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Research Paper

Performance assessment of sewage treatment plants using compliance index

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ABSTRACT

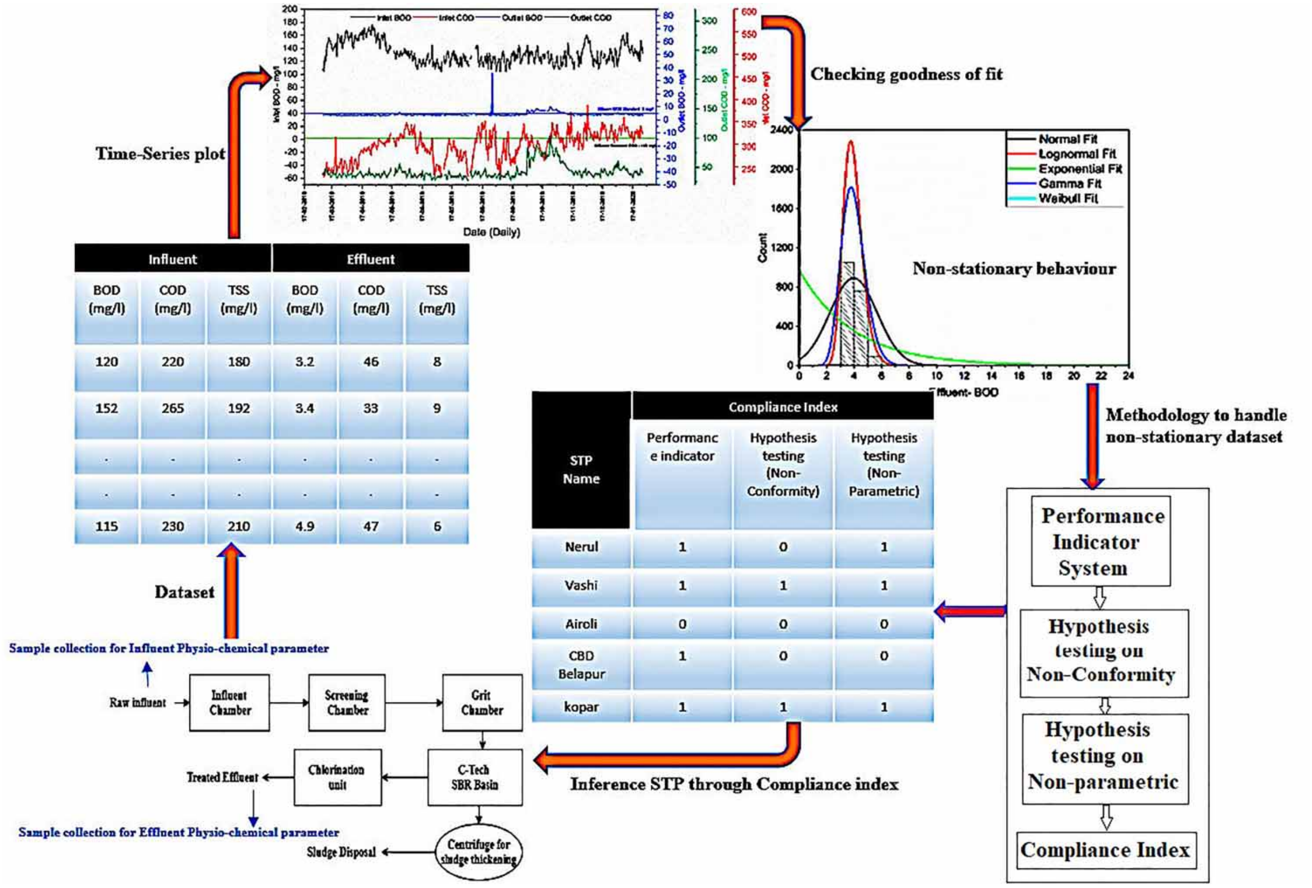
The aim of this study is to infer the performance assessment of sewage treatment plants (STPs) using the compliance index (CI). The methodology includes three steps, (1) estimation of performance indicators from the quality test, parameter test, and conformity test, (2) hypothesis testing of non-conformity, and (3) hypothesis testing using the non-parametric test. The CI integrates the results of the above nine tests through a scoring system based on individual performance. The study area, Navi Mumbai Municipal Corporation (NMMC), India, treats its domestic sewage through seven centralized STPs located in different zones. The influent and effluent parameters, such as flow rate, biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), pH, dissolved oxygen (DO), and temperature, were studied in this work. The removal efficiency (RE) analysis shows the efficiency of BOD, COD, and TSS varies between 96.67 and 97.30%, 84.55 and 89.70%, and 94.04 and 95.81%, respectively, and indicates that all STPs are performing well. The proposed CI infers that all STPs perform well and comply with NMMC standards, except one STP, namely Airoli. Interestingly, RE analysis shows that Airoli STP's BOD is the third-best compared to all other STPs. This study shows that the CI method can infer the performance of STPs better than RE and help the administrators to plan, execute, operate, and maintain STPs to achieve total sanitation in megacities.

Key words: compliance index, NMMC, non-parametric, removal efficiency, STPs, wastewater

HIGHLIGHTS

- Proposed compliance index (CI) computes the performance of sewage treatment plants (STPs).
- The CI is constructed using influent and effluent wastewater quality parameters.
- The methodology was tested with seven STPs in one of India's cleanest cities.
- The advantage of the CI is that it handles non-stationary datasets.
- Proposed CI reveals much better compliance of STPs than the conventional removal efficiency analysis.

