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A Treatment Reliability-Based Method for Supporting Infrastructure Asset Management of Wastewater Treatment Plants

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Abstract: A simple and consolidated reliability-based method widely used to unveil the real reliability and stability of wastewater treatment plants (WWTPs) is herein proposed to trigger decision making on operational improvements and asset management for maintaining or improving treatment effectiveness, reliability, and efficiency. Five-year data (2015–2019) from 16 Portuguese activated sludge WWTPs were used. For the 73% of the yearly data which fitted a lognormal distribution, Niku's coefficient was computed to assess the plant annual reliability for biological oxygen demand (BOD_5), chemical oxygen demand (COD), and total suspended solids (TSS). The standard deviation of the annual concentrations was used to characterize the plant stability, and the maximum standard deviations allowed to comply with the European discharge requirements for urban WWTPs were derived. The results demonstrate extended aeration WWTPs were more reliable and stable than conventional aeration WWTPs (0.98 reliability vs. 0.82 for BOD_5, 0.97 vs. 0.91 for COD, and 0.94 vs. 0.89 for TSS). Furthermore, the lower reliabilities and stabilities were found for the smaller WWTPs. These results are important for strategic asset management for designing and rehabilitation of the wastewater treatment system. At tactical and operational levels, for resources' allocation and operating conditions set up, the computed WWTP's coefficient of variation allows establishing the mean effluent concentrations required for compliance with a given reliability for different scenarios of discharge requirements.

Keywords: reliability; wastewater treatment plants; activated sludge systems; infrastructure asset management

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1. Introduction

Wastewater treatment plants (WWTPs) are being increasingly challenged to improve resources' use efficiency and to provide higher levels of treatment to meet more stringent discharge consents and/or water reuse opportunities.

To manage or upgrade existing WWTPs or plan new ones, an important design factor is the reliability in meeting permit requirements. Reliability of a treatment plant may be defined as the probability of adequate performance for a specified period under specified conditions, i.e., the percent of the time that effluent concentrations meet specified permit requirements [1].

The need to continuously provide an effective and efficient service while infrastructures are ageing calls for increasingly sustainable infrastructure asset management (IAM) on strategic, tactical, and operational levels of planning [2]. Different approaches are used worldwide for business managers and accounts, water engineers, asset maintenance managers, and many elected officials, but the key role of performance metrics for IAM is consensual [3], as established in ISO 55000/55001/55002 standards on asset management [4–6]. Namely, the metrics are essential for diagnosing the performance in the status-quo scenario and for predicting it, considering different future scenarios, based on which measures/alternatives can be prioritized and results can be monitored [7,8].

Assessing the compliance with the discharge requirements is a rather complex process for WWTPs in EU Member States, since it requires the integration of a large volume of data and several criteria according to EU Directives 91/271/EEC [9] and 2000/60/EC [10]. To assist this process, we have developed a tool for a comprehensive assessment of treated wastewater quality that integrates performance indicators (PIs) and performance indices [11]. The indices tackle the plant reliability, i.e., they allow to easily compare the performance of different parameters over time and identify when the performance satisfied or failed the pre-established objectives and the distance remaining to achieve the targets set [11]. However, this assessment of reliability is not quantitative, and this feature limits its use as an IAM metric.

Herein, the novelty of the current work is to use a simple and consolidated reliability-based method to trigger decision making on operational improvements and asset management for maintaining or improving treatment effectiveness and efficiency. Such method allows to (i) diagnose the WWTP reliability, (ii) estimate it for different scenarios of discharge requirements, (iii) estimate the design/operating mean value of each parameter to meet the requirement with a given reliability, and (iv) derive the stability cut-off points to achieve the reliability needed for the compliance.

The use of probabilistic methods in setting discharge standards is a realistic and practical approach from an operational point of view [12]. When the plant effluent concentrations fit a lognormal distribution, the coefficient of reliability (COR) proposed by USEPA [13] is a simple and widely used method for reliability analysis [12,14]. To compare different WWTPs, a stability measure is needed, and the standard deviation is being used as the most appropriate stability indicator, as proposed by Niku et al. [13]. Other concentration distributions, e.g., Weibull or Gamma, require other probability models [15–19] or fault tree analysis. For example, fault tree analysis and Monte Carlo simulation has been used for mechanical reliability, to analyze risk of drinking water and, ultimately, for assessment of the violation of effluent biological oxygen demand (BOD_5) from the standard limit for landscape irrigation to identify the causal failure [20].

The reliability approach based on Niku's COR parameter [13] and on Silva et al.'s discharge compliance PI [11] is herein tested for 16 Portuguese WWTPs with activated sludge (AS) systems, the most widely used treatment around the world [21], with extended or conventional aeration regimes and different capacities.

Despite the high potential of this simple and consolidated method, to our knowledge, it has not been fully explored for supporting IAM.

2. Methods

2.1. WWTPs Analysed

Five-year (2015–2019) data of 16 Portuguese activated sludge WWTPs were used. As presented in Table 1, the WWTPs analyzed cover different capacities (763–54,000 m^3/d) and treated volumes (446–38,974 m^3/d 5-year medians), and two treatment sequences: (i) activated sludge after primary sedimentation, designed for conventional aeration (CAS) (not necessarily operated as so, if the plant is underutilized) and (ii) activated sludge without primary sedimentation, designed for extended aeration (EA). Namely, 7 CAS-WWTPs (with 5-year median inflows in the range of 4460–33,140 m^3/d) and 9 EA-WWTPs (446–38,974 m^3/d) were analyzed towards effluent BOD_5, chemical oxygen demand (COD), and total suspended solids (TSS) compliance with the European discharge consents for urban wastewater treatment, namely, 25 mg/L BOD_5, 125 mg/L COD, and 35 mg/L TSS (EU Directive 91/271/EEC).

Table 1. Treatment type, designs capacity, and operating conditions of the 16 WWTPs analyzed. Values shown are 5-year medians (P50) and P25–P75 are between brackets.

