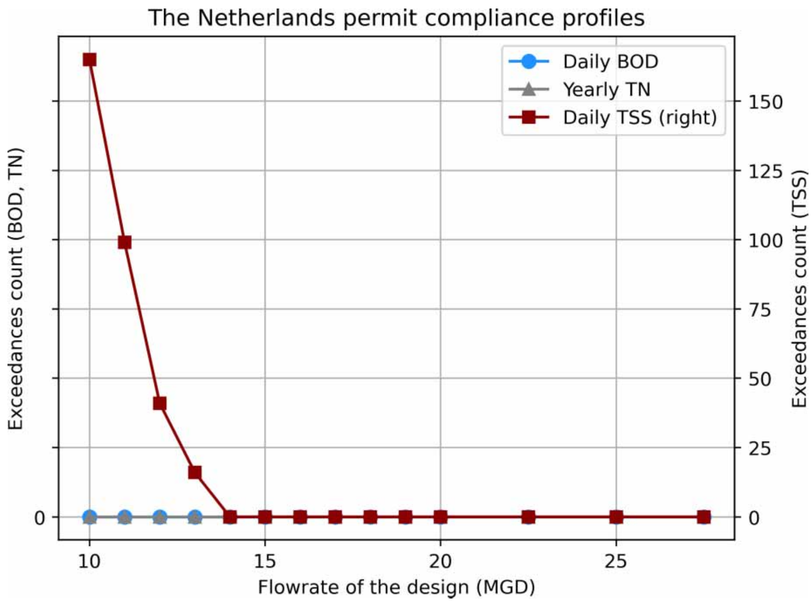

Figure 3 | Number of limit exceedances for the most stringent effluent parameters according to the Dutch permit. Simulations and compliance verification were executed for design sizes ranging from 10 to 40 MGD.

determined by the daily TSS concentration limit. The second most stringent parameter is BOD_5, for which the base-case design at 20 MGD would suffice. NH_4 and total nitrogen (TN) turn out to be the least stringent parameters with only a couple of exceedances for the smallest design sizes, even though influent nitrogen concentrations vary considerably. For BOD_5 and TSS, the results show an initial swift decrease in the number of effluent permit exceedances with increasing

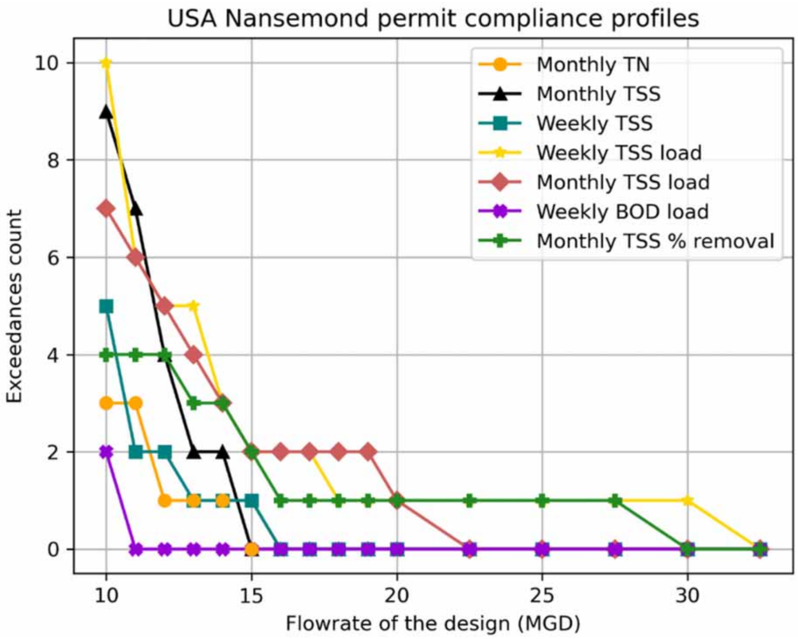

Figure 4 | Number of limit exceedances for the most stringent effluent parameters according to the USA permit. Simulations and compliance verification were executed for design sizes ranging from 10 to 40 MGD.

design size. However, at some point, this decreasing trend levels off, and from this point on, it takes a considerable additional increase in design size to eliminate the last remaining effluent exceedances. These are permit exceedances that are related to extreme events such as storm weather.