GRAPHICAL ABSTRACT



ABBREVIATIONS AND NOTATIONS

ADB	Asian Development Bank
APHA	American Public Health Association
BOD	biochemical oxygen demand
CI	compliance index
COD	chemical oxygen demand
CPCB	Central Pollution Control Board
DO	dissolved oxygen
Ha	alternate hypothesis
Ho	null hypothesis
m_i	Conformity of standard by parameter
MoEF&CC	Ministry of Environment, Forest & Climate Change
MoHUA	Ministry of Housing and Urban Affairs
MPCB	Maharashtra state Pollution Control Board
n	Number of parameters studied
NGT	National Green Tribunal
NMMC	Navi Mumbai Municipal Corporation
n_p	Number of pollutant parameters studied at each STP
N_p	Number of pollutant parameters to be studied as per standards at each STP
n_q	Number of quality tests carried out per year at each STP
N_q	Number quality of tests required as per standards per year at each STP
P	Probability of failure
p	Acceptable proportion of failure
P_T	Parameter test

Q_T	Quality test
RE	Removal efficiency
s	Number of measured data points
SBR	Sequential batch reactor
SC_T	Standard conformity test
SD	Standard deviation
STP	Sewage treatment plant
TSS	Total suspended solids
X	Number of data points outside the effluent standard in numbers
Z	*Z*-test

1. INTRODUCTION

As per ADB (2019), urban areas contribute 55% of the world's population, which will rise to 60% by 2030. This tremendous increase in population around urban areas imparts enormous pressure on basic amenities (Kumar & Tortajada 2020). Access to safe drinking water and sustainable sanitation are the basic needs for the improvement of health and hygiene. The 2015 Millennium Development Goal envisions abolishing open defecation, and out of 17 goals of Sustainable Development Goals, it prioritizes 'clean water and sanitation' as prime importance with sustainable infrastructure (Roy & Pramanick 2019). The Indian government launched multiple schemes, such as the Swachh Bharat Mission, Atul Mission for Rejuvenation and Urban Transformation, Namami Gange, and many more, for the sustainable infrastructure of water supply networks, robust sewerage, and sewage treatment plants (STPs).

An STP eliminates dangerous pollutants, making the effluent disposable or valuable for reuse. An STP is a dynamic system where the entire treatment process should perform in line with the design to achieve better reliability. Each unit of STP is designed for incoming sewage and intended pollutant removal. The removal efficiency (RE) of each unit or entire plant is the percentage of the pollutant removed through the treatment process. It was reported that RE can infer the performance of an STP as a better estimate of the specific pollutant reduction (Khan *et al.* 2014). RE was further improved by integrating the efficiency of multiple pollutants (Jamwal *et al.* 2009). It is also reported that RE varies with time as the influent and effluent pollutant parameters are stochastic in nature. The effectiveness of an STP in achieving the desired effluent standard has been studied using different distribution functions, such as normal, log-normal, and Weibull (Padalkar & Kumar 2018).

Niku *et al.* (1979) provided a model to compute the compliance percentage of an effluent parameter in an STP, it requires the data to follow normal or log-normal distribution. Many works on performance assessment of STP has been reported with the datasets following normal or log-normal distribution (Oliveira & Von Sperling 2008; Redda 2008). When the dataset do not follow normality, non-parametric studies were carried out in other water quality research works, such as river rejuvenation and groundwater studies (Elçi & Polat 2011; Ofman *et al.* 2017). The present work proposes to infer the compliance of STP through the compliance index (CI), which integrates various tests that does not require the data to follow normality. It is aimed that CI can overcome the shortcoming of RE, the first of its kind assessment for large-scale STPs. The CI is designed by integrating a performance indicator system, a hypothesis testing system using non-conformity and non-parametric tests.

This paper presents the following works carried out for seven STPs in Navi Mumbai Municipal corporation (NMMC), Maharashtra, India.

1. To estimate the descriptive statistics and RE of various pollutant parameters.
2. To study the effectiveness of STPs using the performance indicators for wastewater discharge in receiving waters criterion.
3. To perform hypothesis testing concerning non-conformity and non-parametric testing on effluent pollutant parameters.
4. To integrate various tests to infer the performance of STPs using CI.

The rest of the paper discusses the study area, the methodology adopted, descriptive statistics, RE analysis, CI of STPs, and conclusions emanated from the study.

2. STUDY AREA

Urban centers of Maharashtra state in India produce $9,107 \times 10^3$ m^3/day of sewage, the highest in the country, which denotes the extent of urbanization (CPCB 2021). NMMC is a planned city adjacent to Mumbai, Maharashtra, India with eight nodes to decongest Mumbai. The Ministry of Housing and Urban Affairs (MoHUA), Government of India, ranked NMMC as India's third cleanest city, with a population of over one million (MoHUA 2020). MoHUA ranks the cities by conducting a city-level survey on various indicators with weightage for the cleanliness of sustainable cities, such as collection and transportation of waste, processing and disposal, education and communication, capacity building and innovation, and sustainable sanitation infrastructure. Thus, sustainable sanitation is crucial for a city's cleanliness in which better performing STPs are of prime importance.