WWTP	AS	Design Capacity (10^3 m^3/d)	Treated Wastewater (10^3 m^3/d)	Influent BOD_5 (mg/L)	Influent COD (mg/L)	HRT in Reactor (h)	MLSS (mg/L)	SRT (d)	F/M (d^{-1})
A	CAS	9.5	4.5 (3.8–5.5)	420 (320–540)	729 (509–980)	23 (18–27)	3412 (2590–4140)	38 (15–51)	0.09 (0.07–0.13)
B	CAS	4.4	5.9 (4.8–7.5)	268 (187–377)	528 (325–711)	6.9 (5.5–8.5)	2,840 (2250–3690)	5.7 (3.7–8.3)	0.25 (0.16–0.42)
C	CAS	42.9	11.6 (9.9–13.6)	500 (390–640)	900 (714–1100)	21 (18–25)	3428 (2873–4086)	21 (16–32)	0.13 (0.09–0.16)
D	CAS	27.9	12.8 (11.9–14.0)	490 (370–590)	983 (840–1113)	14 (13–26)	4770 (3870–5683)	21 (13–35)	0.13 (0.11–0.17)
E	CAS	26.0	17.5 (16.3–18.9)	331 (250–412)	560 (415–707)	5.8 (5.4–6.3)	1100 (800–1500)	1.8 (1.1–2.6)	0.81 (0.56–2.6)
F	CAS	18.4	22.0 (17.3–26.9)	225 (164–303)	501 (365–692)	7.2 (5.9–9.2)	3000 (2610–3507)	4.7 (3.9–5.9)	0.23 (0.17–0.32)
G	CAS	54.0	33.1 (30.8–35.4)	340 (250–560)	642 (491–893)	11.4 (10.6–12.3)	3580 (2915–4815)	8.9 (6.8–11.5)	-
H	EA	1.2	0.45 (0.39–0.54)	258 (176–346)	520 (320–700)	39 (32–45)	2240 (1750–2713)	56 (50–74)	0.13 (0.08–0.18)
I	EA	0.76	0.78 (0.61–1.2)	208 (107–358)	459 (293–760)	32 (22–43)	3625 (2600–5100)	17 (12–27)	0.05 (0.03–0.09)
J	EA	11.4	8.6 (6.9–10.8)	165 (110–240)	311 (234–483)	32 (26–40)	2613 (2048–3398)	17 (11–25)	0.07 (0.05–0.09)
K	EA	15.1	10.6 (8.6–12.7)	320 (277–355)	924 (758–1059)	32 (26–39)	4218 (3910–4586)	17 (17–20)	0.07 (0.06–0.09)
L	EA	28.1	16.0 (12.5–20.7)	283 (232–326)	813 (669–956)	28 (20–37)	3375 (3100–3640)	14 (9–17)	0.10 (0.07–0.13)
M	EA	35.9	19.9 (16.6–23.3)	550 (371–630)	938 (730–1064)	19 (16–22)	3710 (3433–4085)	14 (11–17)	-
N	EA	25.6	21.3 (16.5–25.4)	320 (277–355)	924 (758–1059)	31 (26–40)	4890 (4505–5200)	21 (19–24)	0.07 (0.06–0.08)
O	EA	24.9	22.2 (14.9–27.4)	246 (189–296)	772 (575–925)	27 (22–39)	4280 (3879–4650)	19 (16–23)	0.06 (0.05–0.08)
P	EA	44.3	39.0 (32.0–45.5)	335 (243–398)	871 (587–1134)	30 (25–37)	5270 (4595–5920)	24 (21–28)	0.06 (0.04–0.08)

CAS: activated sludge system downstream from primary sedimentation, EA: activated sludge without primary sedimentation.

The influent wastewater median concentrations varied from 165 mg/L to 550 mg/L BOD_5 and from 311 mg/L to 983 mg/L COD depending on the industrial contribution. The percentile 25–75 range (P25–P75) of the BOD_5 mass load to the reactor was 0.19–0.48 kg BOD_5/m^3·d. Figure 1 presents the boxplot results of capacity utilization (treated volume/design capacity ratio), hydraulic retention time (HRT), mixed-liquor suspended solids (MLSS), Food/Microorganisms ratio (F/M), and solids retention time (SRT) for the two AS-WWTP types. As expected, the analyzed EA-WWTPs presented higher HRT than the CAS-WWTPs (P25-P75 of 28-32 h vs. 7–21 h), higher MLSS (median 3710 mg/L vs. 3412 mg/L), higher SRT (16–23 d P25-P75 and 17 d median vs. 5–21 d P25-P75 and 9 d median), and lower F/M (0.06–0.09 d^{-1} P25-P75 and 0.07 d^{-1} median for EA-WWTPs vs. 0.12–0.39 d^{-1} P25–P75 and 0.18 d^{-1} median for CAS-WWTPs). Some CAS-WWTPs are underutilized (Figure 1), and therefore the operating conditions are closer to those typical of EA.

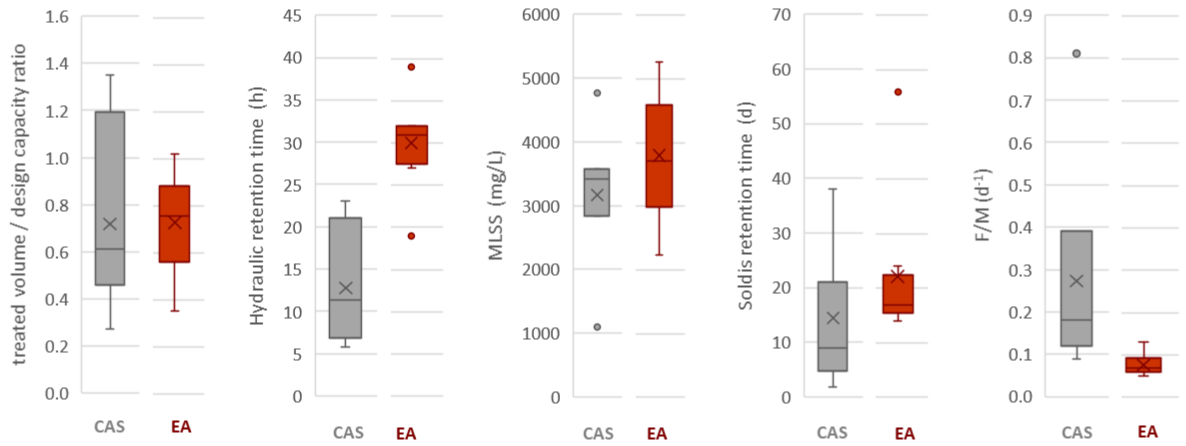

Figure 1. Boxplots of the operating conditions for the two clusters of AS-WWTPs (5-year data, 9 CAS-WWTPs and 7 EA-WWTPs).

The Kolomogorov–Smirnov (K–S) test was used to verify if the concentration results of the 16 WWTPs analyzed in each year of the 5-year period fit a lognormal distribution at significant levels of 1 percent. Overall, more than 73% of the data fit a lognormal distribution (test results in Supplementary Materials, Tables S1–S3). Therefore, the Niku's COR method based on the lognormality of the data could be used to estimate the reliability of these plants. Deviations from the lognormal distribution were mostly found for plant data series with many results below the limit of quantification (LOQ), i.e., with a plateau at LOQ.