The minimum required design flow rate for the permit of The Netherlands is 14 MGD and is also determined by the daily TSS concentration limit. None of the other parameters pose an issue for effluent compliance in the range of design sizes that were simulated. The fact that this permit allows a certain percentage of exceedances to accommodate extreme conditions has a large effect on the required design size. Despite the fact that the maximum allowed concentration for TN is considerably stricter for The Netherlands than for the Chinese permit and that for The Netherlands also a % reduction limit is specified, it never poses an issue for compliance since it is evaluated on a yearly rather than a daily basis.

The minimum design size needed for full compliance according to the selected USA permit is 32.5 MGD. The most limiting factor is the weekly TSS load, closely followed by the monthly TSS reduction. The third place is the monthly TSS load. Noteworthy, the monthly TSS load permit limit threshold is considerably more severe than the weekly threshold (Table 3), but the fact that the results are averaged over a month instead of a week dampens the variability in treatment performance a little more and helps achieve compliance quicker. The results also show that the concentration-based limits are much less restrictive than the load limits. To comply with the monthly TSS concentration limit, a design capacity of 15 MGD is required, while it rises to 22.5 MGD for the monthly TSS load limit. When employing loads, an additional amount of variability comes in play which is linked to the important fluctuations in influent flow throughout the year.

It is interesting to note that the monthly TSS concentration limit value for the USA permit is the same as the daily limit value for the Dutch permit (Table 3) and both result in about the same required design size, respectively, 15 vs. 14 MGD. It means that the daily limit value with 11.5% allowed exceedances appears to be comparable to monthly averaging. Also, the TN limit value for the USA permit is similar to that for The Netherlands (Table 3), but it is evaluated on a monthly rather than a yearly basis. This makes it stricter for the USA, giving rise to some limit violations for smaller designs. Just as with the China permit, the results for the weekly TSS load and monthly TSS reduction for the USA show an initial rapid decrease in effluent violations with increasing design size up until a certain point where only one violation is left. From there one needs to roughly double the design capacity to eliminate this last violation. It makes one question about the efficacy of this additional capacity. At a certain point, perhaps other options should be explored to improve receiving water quality that would lead to better overall results.

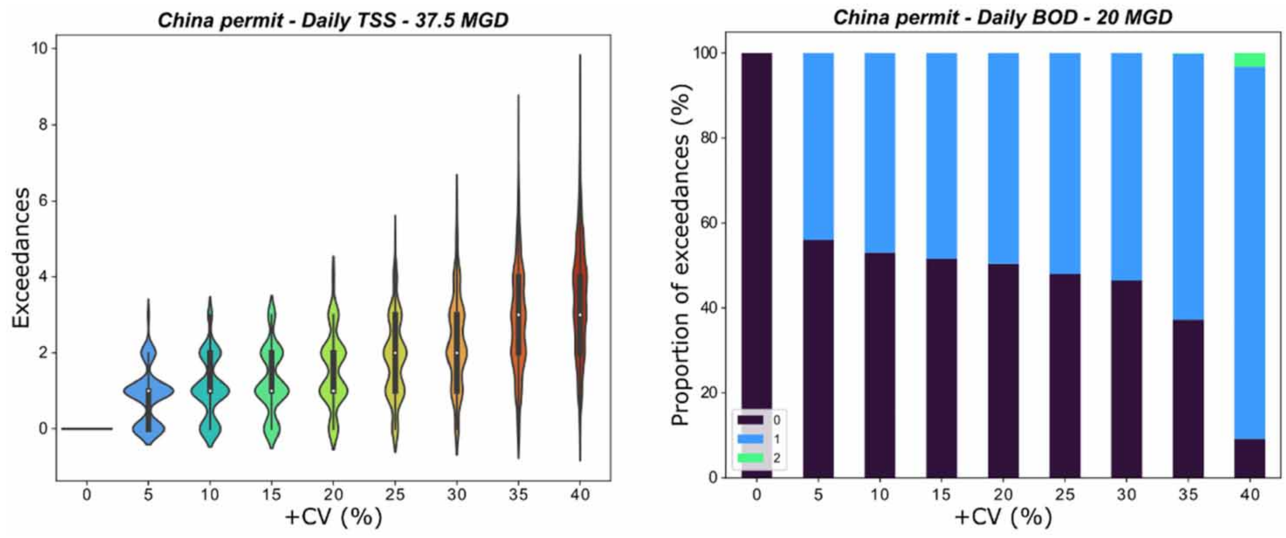

Figure 5 | Graphical representation of the number or percentage of 500 simulated effluent series with noise addition per 5% increments in CV that exceeds the Chinese permit for daily TSS concentration for a 37.5 MGD WRRF design (left) and for daily BOD concentration for a 20 MGD WRRF design (right).