The performance of STPs in India is inferred from their compliance with effluent standards for disposal provided by government bodies such as the National Green Tribunal (NGT), central and state pollution control boards. Recently, NGT standards are followed as reference standard across India for STPs effluent discharge norms. Table S1 in the Supplementary Material provides the standards set by NGT, Ministry of Environment, Forest & Climate Change (MoEF&CC), NMMC's influent design value of STPs, and effluent discharge standards of NMMC. NMMC follows effluent discharge standards even more stringent than the NGT and the Maharashtra state pollution control board (MPCB) standards. NMMC upgraded the old aerated lagoon STPs with the sequential batch reactor (SBR) method of treatment to meet this stringent effluent standard. Seven STPs were constructed in different sectors to treat its domestic sewage, having a combined capacity of 454×10^3 m^3/day; the location details of STPs are depicted in Figure S1 of Supplementary Material. It is worth mentioning that, NMMC, a well-planned city, has all its industrial area separately and is well equipped with the common effluent treatment plant. This study is only about the municipal domestic sewage, collected, treated, and disposed in the domestic area. The name, capacity, and data availability of each STPs are given in Table 1. All the seven STPs are equipped with the secondary treatment facility, and the flowchart of the treatment process is given in Figure S2 of Supplementary Material. The SBR technology uses fill, react, settle, decant, and idle processes having a hydraulic retention time of 3–4 h depending on the number of SBR tanks and sewage inflow. Grab samples are collected at the inlet and outlet of the STP, and all the quality tests were carried out by standard methods as per (APHA 2005). In the present study, data from operational records maintained at each STP were collected and utilized for analysis.

3. METHODOLOGY

The compliance of STP is studied using influent and effluent physio-chemical parameters, such as flow rate, biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), pH, dissolved oxygen (DO), and temperature with a retrospective dataset. The step-by-step methodology adopted in the study to derive CI of STPs is depicted in Figure 1.

As shown in Figure 1, the first step is estimation of descriptive statistics of all the effluent parameters to get insight into the data and distribution characteristics. Using the statistical analysis, the RE of each pollutant parameter (BOD, COD, and TSS) at each STP has been estimated. From the analysis, it is found that the data are not following normal distribution and hence CI method is proposed in this study.

In the second step, CI is formulated by integrating three tests such as performance indicator test, hypothesis testing concerning non-conformity of standards, and a non-parametric test through scoring. Each test involved in CI analysis is explained below.

Table 1 | Capacity of STPs in the NMMC area

S. No.	Location of STP	Design capacity ($\times 10^3$ m^3/day)	Treatment process	Data length used
1	Nerul	100	Primary treatment and secondary treatment by cyclic activated sludge process (SBR)	Jan 2014 to Dec 2018
2	Vashi	100		Jan 2019 to Dec 2020
3	Koparkhairane	87.5		Jan 2019 to Dec 2020
4	Sanpada	37.5		Jan 2018 to July 2020
5	Ghansoli	30		Jan 2017 to Dec 2019
6	CBD Belapur	19		Jan 2015 to Dec 2019
7	Airoli	80		Jan 2019 to Dec 2019
Total		454		

CBD, Central Business District; NMMC, Navi Mumbai Municipal Corporation; STP, Sewage Treatment Plant.