2.2. Reliability Determination

The COR parameter developed by Niku et al. [13] was used to estimate the WWTP reliability for each parameter with minimum requirements set for discharge or reuse. In this method, the mean value (m_x) is related to the standard (X_s) that must be achieved on a probability basis (Equation (1)):

$$m_x = \mathrm{COR}\ X_s \quad (1)$$

The coefficient of reliability is determined by Equation (2):

$$\mathrm{COR} = [(V_x^2 + 1)^{1/2}] \exp\{-Z_{1-\alpha}[\ln(V_x^2 + 1)]^{½}\} \quad (2)$$

where V_x is the coefficient of variation (standard deviation divided by mean), α is the probability of failure of meeting the standards, $1-\alpha$ is the reliability level, and $Z_{1-\alpha}$ is the number of standard deviations away from the mean of a normal distribution.

$Z_{1-\alpha}$ was computed by Equation (3):

$$Z_{1-\alpha} = -\frac{\ln[m_x/X_s\,(V_x^2+1)^{-½}]}{[\ln\ (V_x^2+1)]^{½}} \quad (3)$$

and reliability $1-\alpha$ is determined using the function NORM.S.DIST($Z_{1-\alpha}$,TRUE) in excel.

2.3. Compliance Indicator

In line with the EU legislation for urban wastewater discharge, the PI "wtWQ03.2a, Compliance of discharged wastewater quality with Directive 91/271/EEC [%]" presented by Silva et al. in [11] involves the assessment of treated wastewater compliance with each parameter ($J_i = 1$, compliance; $J_i = 0$, no compliance), Equation (4):

$$\mathrm{wtWQ03.2a} = \frac{\sum_{i=1}^{m} J_i}{m} \times 100 \quad (4)$$

The determination of J_i integrates the several criteria defined in the directive, namely, for each parameter (BOD_5, COD, TSS), the parametric values (X_s), the deviations allowed from the X_s, the minimum annual number of samples, and the maximum number of samples which are allowed to fail the X_s. A flowchart for a straightforward assessment of compliance is presented in Silva et al. [11].

3. Results and Discussion

3.1. Reliability vs. Compliance

Reliability and compliance were computed for BOD_5, COD, and TSS, annually (2015 to 2019), for the 16 WWTPs analyzed whose yearly data fit the lognormal distribution. The results obtained are presented in Table 2, which also includes the number of samples and the mean values of the effluent concentration that were used to compute the COR values using Equations (1) and (2).

The reliability results were plotted against compliance, as shown in Figure 2, to establish the minimum reliability needed to comply with the EU directive discharge requirements, i.e., for ensuring X_s (Equation (1)) of 25 mg/L BOD_5, 125 mg/L COD, and 35 mg/L TSS.

The aggregated results of all WWTPs analyzed during the 5-year period show the minimum reliability was 0.90 for BOD_5 and COD and was 0.84 for TSS. These values are coherent with the maximum number of tests that are allowed to fail the X_s in relation with the minimum number of tests carried out. For example, when 12 tests are carried out, 2 tests are allowed to fail the X_s, which corresponds to 0.83 compliance; for 52 tests carried out, 0.90 compliance is required. However, a reliability value equal or above these cut-offs could result in a noncompliance if the maximum deviation is exceeded, as shown in Figure 2. The recommendation of Andraka and Dzienis for wastewater treatment plants under 50,000 equivalent population (1 EP = 60 g BOD_5/d, EU Directive) is a minimum reliability of at least 0.94 for all parameters [16].

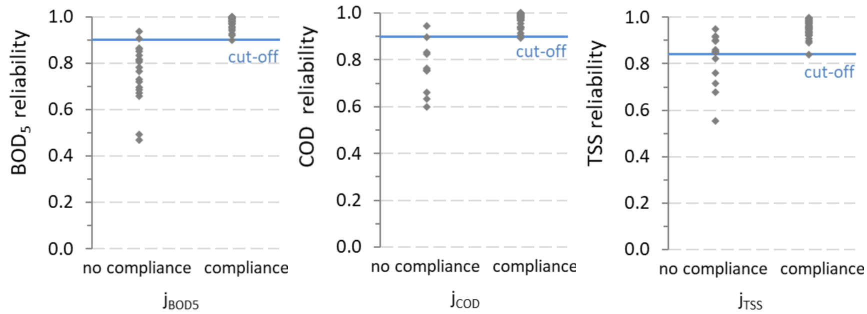

Figure 2. Plant reliability vs. compliance with the EU discharge requirements for urban WWTPs towards BOD_5, COD, and TSS (5-year data, 16 activated sludge WWTPs).

Table 2. WWTP reliability and compliance (J_i) for BOD_5, COD, and TSS ("-"data do not fit a lognormal distribution).

WWTP	Year	Treated Volume (m³/d)	BOD_5				COD				TSS			
			no. Samples	m_x (mg/L)	J_i	COR	no. Samples	m_x (mg/L)	J_i	COR	no. Samples	m_x (mg/L)	J_i	COR
A	2015	4606	52	18.70	0	0.85	52	69.90	1	0.98	52	18.00	1	0.96
A	2016	5795	66	16.30	1	0.92	374	60.40	1	0.99	65	19.70	1	0.96
A	2017	4328	63	17.90	1	0.90	363	73.30	1	0.98	63	19.90	1	0.94
A	2018	5178	63	19.63	0	0.76	375	85.59	1	0.89	64	22.48	1	0.89
A	2019	4943	67	14.33	1	0.93	369	64.47	1	0.98	66	16.33	1	0.96
B	2015	6251	53	24.42	0	-	105	86.22	0	0.82	105	33.20	0	-
B	2016	5852	51	18.92	0	0.80	102	68.43	1	0.90	102	25.55	0	-
B	2017	5217	53	28.32	0	0.47	105	100.80	0	0.76	107	33.90	0	-