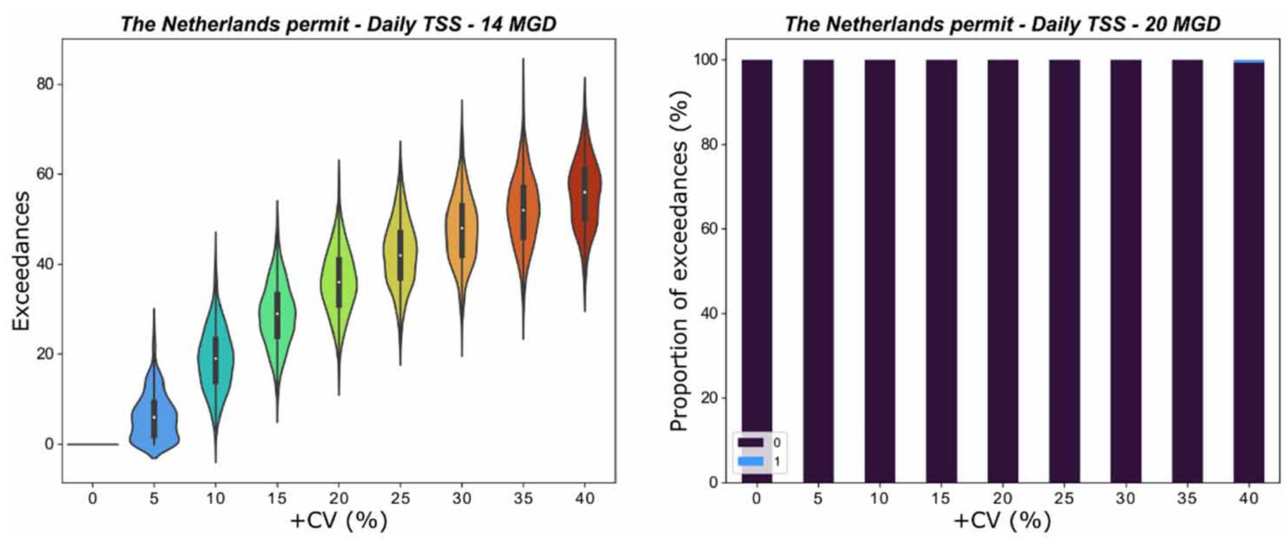

Figure 6 | Graphical representation of the number or percentage of 500 simulated effluent series with noise addition per 5% increments in CV that exceeds the permit for The Netherlands for daily TSS concentration for a 14 MGD WRRF design (left) and a 20 MGD WRRF design (right).

The effect of added variability on permit compliance

Figures 5–7 show how the number of permit exceedances evolves for, respectively, the Chinese, the Dutch and the USA permits with increasing levels of added random variability to the effluent results (see the Methodological Approach for more details). A violin plot is used when the range of effluent violations in the results for a certain parameter exceeds 6 and a bar chart for the others. The surface area of each violin, i.e., per increment of 5% CV, represents 500 realizations of added noise to the effluent series. The shape of the violin informs on the amount and distribution of runs with a certain number of exceedances. In the bar plots, each bar represents 500 runs, and the colour and legend indicate how many runs have a certain number of effluent violations.

The Chinese permit is the most demanding permit as it requires the largest design of all permits to be compliant. However, Figure 5 shows that as soon as a little random noise is added to the effluent series used to evaluate compliance, effluent