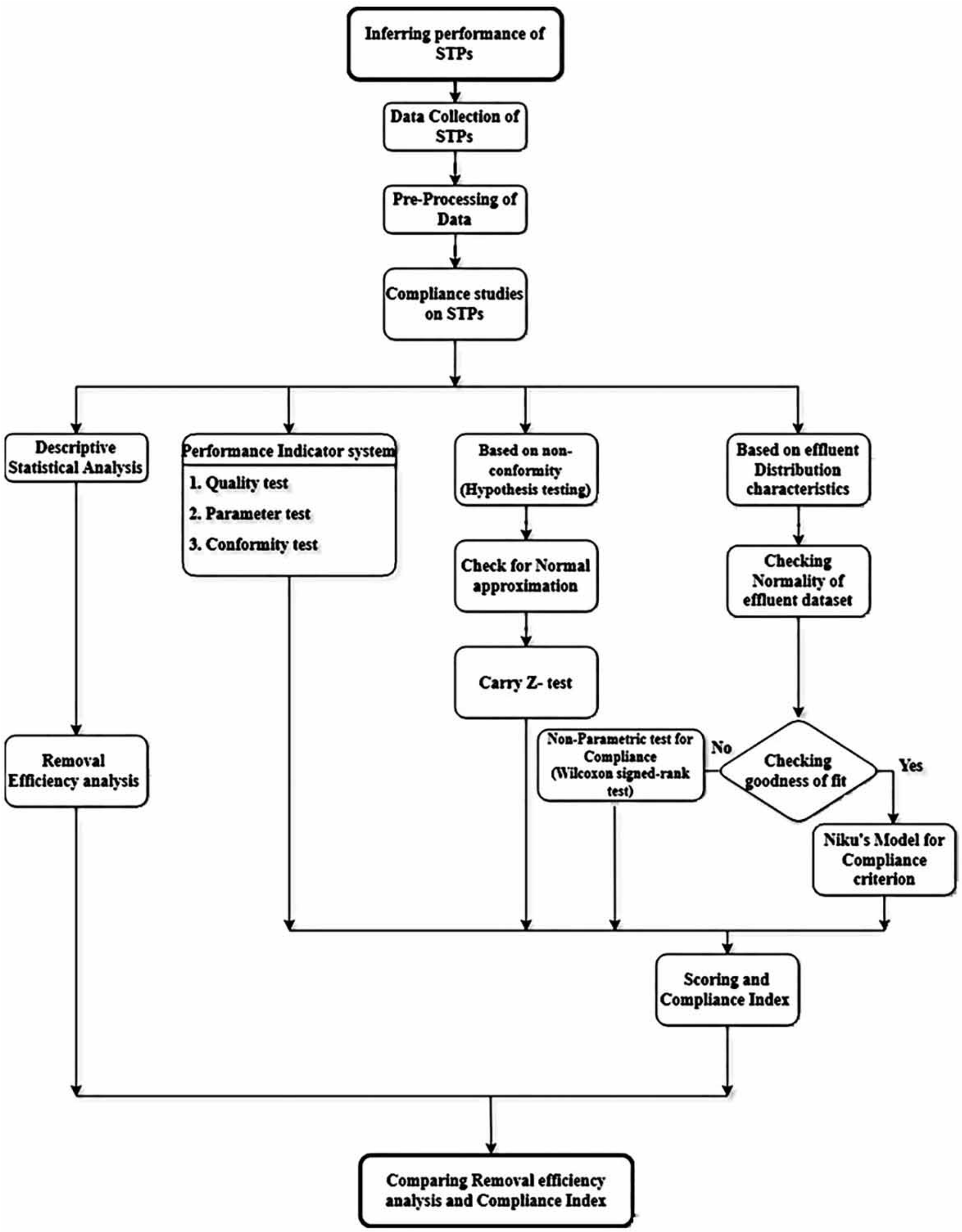


Figure 1 | Methodology adopted in the study for the compliance of STPs.

The performance indicator for wastewater effluent discharge into receiving waters requires the following tests: quality tests (number of day the effluents are tested), parameter tests (number of parameter tested), and conformity tests (Quadros *et al.* 2010). The conformity test measures the ratio of number of samples that confirms the effluent discharge standard in the present study. The performance indicator's conformity test does not include conclusions about the confidence level and the data variability. Thus, another way to study the conformity is calculating the amount of the non-conformity (percentage of failure samples) samples and checking with hypothesis testing to conclude the failure samples are less than the maximum allowable failure proportion of samples as per standards.

A Z-test for proportions of non-conformity of standards is carried out to conclude the effectiveness at 95% confidence level. The advantage of using this method is that Z-test follows a binomial distribution that does not require data normality; normal approximation is acceptable when the dataset follows conditions provided in Equations (1) and (2) (Von Sperling *et al.* 2020). To get enough confidence about the conformity, the hypothesis was formulated and tested in three ways: a two-tailed, left-tailed, and right-tailed test. The scenario in which a one-tailed or two-tailed hypothesis test is to be selected is explained in detail in the supplementary section. Equation (3) is used to calculate *Z*-statistic. This non-conformity test has been carried out for BOD, COD, and TSS, the parameters that need to be tested in STPs as per the standards.

$$P - 2\sqrt{\frac{P * (1 - P)}{n}} > 0 \quad (1)$$

$$P + 2\sqrt{\frac{P * (1 - P)}{n}} < 1 \quad (2)$$

$$Z \cong \frac{X - s * p}{\sqrt{s * p * (1 - p)}} \quad (3)$$

where, P is the probability of failure, s is the number of measured data points, X is the number of data points outside the effluent standard in numbers, and p is the acceptable proportion of failure.

The non-conformity test considers the hypothesis testing on number of failure samples to estimate CI, but it does not consider the magnitude of effluent characteristics. This magnitude of effluent parameters is tested using non-parametric test. Since, the effluent data of BOD, COD, and TSS are not following normality, they were tested using the Anderson-Darling, and Kolmogorov Smirnov tests to confirm normality. In order to compute compliance, Niku's model requires effluent distribution to follow normal or log-normal. All the effluent parameters of the present STP are tested with distributions such as normal, log-normal, exponential, gamma and Weibull. To handle the dataset which is not following normality, a non-parametric test approach, namely the Wilcoxon signed-rank test was performed to confirm STPs compliance concerning the median of the pollutant parameter. Thus, the above results of nine tests were integrated to derive the CI of STPs. The details of deriving the scores to make CI matrix are given in Section 5.

4. RESULTS AND DISCUSSION

In this study, retrospective data collected from seven STPs of NMMC are utilized for analysis. Statistical analysis was carried out for all parameters from all STPs; in particular, the result of the BOD, COD, and TSS of Sanpada STP is explained in detail; other parameters like flow rate, pH (Yan *et al.* 2013), DO, and temperature are presented in the Supplementary Material. The descriptive statistics, such as mean, median, standard deviation (SD), kurtosis, and coefficient of variation for the influent and effluent sewage are estimated. The results of the statistics of all the influent and effluent parameters pertaining to seven STPs are given in Tables S2 and S3, respectively, in the Supplementary Material. In order to see the range of the influent and effluent parameters of all the STPs, they are depicted as a box plot in Figure 2 along with the NMMC effluent discharge standard value to be followed. The RE of BOD, COD, and TSS of all the STPs is depicted in Table S4 of the Supplementary Material. Since the RE of all STPs are almost similar, the results of Sanpada STP are explained below in detail since this STP has large fluctuations in the influent and effluent characteristics. After explaining the RE, the inputs required to estimate CI, namely performance indicators, non-conformity test, and non-parametric test are explained. The estimation of CI is explained in Section 5 separately.

4.1. Descriptive statistics and RE analysis

4.1.1. Biochemical oxygen demand

BOD provides essential information about the amount of DO required to disintegrate organic pollutants. From Table S2 of the Supplementary Material, it can be seen that, the mean of influent BOD in NMMC STPs ranges from 105.9 to 159.1 mg/l, with an SD of 6.3 to 46.2 mg/l. It is also seen that the skewness varies between 0.26 and 1.96, and kurtosis varies between −0.31 and 5.8, indicating that the data may not follow normal distribution. NMMC maintains a stringent effluent BOD discharge limit of 5 mg/l after secondary treatment, since the effluent is discharged directly into the creek. The mean effluent BOD in NMMC STPs ranges from 3.5 to 4.3 mg/l, well within the standard. The box plot depicted in Figure 2(b) for BOD indicates that all STPs brings down the effluent BOD lesser than the prescribed standard value of 5 mg/l.