B	2018	6587	53	22.74	0	0.67	105	66.45	1	0.94	105	25.27	1	-
B	2019	6507	107	18.79	1	-	107	61.00	1	0.97	107	24.47	1	-
C	2015	11,164	103	12.91	1	0.95	103	61.65	1	1.00	103	17.96	1	0.98
C	2016	12,718	104	11.99	1	-	104	52.91	1	0.99	104	14.93	1	-
C	2017	12,098	100	21.99	0	0.70	101	84.32	0	0.90	100	20.56	1	0.92
D	2015	12,358	51	23.37	0	0.68	36	118.12	0	0.66	125	30.45	0	0.71
D	2016	12,935	52	18.56	0	0.78	26	101.42	0	0.75	52	16.00	1	0.95
D	2017	12,264	52	27.04	0	0.73	26	88.85	0	0.83	53	21.58	0	0.86
D	2018	13,739	88	39.92	0	0.49	26	124.27	0	0.63	113	45.48	0	0.55
D	2019	14,387	24	25.42	0	0.66	26	137.00	0	0.60	24	21.38	0	0.85
E	2015	16,597	83	15.50	0	0.86	83	50.60	1	0.99	83	27.30	0	0.76
E	2016	17,069	78	10.10	1	0.98	78	30.00	1	1.00	78	10.40	0	0.95
E	2017	17,077	83	21.90	0	0.72	84	44.80	1	0.98	83	20.70	0	0.85
E	2018	17,342	92	16.89	0	0.81	91	55.78	0	0.94	92	15.29	0	0.92
E	2019	20,775	92	14.26	0	0.86	92	54.68	1	0.99	91	11.71	1	0.97
F	2015	21,579	139	14.16	1	0.94	349	73.04	1	-	141	18.76	1	0.95
G	2015	32,060	70	12.69	1	0.99	70	53.60	1	1.00	70	20.33	0	0.92
G	2016	34,013	73	11.36	1	0.98	73	49.08	1	1.00	73	20.58	0	0.90
G	2017	33,073	68	10.96	1	0.98	68	52.38	1	1.00	68	17.32	1	0.93
G	2018	33,153	76	12.71	1	0.96	77	61.88	1	0.98	77	19.42	1	0.93
G	2019	32,810	65	11.95	1	0.97	76	52.40	1	1.00	76	21.30	1	0.94
H	2017	433	66	16.00	0	-	66	40.20	1	1.00	70	15.50	1	-
H	2018	558	40	10.67	0	0.94	43	35.26	1	0.99	43	8.58	1	0.99
H	2019	406	33	6.27	1	1.00	33	35.18	1	1.00	33	5.36	1	1.00
I	2016	1582	25	12.83	1	-	24	46.42	1	-	24	16.96	1	0.94
I	2017	733	24	30.92	0	-	24	99.00	0	0.76	24	35.71	0	0.68
I	2018	928	24	15.79	0	-	24	61.10	1	0.91	24	21.88	1	0.84
I	2019	947	12	18.33	0	0.82	12	67.30	1	0.97	12	22.73	1	0.92
J	2015	8296	97	15.66	0	-	98	72.03	1	0.93	98	22.59	0	0.85
J	2016	11,079	118	16.29	0	0.83	118	65.84	1	0.94	118	24.47	0	0.82
J	2017	8729	104	12.65	0	0.91	104	55.18	1	1.00	104	14.95	1	0.98
J	2018	9341	105	15.70	0	-	105	62.90	1	0.94	105	18.39	1	0.90
J	2019	8968	98	8.09	1	1.00	98	52.99	1	0.99	98	13.28	1	0.98
K	2015	9710	60	6.62	1	-	241	57.31	1	1.00	241	9.07	1	-
K	2016	10,791	35	10.72	1	1.00	244	59.95	1	1.00	244	15.34	1	0.98
K	2017	9866	34	9.53	1	1.00	241	70.66	1	1.00	241	18.72	1	0.95
K	2018	11,218	35	10.89	1	0.99	236	66.66	1	0.98	236	19.36	1	0.94
K	2019	11,053	33	10.79	1	1.00	232	68.76	1	0.97	224	18.74	1	0.93
L	2015	15,244	60	7.28	1	1.00	241	80.68	1	-	241	6.79	1	-
L	2018	16,824	36	7.42	1	1.00	237	81.82	1	-	237	6.92	1	-
L	2019	17,826	36	7.36	1	1.00	243	79.89	1	0.98	243	6.42	1	-
M	2015	16,201	66	5.89	1	-	66	33.27	1	1.00	66	7.34	1	1.00
M	2016	23,799	69	7.95	1	1.00	69	38.12	1	1.00	69	12.01	1	0.99
M	2017	18,212	56	7.86	1	1.00	72	37.29	1	1.00	72	11.26	1	1.00
M	2018	23,462	66	9.68	1	0.98	68	51.01	1	0.99	68	19.17	0	0.90
M	2019	24,952	54	10.50	1	0.97	60	50.40	1	0.99	60	17.75	1	0.96
N	2015	20,813	60	6.58	1	-	241	59.68	1	1.00	241	9.42	1	-
N	2016	24,526	35	11.51	1	0.98	244	70.78	1	0.98	244	15.60	1	0.96
N	2017	19,378	34	9.12	1	1.00	243	69.28	1	1.00	243	14.23	1	0.97
N	2018	20,888	35	12.31	1	0.97	216	74.82	1	0.97	210	18.80	1	0.92
N	2019	20,943	34	13.50	1	0.95	210	76.66	1	0.95	210	20.74	1	0.91
O	2016	20,845	34	8.00	1	1.00	244	57.92	1	1.00	244	8.11	1	-
O	2017	17,631	34	7.29	1	1.00	241	66.84	1	-	241	9.37	1	-
O	2018	23,053	36	8.86	1	0.99	236	66.58	1	-	236	7.98	1	-
O	2019	24,009	35	7.74	1	1.00	241	58.87	1	-	241	6.56	1	-
P	2015	35,792	59	11.49	1	1.00	243	65.47	1	0.98	243	12.68	1	0.98

P	2016	39,503	34	10.88	1	0.99	243	55.60	1	0.98	243	13.15	1	0.98
P	2017	35,656	34	9.38	1	1.00	241	59.24	1	1.00	241	12.63	1	0.99
P	2018	39,075	35	9.80	1	0.99	237	51.10	1	-	237	9.77	1	-
P	2019	40,380	35	8.86	1	1.00	241	52.76	1	1.00	241	8.95	1	-

3.2. Reliability and Compliance vs. Stability

Stability is a measure of variation from the mean, and the standard deviation was herein used as the stability indicator [13]. Figure 3 displays the results of the 16 WWTPs analyzed during 2015–2019 with lognormal data distribution. The results show that higher standard deviations are associated with lower reliability, as expected, and aid in identifying the stability cut-off points to achieve the compliance.

For the pools of WWTPs studied, the maximum standard deviations of each parameter to achieve compliance are 6.4 mg/L for BOD_5, 32 mg/L for COD, and 10.3 mg/L for TSS (Figure 3). These cut-off values must be read in Figure 3 (right) for no "compliance data" (above them, compliance may or may not be achieved).

These results are also consistent with Niku et al.'s conclusions [13], which found that plants with standard deviations greater than 10 mg/L for both BOD_5 and TSS may be considered unstable.