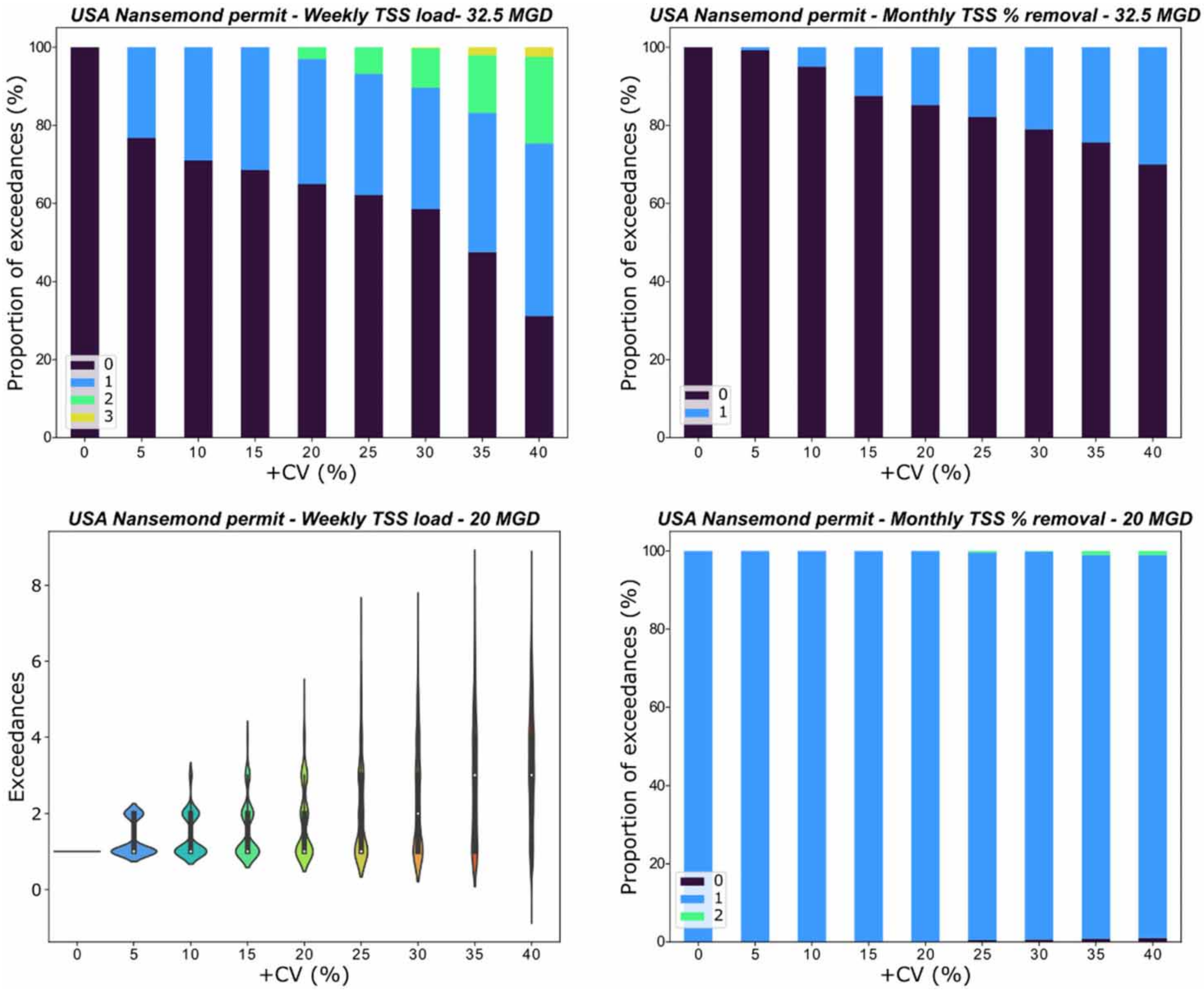

Figure 7 | Graphical representation of the number or percentage of 500 simulated effluent series with noise addition per 5% increments in CV that exceeds the permit for the USA for weekly TSS load (left) and monthly TSS reduction (right) for a 32.5 MGD (top) and 20 MGD (bottom) WRRF design.

violations start to appear again for the majority of the 500 runs, making the plant no longer compliant. Designing a WRRF according to a permit with effluent limits based on daily values and no concession for any type of limit exceedances thus appears cumbersome. Wastewater treatment is an intrinsically stochastic process. Raw wastewater flow, strength and composition, treatment performance, sampling and chemical analyses are all subject to variability. A permit that does not take this into account will result in costly investments in treatment capacity for trying to be compliant in all possible situations, while never being able to achieve this fully.

The results in Figure 6 show that the small 14 MGD design for the Dutch permit cannot handle any added variability at all. Even a small increase in the coefficient of variation immediately leads to many permit exceedances. However, only a small design capacity increase to 20 MGD is needed to adequately handle all tested ranges of added variability. In contrast to the Chinese permit, the stipulation that a certain number of exceedances is allowed in the Dutch permit thus provides a more stable ground for WRRF design and achieving compliance under all circumstances. Permit writers can tailor the limit values of this style of permits in the function of the environmental objectives that are pursued more effectively and with less risk for overdesign.