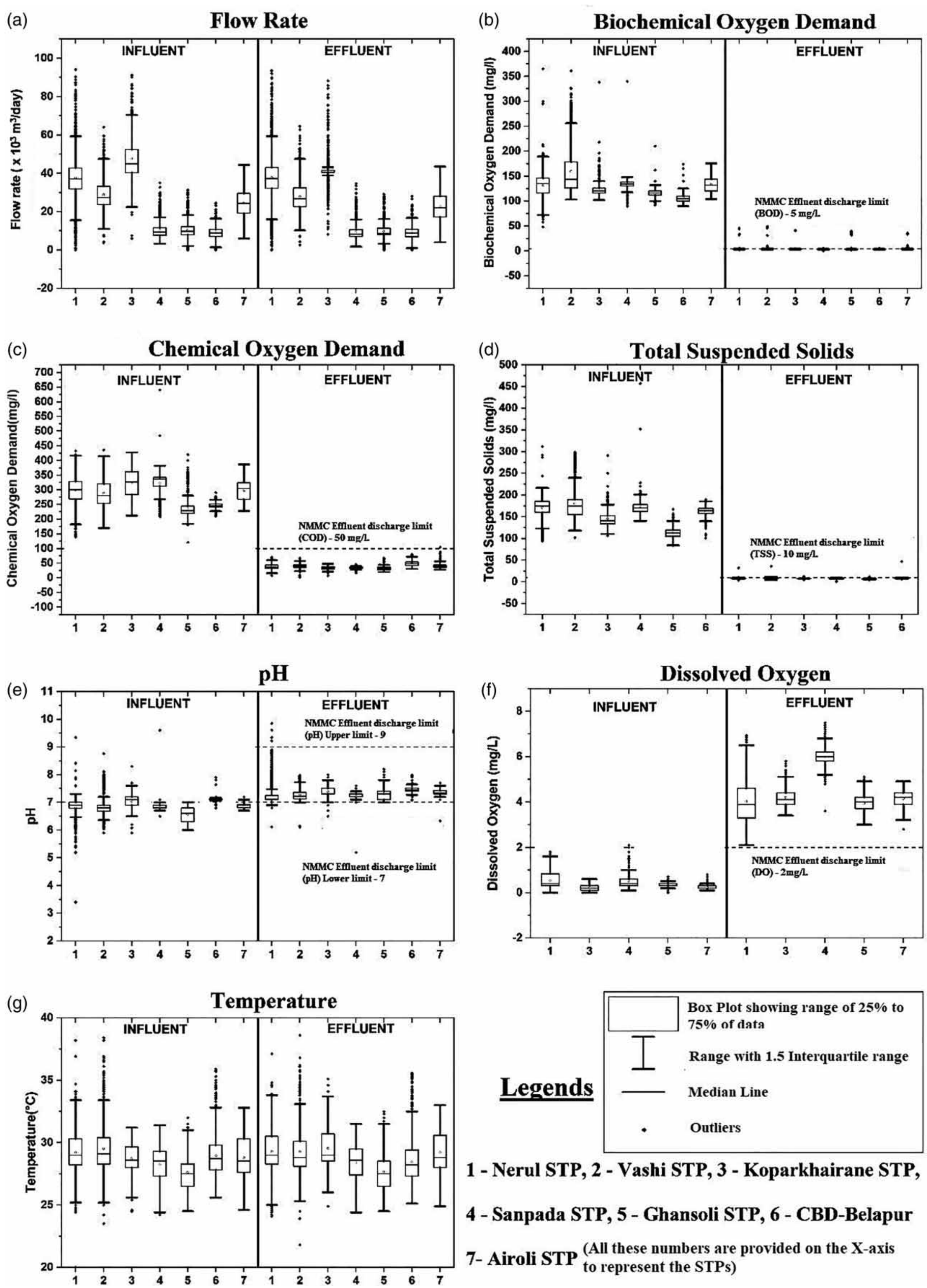


Figure 2 | Box plots on influent and effluent parameters of Navi Mumbai Municipal corporation sewage treatment plants (STPs).

Sanpada influent BOD touched a maximum of 340 mg/l during the study period, which is a summer season. The mean influent BOD is 132.3 mg/l with an SD of 13.6 mg/l. To understand the variation of the influent and effluent parameters of Sanpada STP, the time series plot is given in Figure S3 of the Supplementary Material. From Figure S3, it can be seen that the influent BOD value recorded the maximum of 340 mg/l once during the study period, which is above the design influent BOD value of 250 mg/l. The mean effluent BOD in Sanpada STP is 3.7 mg/l with a SD of 0.4 mg/l. The effluent BOD recorded a one-day infringement with a magnitude of 6.2 mg/l depicted in Figure S3.

From Table S4 of the Supplementary Material, it can be seen that the RE of BOD in NMMC STPs ranges between 96.67 and 97.30%, way higher than most of the studies reported in other case studies in India (Khan *et al.* 2014; Bhave *et al.* 2020). The RE of Sanpada is 97.19%, the second highest among all STPs.

4.1.2. Chemical oxygen demand

COD is the DO utilized in the chemical oxidation of organic materials by oxidizing agents. From the COD analysis provided in Table S2, it is seen that the mean influent COD varies between 237 and 325 mg/l with an SD varying between 8.3 and 47.9 mg/l. The skewness and kurtosis show that the COD also may not follow normal distribution, and a box plot showing variations in the COD is depicted in Figure 2(c). Figure 2(c) shows that the variation of COD in all STPs shows a similar range concerning first and third quantiles. The effluent COD of NMMC STPs are below the standards of 50 mg/l, depicted in Figure 2(c), except Airoli recorded a one-day infringement with a magnitude of 104 mg/l. The mean effluent COD in NMMC STPs ranges from 33.3 to 40.5 mg/l, much lesser than the standard value of 50 mg/l.