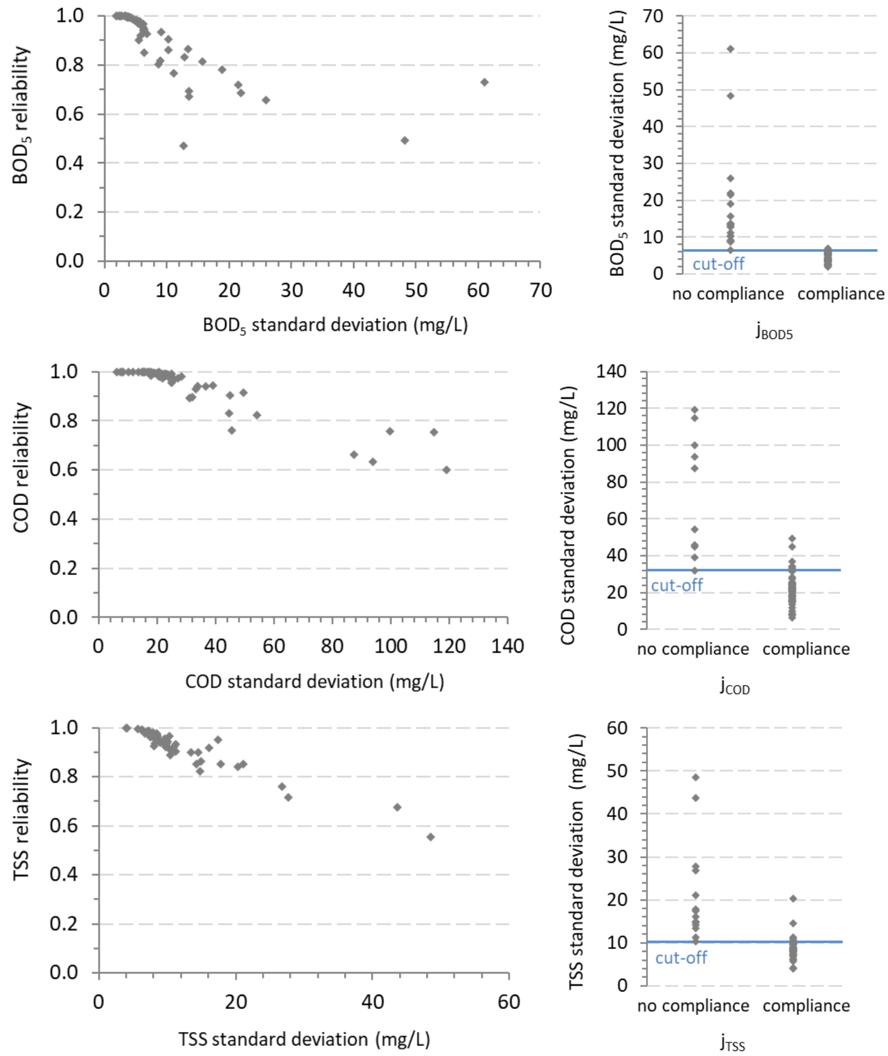

Figure 3. Plant reliability vs. standard deviation and standard deviation vs. compliance with EU discharge requirements for urban WWTPs towards BOD_5, COD, and TSS (5-year data, 16 activated sludge WWTPs).

3.3. Reliability and Stability of the Two Treatment Sequences Analyzed

Niku et al. [13] found reliability and stability of activated sludge processes to depend on the type of treatment, with step-aeration modification of activated sludge being more reliable and stable for BOD_5 and conventional activated sludge being more reliable and stable for TSS.

Within our pool of 5-year results from 16 WWTPs, reliability and stability did not correlate with the AS operating conditions shown in Table 1. However, Welch F tests (used in the case of unequal variances) were conducted and showed a significant difference (p-values < 0.05) between the two AS clusters, CAS-WWTPs and EA-WWTPs, for both reliability and stability of BOD_5 and COD effluent concentrations (results in Supplementary Materials, Table S4).

For the three parameters analyzed (BOD_5, COD, and TSS), Figure 4 shows the EA-WWTPs (each number in the x-axis corresponds to a given WWTP each year) presented higher reliability (0.98, 0.97, and 0.94 mean values for BOD_5, COD, and TSS in EA vs. 0.82, 0.91, and 0.89 for CAS) and higher stability (mean standard deviations of 4.7, 23.5, and 10.6 mg/L for BOD_5, COD, and TSS in EA vs. 14.0, 37.8, and 14.3 mg/L for CAS). Niku et al. also present higher stability for extended aeration (5.3 mg/L for BOD_5 and TSS) than for conventional activated sludge systems (9.5 mg/L for BOD_5 and 16 mg/L for TSS) [13].

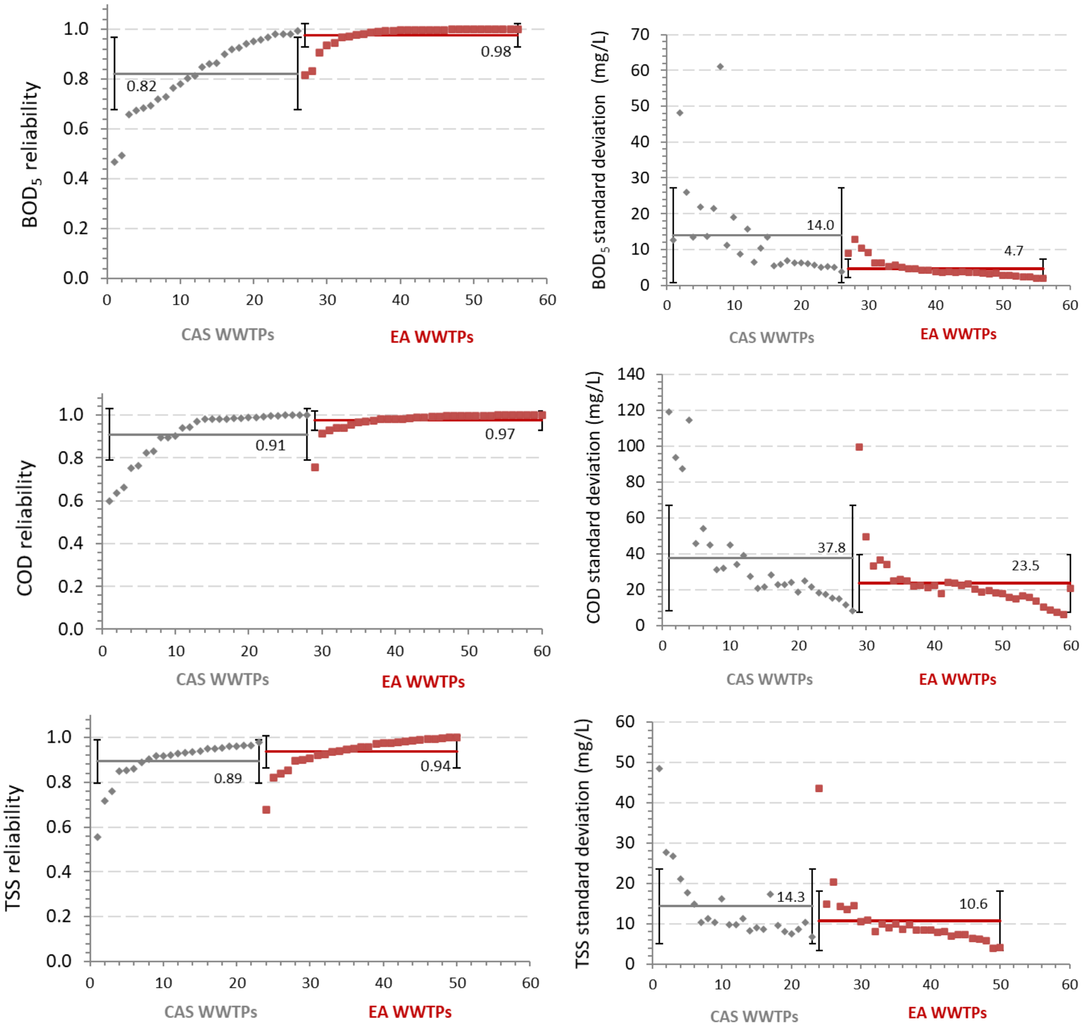

Figure 4. Plant annual reliability and standard deviation of BOD_5, COD, and TSS effluent concentrations (each number in the x-axis corresponds to a given WWTP each year; 5-year data, 7 CAS-WWTPs and 9 EA-WWTPs).