The results in Figure 7 show that a plant designed according to the USA permit can handle more variability than the Chinese permit. The weekly and especially monthly averaging is able to even out a lot of the random variation. At the same time, averaging does not remove all risks of non-compliance without having to overdesign the plant to a certain extent. The results for monthly suspended solid reduction at 20 MGD indicate that it really is just 1 month of bad performance that hinders compliance for this parameter. Based on these kind of results, one can make a case to have a closer look at the potential environmental impact of breaching the permit during this month and to come up with alternative solutions to provide environmental protection. The procedure described in this paper thus allows finding trade-offs when designing treatment plants, where further investment in conventional treatment capacity would result only in marginal effluent quality gains and potentially still not provide full assurance for compliance.

General discussion

The combined results of this modelling case study reveal the huge impact that the permit structure has on the required plant design and the risk of non-compliance. The Chinese permit requires a design that is more than 250% larger than for a plant to be installed in The Netherlands and still does not guarantee full compliance under extreme conditions. It speaks for itself that such a permit structure does not foster much willingness to test new technologies or operational strategies for which the outcomes might be promising but uncertain. A permit like the Chinese with strict, not-to-exceed effluent limits also does not provide any incentive to increase monitoring efforts (e.g. by introducing online water quality sensors) since this increases the chances of the detection of a non-compliance event. Yet, extensive monitoring is key to improve operations. Also, the stipulation of multiple limits for the same effluent parameter, such as in the USA permit that combines concentration, load and reduction limits over different time scales, appears overly restrictive and does not help in providing an incentive for utilities to test out new strategies.

The strictest effluent parameter for each of the evaluated permits turned out to be TSS-related. This could suggest that the used Metcalf & Eddy design procedure is much more conservative for nitrogen, BOD and COD removal than for TSS. However, one needs to keep in mind that the chosen permits for this study tend not to be overly strict for nutrient removal. One also has to consider the limitations of the used Takács settler model which was never meant to accurately predict effluent concentrations. The settler model parameters could be adjusted to mimic better-settling sludge, but this was deemed arbitrary and also not necessary since the TSS effluent results perfectly allowed making the distinctions between different permit structures. This was the aim of the study.

CONCLUSIONS

The proposed procedure to assess the equivalence of permit structures was illustrated using a realistic and dynamic modelling case study mimicking a 20 MGD Modified Ludzack-Ettinger treatment plant for carbon and nitrogen removal. An initial plant design was proposed according to the well-known Metcalf & Eddy guidelines. Three different effluent discharge permits that are illustrative of the diversity in worldwide permitting approaches were chosen from China, The Netherlands and the USA, and for each of these permits, the required design capacity to comply with the permit was calculated. The relation between the design size and permit compliance as well as the sensitivity of compliance to additional variability added to the effluent data was assessed.

The case study shows how the equivalence of different effluent standards can be investigated by exploring and quantifying the interactions between regulations, plant design and compliance performance. The obtained results clearly indicate that the optimal plant capacity is very different depending under which permit regime the plant is operating. Permits with compliance tested daily against not-to-exceed limit values tend to be the most severe and increase the risk of overdesigning the plant while not fully eliminating the risk of non-compliance. A permit that allows for a certain number of exceedances throughout the year seems more appropriate for WRRFs that naturally operate under very variable conditions and are occasionally subject to extreme events. The methodology proposed in this study can help determine trade-offs where it makes sense to investigate alternative solutions to protect environmental objectives rather than expanding plant capacity with limited meaningful gains in effluent quality.

Finally, the proposed methodology also allows the selecting of more suitable regulation schemes in support of innovation towards the 'utility of the future' and the optimization of investment costs for environmental protection. Legislative and regulatory requirements and restrictions can be a major barrier to the adoption of new technologies. The latter is important since innovation in the wastewater industry is not only needed in view of environmental protection but also because a paradigm shift is occurring with wastewater treatment plants becoming WRRFs. Regulators, consultants and utilities can thus employ the proposed methodology to identify the advantages and shortcomings of certain regulatory practices and promote purposeful and pertinent permitting.

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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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