Statistical analysis reveals that the second-highest influent mean of an STP is recorded in Sanpada as 323.5 mg/l, with an SD of 30.3 mg/l. The distribution characteristics of influent COD are approximately symmetrical, and leptokurtic, as provided in Table S2. Effluent COD is well within discharge standards, depicted in Figure S3, with a mean of 33.3 mg/l.

Table S4 of the Supplementary Material provides the RE of COD varying between 84.55 and 89.70% in the seven STPs and RE of COD in Sanpada is 89.70%, the best among all STPs. The reason for being recorded with the highest RE of Sanpada STP is that the mean influent COD is highest among other STPs and better performance in COD treatment. In other words, higher the influent magnitude can lead to produce better RE. Thus, just relying on RE can infer systems sometime erroneously.

4.1.3. Total suspended solids

Testing of TSS was performed in six STPs, except the Airoli STP. The mean influent TSS varies from 113 to 180 mg/l for the six STPs in NMMC Corporation. The statistical analysis of influent and effluent TSS is given in Tables S2 and S3 of the Supplementary Material. Figure 2(d) provides the variations of influent and effluent TSS of six NMMC STPs. Apart from Sanpada STP, all other STP shows a similar trend in skewness and kurtosis for TSS influent, and the results are provided in Table S2. The mean effluent TSS in the six STPs ranges from 6.8 to 8.3 mg/l much lesser than the standard value of 10 mg/l.

In contrast, the Sanpada STP's distribution is highly asymmetric with a leptokurtic kurtosis. Though Sanpada STP has a wide range of TSS influent values, it performed well in treating TSS with no failures, as depicted in Figure S3. The mean effluent TSS of Sanpada STP is 7.2 mg/l with an SD of 0.8 mg/l.

RE of TSS across NMMC STPs varies from 94.04 to 95.81%, provided in Table S4. Sanpada STP is best in the RE (95.81%) of TSS concerning all other STPs.

4.2. Performance indicator system for STPs

In order to estimate the CI matrix, the first step is to find the performance indicator system. The performance indicator system requires three features to infer the compliance of STPs for wastewater discharge in receiving waters criterion (Quadros *et al.* 2010; Silva *et al.* 2014a). The three criteria are listed below.

4.2.1. Quality test

Quality test (Q_T) is the ratio of number of quality test carried out at STP with that of the number of quality test required to be carried out at an STP as per the standard. The value of Q_T varies between 0 and 1. If an STP carries out all tests required as per standard, the value of Q_T will be '1', else it will be less than 1.

$$Q_T = \frac{n_q}{N_q} \tag{4}$$

where n_q is the actual number of quality test carried out per year at each STP, N_q is the number of quality test required as per standards per year at each STP (365 in the present case (i.e.) all the test has to be carried out daily).

4.2.2. Parameter test

Parameter test (P_T) is the ratio of the number of pollutant parameters studied at each STP with that of the number of pollutant parameters to be studied at each STP as per standards. If an STP studies all the parameter as per standard, the value of P_T will be '1', else less than 1.

$$P_T = \frac{n_p}{N_p} \tag{5}$$

where n_p is the actual number of pollutant parameters studied at each STP, N_p is the number of pollutant parameters to be studied as per standards at each STP. (BOD, COD, and TSS tests need to be studied at each STP as per standards).

4.2.3. Standard conformity test

Standard conformity test (SC_T) results are computed as per Equation (6). The variable (m_i) requires encoding of '0' for non-conformity and for '1' conformity.

$$SC_T = \frac{\sum_{i=1}^{n} m_i}{n} \tag{6}$$

where n is the number of parameters studied, m_i is the conformity of standard by parameter 'i' (0 = non-conformity, 1 = conformity).

Concerning the quality tests, the MPCB mandates all corporations to test wastewater quality every day. All the seven NMMC STPs perform daily test on pollutant parameters; and thus, Q_T is '1' for all STPs. The scoring of Q_T to estimate CI matrix is given in Table 2.

CPCB (2013) mandates testing of pollutants, such as BOD, COD, and TSS, all STPs are 100% efficient in this criterion, except one STP, namely, Airoli; where TSS test is not performed, thus, P_T is '1' for all STPs except Airoli. In the case of Airoli, only two tests (BOD and COD) are carried out and hence P_T, is 0.67 for Airoli STP as given in Table 2.

For the conformity test, the literature indicates that the proportion of samples failing to confirm the effluent standards should not be more than 10% of total samples for large-scale STPs (Silva *et al.* 2014b). However, more stringent effectiveness values were utilized in some literature, if the population equivalent is more than 50,000, then the conformity of samples should be at least 93.72% (Bugajski & Nowobilska-Majewska 2019; Jucherski *et al.* 2019). The effectiveness of NMMC STPs in handling pollutants within the effluent standard is given in Table S5 of the Supplementary Material. The value provided in Table S5 indicates the percentage of samples that confirmed the discharge standards. The effectiveness provided in Table S5 is utilized for encoding the value of 'm_i' as '0' and '1'. NMMC STPs parameter effectiveness are above 93.72% for BOD, COD, and TSS, hence SC_T values are 1, except Airoli. Since Airoli STP tested only two parameters namely BOD and