3.4. Reliability and Stability vs. Treatment Capacities

Wastewater flowrate affects most operating conditions determining the treatment effectiveness (e.g., detention times, loads) and efficiency (e.g., unit energy consumption [22]). Therefore, the effect of the treated wastewater volume on treatment reliability and stability was analyzed.

Figure 5 shows no linear correlation between treatment reliability and treated volume, but WWTPs treating more than 15,000 m^3/d (EA-WWTPs) and particularly more than 20,000 m^3/d (EA-WWTPs and CAS-WWTPs) were more reliable (>0.90) and stable. These results agree with literature; Niku et al. [13] found no relationship between plant size and stability. However, Bunce et al. [14] reported that the smallest WWTPs appeared to be less stable than the slightly larger WWTPs across all technology types.

These results are important for strategic asset management concerning the designing and rehabilitation of the wastewater treatment system in terms of number of plants, their capacity, and treatment sequence. For example, after this study, the water utility of the underutilized CAS-WWTP C decided to decommission the primary sedimentation and to properly operate the plant as an EA-WWTP.

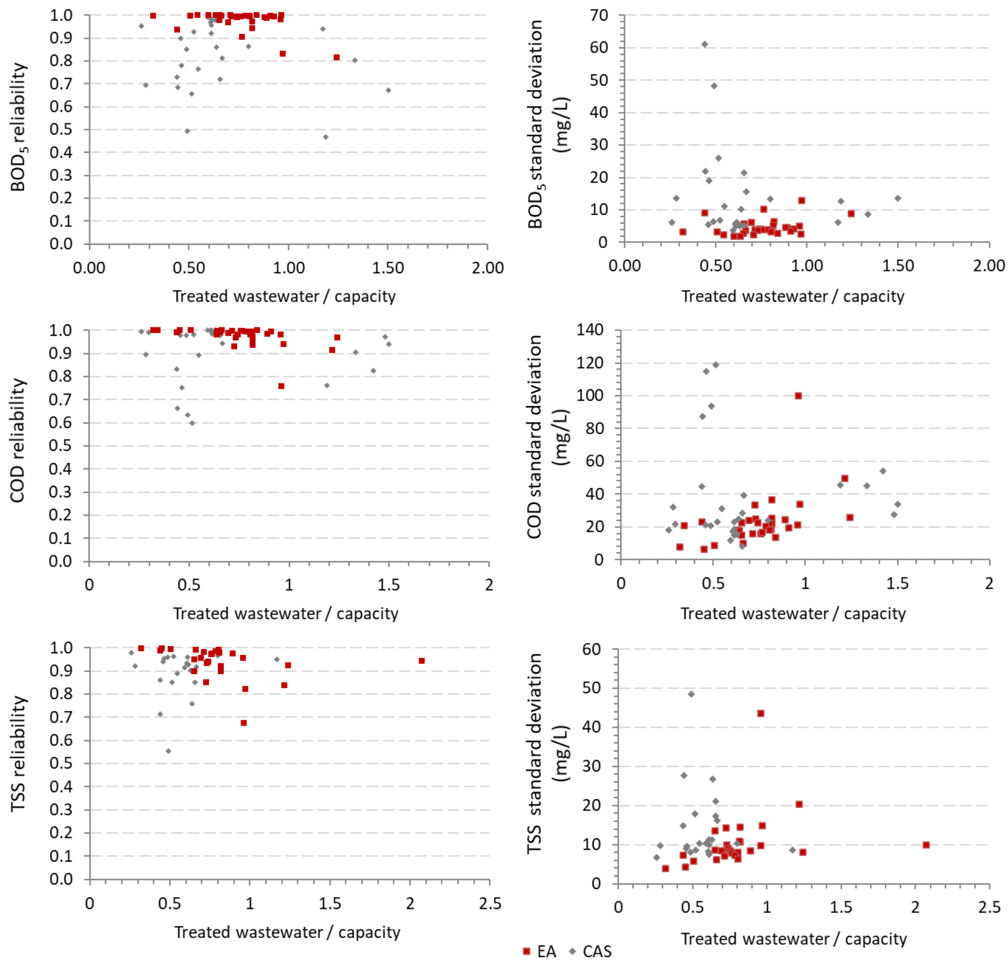

Figure 5. Plant annual reliability and standard deviation of BOD_5, COD, and TSS effluent concentrations vs. treated wastewater (5-year data, 9 EA-WWTPs and 7 CAS-WWTPs).

3.5. Estimating the Target Effluent Mean Values for a Given Reliability

After characterizing the plant reliability, namely its coefficient of variation (V_x in Equation (2)), one can estimate the target mean value (m_x, in Equation (1)) that should have been met in each year for achieving the desired objective (X_s) of each parameter with a given reliability. The higher the latter, the lower (more stringent) the target mean value is. The target mean values for BOD_5, COD, and TSS were estimated for reliability values of 0.85, 0.9, 0.95, and 0.99. The results aggregated per AS type are show in Figure 6, and those of each WWTP are presented in Table 3 for 0.85 and 0.95 reliability.

Assuming similar performance and influent scenarios are likely to occur, this back casting supports establishing the target mean values for the daily WWTP operation. For example, for WWTP B with a coefficient of variation (V_x) of 0.3–0.5 of the BOD_5 (5-year range), changing the reliability from 0.85 to 0.95 implies a reduction of target mean values from 17.5–19.0 mg/L to 13.4–15.7 mg/L BOD_5. Furthermore, this back casting step allows assessment of the impact of a reliability change in the discharge requirements and the feasibility of its compliance, which triggers the rehabilitation measures.

The aggregated results of the EA-WWTPs (Figure 6) and of the CAS-WWTPs (Figure 7) can be used as reference ranges for WWTPs within each cluster diversity (influent characteristics, capacities, and operating conditions) for plant design or performance benchmarking. For example, for 0.95 reliability, the medians of target mean values for the nine EA-WWTPs studied were 13.8 mg/L BOD_5, 77.3 mg/L COD, and 16.7 mg/L TSS; for the seven CAS-WWTPs studied, they were 12.8 mg/L BOD_5, 69.6 mg/L COD, and 17.2 mg/L TSS. The higher the AS-specific coefficient of variation (higher for CAS than for EA), the lower the design values must be. Niku et al. proposed, as recommended design values of CAS-WWTPs, 14.5 mg/L for effluent BOD_5 and 11.6 mg/L for effluent TSS [13].

The target mean values (m_x) for 0.85 reliability (close to the reliability cut-off for compliance with the EU minimum requirements for urban WWTP discharge when 12 tests are carried out) are significantly lower than the EU minimum requirements (P25 of m_x of all WWTPs varied from 60% to 70% of X_s, depending on the parameter). This behavior was observed to a larger extent for the CAS-WWTPs than for the EA-WWTPs (P25 values in Figures 5 and 6, namely 15.1 mg/L BOD_5, 81.2 mg/L COD, and 21.2 mg/L TSS for CAS-WWTPs vs. 17.3 mg/L BOD_5, 87.5 mg/L COD, and 22.7 mg/L TSS for EA-WWTPs).

These are important data to consider in the IAM plans (strategic, tactic, and operation) for treatment type and capacity selection, resources allocation, and operating conditions set up.

Taheriyoun and Moradinejad [20] identified the human factor as a priority to improve the reliability of the plant, along with complementary actions such as the automation level increase. The same lesson was learned within the iEQTA project, although no quantitative assessment of reliability vs. human resources (number and skills) was conducted.

Table 3. BOD_5, COD, and TSS target mean values for each WWTP in each year, for 0.85 and 0.95 reliability.

WWTP	Year	BOD_5			COD			TSS		
		V_x	m_x (mg/L)		V_x	m_x (mg/L)		V_x	m_x (mg/L)	
			COR = 0.85	COR = 0.95		COR = 0.85	COR = 0.95		COR = 0.85	COR = 0.95
A	2015	0.34	18.7	15.3	0.29	96.9	81.6	0.45	24.6	18.9
A	2016	0.36	18.5	15.0	0.31	95.6	79.5	0.38	25.6	20.5
A	2017	0.31	19.1	15.9	0.29	96.9	81.6	0.45	24.6	18.9
A	2018	0.57	16.6	12.0	0.36	92.2	74.4	0.46	24.4	18.7
A	2019	0.48	17.3	13.1	0.35	92.9	75.4	0.52	23.7	17.6
B	2015	-	-	-	0.63	81.2	57.1	-	-	-
B	2016	0.46	17.5	13.4	0.66	80.4	55.8	-	-	-
B	2017	0.45	17.6	13.5	0.45	87.7	67.4	-	-	-
B	2018	0.60	16.4	11.7	0.51	85.2	63.5	-	-	-
B	2019	-	-	-	0.45	88.0	67.8	-	-	-
C	2015	0.48	17.3	13.1	0.29	96.7	81.2	0.38	25.6	20.5
C	2016	-	-	-	0.41	89.9	70.8	-	-	-
C	2017	0.62	16.3	11.5	0.38	91.4	73.2	0.47	24.3	18.5
D	2015	0.94	15.0	9.3	0.74	78.4	52.4	0.91	21.2	13.2
D	2016	1.02	14.9	8.9	1.13	73.7	42.4	0.6	23.0	16.4
D	2017	2.26	15.3	6.8	0.50	85.5	64.0	0.69	22.3	15.2
D	2018	1.21	14.7	8.2	0.75	78.1	51.9	1.07	20.7	12.2

D	2019	1.02	14.9	8.9	0.87	76.1	48.2	0.83	21.5	13.8
E	2015	0.66	16.1	11.1	0.49	86.1	64.9	0.98	20.9	12.7
E	2016	0.53	16.9	12.5	0.27	98.4	83.7	1.67	20.6	10.2
E	2017	0.98	15.0	9.1	0.63	81.1	57.1	1.02	20.8	12.5
E	2018	0.93	15.1	9.3	0.70	79.2	53.9	1.05	20.8	12.3
E	2019	0.94	15.0	9.2	0.44	88.3	68.3	0.88	21.3	13.4
F	2015	0.44	17.7	13.7	-	-	-	0.46	24.5	18.7
G	2015	0.30	19.3	16.1	0.22	102.2	89.6	0.5	23.9	17.9
G	2016	0.45	17.6	13.5	0.31	95.5	79.3	0.55	23.5	17.2
G	2017	0.46	17.4	13.3	0.29	97.1	81.8	0.65	22.6	15.8
G	2018	0.48	17.3	13.2	0.37	92.0	74.0	0.51	23.9	17.9
G	2019	0.47	17.4	13.2	0.33	94.3	77.5	0.39	25.5	20.3
H	2017	-	-	-	0.51	85.2	63.6	-	-	-
H	2018	0.85	15.3	9.7	0.66	80.4	55.9	0.85	21.4	13.6
H	2019	0.52	17.0	12.6	0.21	102.7	90.4	0.74	22.0	14.7
I	2016	-	-	-	-	-	-	0.59	23.1	16.5
I	2017	-	-	-	1.01	74.5	44.8	1.22	20.5	11.5
I	2018	-	-	-	0.81	77.0	50.0	0.93	21.1	13.1
I	2019	0.49	17.2	13.0	0.38	91.2	72.8	0.35	26.0	21.1
J	2015	-	-	-	0.46	87.2	66.7	0.63	22.7	16.0
J	2016	0.79	15.5	10.1	0.52	85.0	63.2	0.61	22.9	16.3
J	2017	0.81	15.4	10.0	0.30	96.1	80.2	0.53	23.7	17.5
J	2018	-	-	-	0.58	82.6	59.5	0.79	21.7	14.2
J	2019	0.47	17.4	13.2	0.38	91.3	73.0	0.55	23.5	17.2
K	2015	-	-	-	0.31	95.5	79.4	-	-	-
K	2016	0.36	18.5	15.0	0.26	98.9	84.5	0.46	24.5	18.8
K	2017	0.30	19.3	16.1	0.21	103.0	90.7	0.46	24.5	18.7
K	2018	0.38	18.2	14.6	0.34	93.8	76.7	0.47	24.4	18.6
K	2019	0.34	18.7	15.3	0.36	92.5	74.7	0.53	23.7	17.5
L	2015	0.33	18.9	15.6	-	-	-	-	-	-
L	2018	0.26	19.9	17.0	-	-	-	-	-	-
L	2019	0.26	19.8	16.9	0.23	101.7	88.8	-	-	-
M	2015				0.19	104.8	93.6	0.57	23.2	16.8
M	2016	0.46	17.5	13.4	0.27	98.6	84.1	0.52	23.8	17.7
M	2017	0.42	17.8	13.9	0.23	101.5	88.5	0.51	23.9	17.8
M	2018	0.59	16.5	11.8	0.44	88.2	68.1	0.7	22.2	15.1
M	2019	0.59	16.5	11.8	0.47	86.8	66.0	0.48	24.3	18.4
N	2015	-	-	-	0.31	95.5	79.4	-	-	-
N	2016	0.44	17.7	13.7	0.30	96.3	80.5	0.62	22.8	16.1
N	2017	0.43	17.8	13.9	0.23	101.5	88.4	0.59	23.0	16.5
N	2018	0.43	17.7	13.8	0.29	96.7	81.1	0.58	23.1	16.7
N	2019	0.47	17.4	13.2	0.33	94.5	77.8	0.51	23.8	17.8
O	2016	0.34	18.7	15.3	0.23	101.0	87.7	-	-	-
O	2017	0.32	19.0	15.6	-	-	-	-	-	-
O	2018	0.47	17.3	13.2	-	-	-	-	-	-
O	2019	0.32	18.9	15.6	-	-	-	-	-	-
P	2015	0.32	19.0	15.7	0.34	93.7	76.6	0.63	22.7	16.0
P	2016	0.43	17.8	13.8	0.44	88.5	68.7	0.64	22.6	15.9
P	2017	0.35	18.6	15.1	0.31	95.8	79.9	0.51	23.9	17.9
P	2018	0.46	17.4	13.3	-	-	-	-	-	-
P	2019	0.40	18.1	14.3	0.37	92.2	74.3	-	-	-