Table 2 | CI of NMMC STPs

				Hypothesis testing						
	Performance indicator			Non-conformity test			Non-parametric test			
NMMC STPs	Quality test (Q_T)	Parameter test (P_T)	Conformity test (SC_T)	BOD	COD	TSS	BOD	COD	TSS	CI
Nerul	1	1	1	1	1	1	1	1	1	9.00
Vashi	1	1	1	1	1	1	1	1	1	9.00
Koparkhairane	1	1	1	1	1	1	1	1	1	9.00
Sanpada	1	1	1	1	1	1	1	1	1	9.00
Ghansoli	1	1	1	1	1	1	1	1	1	9.00
CBD Belapur	1	1	1	1	1	1	1	1	1	9.00
Airoli	1	0.67	0.5	0	1	0	1	1	0	5.17

COD ($n = 2$), and out of two parameters, BOD is less than 93.72% and COD is above 93.72%, hence $m_i = 1$, thereby $SC_T = 0.5$. This is the first step to estimate CI. This score of SC_T is given in Table 2.

4.3. Hypothesis testing on the proportion of non-conformity of effluent standard

The effluent parameter is tested for non-conformity using hypothesis testing of the proportion of the failure samples. NMMC STPs are tested for failure proportions of $p = 6.28\%$ with a confidence level of 95%. The hypothesis was formulated and tested in three ways: a two-tailed, right-tailed, and left-tailed test.

(a) Ho: $p = 0.0628$, Ha: $p \neq 0.0628$ (Two-tailed)
(b) Ho: $p < =0.0628$, Ha: $p > 0.0628$ (Right-tailed)
(c) Ho: $p > =0.0628$, Ha: $p < 0.0628$ (Left-tailed)

The Z-test results are presented in Table S6 of the Supplementary Material; the scenario of selecting either one-tailed or two-tailed is explained in the Supplementary Material. All three tests are carried out for all the parameters, but the left-tailed test is explained in detail. Before carrying out Z-test, all the parameters are checked for normal approximation. The left-tailed test infers that the treatment system complies with (confirms) the standard. Table S6 provides the p-value of the Z-test; it is observed that all the pollutant parameters of NMMC STPs have a significance level of less than 0.05, other than Airoli's BOD. BOD of Airoli has a p-value of 1, which indicates that the left tail's test, the null hypothesis is true (Ho: $p > =0.0628$). The inference is that sufficient evidence of non-compliance is observed in the Airoli STP concerning BOD. Interestingly, RE analysis shows that Airoli STP has 97.07% efficiency in removing the BOD pollutant. The p-value is used to estimate the score of non-conformity test of BOD, COD, and TSS. The estimation of score is explained in Section 5.

4.4. Compliance of NMMC STPs based on non-parametric test

Most literary works on effluents follows a log-normal distribution with a better distribution of data (Redda 2008; Padalkar & Kumar 2018). To conclude the reliability, the effluent parameters were checked for normality and goodness of fit. None of the distributions fit best for the significance level of 0.05; Sanpada STPs effluent BOD distributions are shown in Figure S4 of the Supplementary Material. In the case of BOD, all STPs work in a similar range to produce effluent BOD of 2.5–5 mg/l, which leads to a minimum range in which the system creates increased frequency on same data and produces non-stationarity. Hence, Wilcoxon signed-rank test was conducted with a significance level of 0.05. Hypotheses formulated in the present study for the non-parametric test are listed below.

(a) Ho: median = standard, Ha: median$< >$standard
(b) Ho: median $< =$standard, Ha: median $>$ standard
(c) Ho: median $> =$standard, Ha: median $<$ standard

The above-mentioned hypothesis is tested for effluent BOD, COD, and TSS. All the STPs satisfy that effluent median is less than the discharge standards. The two-tailed and right-tailed tests on all the pollutant parameters are similar to the Z-test except BOD of Airoli, which failed to meet the standards. However, in non-parametric results, the median is less than the effluent standard. The left-tailed test on the BOD value of Airoli provides a p-value equal to 0.01, which concludes the median is less than the standards for a confidence level of 95%. There is a considerable variation in the p-value of the left-tailed test for the non-conformity and non-parametric tests. The non-parametric test is dependent on the effluent magnitude, whereas the non-conformity test relies on the failure samples. The effluent magnitude is way less than the average magnitude on better performing days, leading to a reduced p-value for non-parametric testing criterion, resulting in effluent BOD less than standard. Thus, it is necessary to study every aspect of the compliance of STP. The results of non-parametric test using Wilcoxon signed-rank test is used to estimate the score of non-parametric test of BOD, COD, and TSS. The estimation of score is explained in Section 5.

5. COMPLIANCE INDEX

Earlier studies reported the compliance of an STP using Niku's model, which requires the data to follow normal and log-normal distribution. In our study area, the effluent parameters do not follow normality; in order to confirm the normality, the data are tested with Anderson–Darling and Kolmogorov–Smirnov tests. Since both tests proved that data do not follow normality, we have devised a new method, namely CI. The methodology includes three steps, (1) estimation of performance indicators, (2) hypothesis testing of non-conformity, and (3) hypothesis testing using the non-parametric test. Each of the above tests is provided with a score of 0–1, and the results of these nine tests is provided in Table 2. Indexing each test is exciting; for example, the performance indicator system requires three tests: quality, performance, and conformity test; the results are provided in Table 2. The output of these performance indicator tests are between 0 to 1, and is the input to form CI matrix. For example, Airoli STP tested the wastewater quality test daily in the laboratory of STP; in that case, Q_T is to be provided with a score of '1'. Airoli STPs 'P_T' is provided with a score of 0.67 because out of three parameters to be studied in STP as per standards (BOD, COD, and TSS), only two parameters are tested during study period, except TSS. SC_T of Airoli STP is '0.5' because out of two parameters tested, only one parameter confirms the standard. Similarly, encoding of all the three tests has been carried out to all STPs and imputed as '1' based on the performance of each parameter as depicted in Table 2 to form CI matrix.