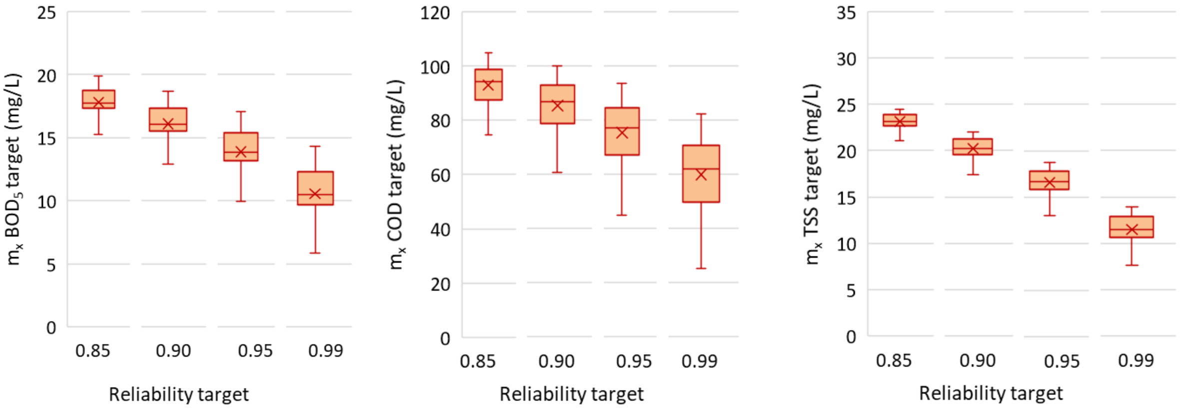

Figure 6. Target mean value (m_x) of BOD_5, COD, and TSS effluent concentrations for achieving different reliability targets in 9 EA-WWTPs (5-year data).

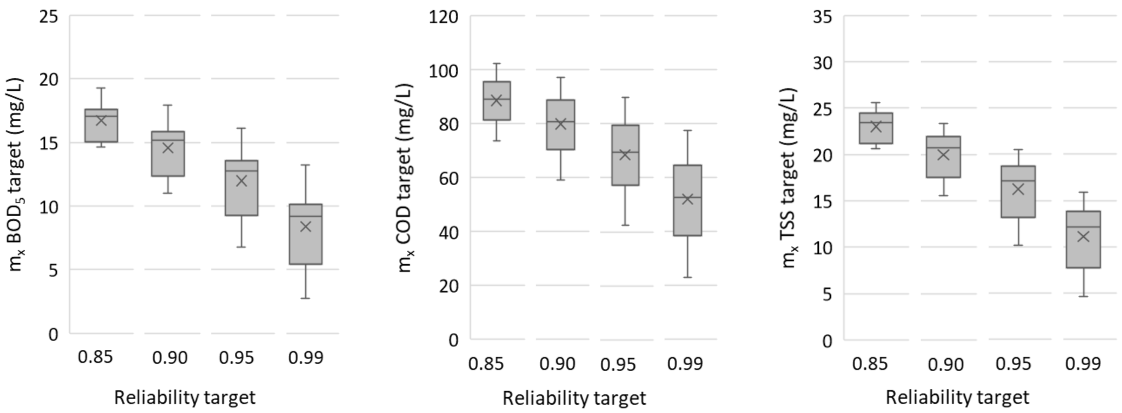

Figure 7. Target mean value (m_x) of BOD_5, COD, and TSS effluent concentrations for achieving different reliability targets in 7 CAS-WWTPs based on 5-year data.

4. Conclusions

The simple and consolidated Niku's reliability-based method was herein integrated with the assessment of the compliance of urban WWTPs with discharge requirements. This integrated analysis allows to estimate the WWTP reliability, stability, compliance and target effluent mean values for a given reliability, which is key information to trigger decision making on operational improvements and asset management (new investment, rehabilitation, or retrofitting).

The results obtained demonstrate that the nine EA-WWTPs were significantly more reliable and stable than the seven CAS-WWTPs analyzed. In addition, EA-WWTPs treating more than 15,000 m^3/d and EA and CAS-WWTPs treating more than 20,000 m^3/d are more reliable (>0.90) and stable.

The results support the tactical and operational levels of IAM (resources' allocation and operating conditions) by estimating, for different scenarios of discharge requirements, the WWTP reliability target, the corresponding effluent mean values, and the stability cut-off point (standard deviations). On a strategic level of IAM, the results can be used as reference ranges for WWTPs within each cluster diversity (influent characteristics, capacities, and operating conditions) for plant design or performance benchmarking.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w14071106/s1, Table S1: Kolomogorov-Smirnov (K-S) test of BOD_5 for each WWTP in each year; Table S2: Kolomogorov-Smirnov (K-S) test of COD for each WWTP in each year; Table S3: Kolomogorov-Smirnov (K-S) test of TSS for each WWTP in each year; Table S4: Welch F tests of the two AS clusters, CAS-WWTPs and EA-WWTPs, for reliability and stability.

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Abbreviations

WWTPs	Wastewater Treatment Plants
IAM	Infrastructure Asset Management
PIs	Performance Indicators
COR	Coefficient of Reliability
BOD_5	Biological Oxygen Demand
AS	Activated Sludge
CAS	Conventional Aeration
EA	Extended Aeration
COD	Chemical Oxygen Demand
TSS	Total Suspended Solids
HRT	Hydraulic Retention Time
MLSS	Mixed-Liquor Suspended Solids
F/M	Food/Microorganisms ratio
SRT	solids retention time
LOQ	limit of quantification

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