The second test is the hypothesis testing of non-conformity of effluent standards using *Z*-test, which involves two-tailed, left-tailed, and right-tailed tests. Non-conformity test is carried out on three major pollutant parameters: BOD, COD, and TSS; each parameter is tested using *Z*-test. Each of the three hypothesis tests on the pollutant parameter should result in the proportion of failure being less than the maximum allowable failure within a confidence level of 95%. In this case, each parameter is coded with a score of '1' for confirming the standards or '0' for not-confirming the standards. For example, Table S6 of the Supplementary Material provides Airoli's BOD as '0' for two-tailed and right-tailed test infers to reject the null hypothesis and accept the alterative hypothesis. Left-tailed test provided a *p*-value of '1', and two-tailed test infers that there is a significant difference between the proportion of actual failure to the maximum allowable sample failure, both one-tailed tests infer that the proportion of failure is greater than maximum allowable sample failure. Thus, there is a clear indication of infringement in all the cases, so it is encoded as '0' in the BOD of Airoli in the CI matrix of non-conformity section. Rest of the parameters are provided with a score of `1', since both two-tailed and one-tailed tests accepted the failure proportions of the sample are less than the standards with a confidence level of 95%.

The third test is a non-parametric test on effluent pollutant parameters, such as BOD, COD, and TSS, similar to the *Z*-test of non-conformity. The difference between these two hypothesis tests in non-conformity depends on failure proportions, whereas the non-parametric test relies on pollutants effluent magnitude. Each pollutant parameter tested with a non-parametric test should result in a median value better than effluent standards within a confidence level of 95% in all three hypothesis tests of the Wilcoxon signed-rank test. Each parameter tested with the non-parametric test is provided with a score of '1' if the median is better than the standards or '0' if the median value is worse than the standards. For example, Airoli's BOD resulted both in one-tailed and two-tailed tests as median of the effluent magnitude is less than the discharge standards. Thus, it is provided with a score of '1', TSS test is not performed in Airoli STP, so it is provided with a score of '0' in non-parametric test.

Thus, overall, there will be nine scores for each STPs, three for the performance indicator system, three for non-conformity, and three for the non-parametric test. It is also worth to mention that the score will be according to the number of pollutant effluent parameters to be tested. In India, BOD, COD, and TSS are the mandated pollutant effluent parameters test to be carried out at an STP. Thus, in this case, an STP can achieve a maximum score of '9' if it passes all the tests. The score in the CI matrix indicates at which test the STP is having an infringement or lacking in performance. From Table 2, it can be seen that STPs are performing better in all parameters, except STP at Airoli in the non-conformity test of BOD and TSS is not tested. This study concludes that there is a need for necessary modification at Airoli STP to comply with the standards.

6. DISCUSSION

A new CI has been proposed to assess the performance efficiency of STPs with respect to the standards. CI integrates three tests: (1) performance indicator system – provides necessary information about the number of tests to be carried out in STP and quality parameters getting tested in STP, (2) hypothesis testing of non-conformity – checks maximum sample failure concerning standards, (3) hypothesis testing using non-parametric test – checks the median of effluent magnitude concerning standards. Thus, CI integrates all the tests required for inferring STPs based on wastewater quality parameters with respect to standards. CPCB (2021) states that in India, out of 900 STPs, a compliance study provides data of only 578 STPs that were found to comply with the standards. Non-complying STPs must be studied in each aspect to understand the underlying problem and to rehabilitate the STP, in which the CI can be beneficial. Moreover, when the observed effluent data do not follow normality, this CI method could be more useful. NMMC STPs perform well in each test and imply compliance with all STPs except Airoli in the *Z*-test for non-conformity. The reason for the infringement is because of continuous 41 days violations of BOD test. During the infringement period, the mean influent BOD is higher than the mean influent BOD of Airoli during better performing days; this is why the third-highest RE of BOD was recorded, and a non-parametric study infers better performance of STP. Thus, it is essential to study each aspect to infer compliance of STPs. CI can be taken as a performance measure; all these tests can improve the confidence of the compliance criterion of STP, and the CI matrix can provide a test at which an STP failed. NMMC keep its cleanest city tag by maintaining sanitation infrastructure by continuous monitoring, upgrading sanitation infrastructure, modeling, forecasting failure events, and taking necessary actions before failure.

7. CONCLUSIONS

A methodology is constructed to infer the performance of STPs with a wastewater quality dataset that does not follow normality. The developed method is applied and tested with retrospective data collected from NMMC STPs. The RE of BOD, COD and TSS varies between 96.67 and 97.30%, 84.55 and 89.70%, and 94.04 and 95.81%, respectively, among the STPs studied. Three different methods are carried out to compute compliance: a performance indicator system, hypothesis testing for non-conformity and a non-parametric test. Integrated scores of CI matrix implies that all STPs are performing well with an index of 9, other than Airoli. RE analysis mentions that BOD of Airoli is the third-best of all STPs; still, CI showed the least. Thus, the present study shows the significance of studying an STP through CI as it involves all the necessary parameters for wastewater quality, number of tests carried out, and conformity of quality with the standards to infer the compliance of STPs.

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DATA AVAILABILITY STATEMENT

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

CONFLICT OF INTEREST STATEMENT

The authors declare there is no conflict.

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