CIENTIFIC Publishing Limited

Journal of Hydrological Ecology and Water Security
https://ojs.ukscip.com/index.php/jhews

Article

Single Index of Ballast Water Quality

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Received: 10 February 2025; **Revised:** 28 March 2025; **Accepted:** 7 April 2025; **Published:** 14 April 2025

Abstract: Ballast water (BW) to maintain a ship's stability carries multitude of aquatic invasive species and poses serious threat to the ecosystems at destination ports. To minimize transfer of harmful aquatic organisms and pathogens at the global level, Ballast Water Treatment Systems (BWTS) were introduced along with the recommendation of IMO standards (Regulation D-2), where indicators are in ratios. However, observations across samples from the same ballast tank are not additive like average speed of cars. The paper describes an index of overall quality of treated BW by multiplicative aggregation of the indicators of viable organisms and specific microbes. The index value ≤ 1 indicates compliance of D-2 standard across all the indicators. The index satisfies desirable properties, including statistical test of the equality of means of two sample GMs (SGMs). Identification of critical indicators and confidence interval around mean SGM, giving a range of index values indicating compliance, are novelties of the paper. The proposed index can be decomposed into the Index of Viable Organisms and the Index of Specific Microbes, facilitating computation of relative importance. A separate index of physical and chemical factors can be computed by multiplicative aggregation. Empirical linear relationships can be fitted with each proposed index as dependent variable and ratio of value of variables in a year (X_{it}) and base year (X_{i0}) as independent variables. Empirical verifications are planned to highlight salient features of the proposed indices along with the efficiency of different filtration units associated with BWTS.

Keywords: Ballast Water Management System; D-2 Standards; Probability Distribution; Multiplicative Aggregation; Confidence Interval; Compliance

1. Introduction

Ballast water (BW) to maintain a ship's stability during navigation also reduces stress on the hull, improves propulsion and manoeuvrability. BW also carries a multitude of aquatic invasive species (AIS), which are non-indigenous and pose a serious threat to biodiversity and the functioning of ecosystems at destination ports [1,2]. The up-taking of BW from one port and discharging it to another out-competes native species, causing serious ecological disturbance, loss of health and even economic losses [3]. The transferred non-indigenous species (NIS), such as bacteria, microbes, phytoplankton, zooplankton, benthic animals, eggs, cysts, and larvae of various species, as well as actinomycetes, carry toxins or introduce antibiotic resistance genes [4]. Such NIS become invasive, out-competing native species and result in a reproductive population in the host environment. Damage to the ecology and environment by invasive species is continuing at an increasing rate, in line with the growing trend of sea-borne trade. One cubic meter of untreated BW contains bacteria (over 100 billion) and one trillion viruses [5]. An epidemic of Cholera in various countries has been found to be associated with the transmission of *V. cholerae* through BW and seafood [6]. *E. coli* with a long lifespan can survive outside the human intestine, posing a health risk to human beings [7]. The estimate of global economic cost of AIS caused by BW-discharge was $162.7 billion (approx.) [8].

Regarding the association between physical parameters of BW and the pathogens, empirical studies showed varied results. No significant relationship was observed between the pathogens and the chosen physical parameters in ballast tanks [9]. Salinity can affect pathogens, but not temperature [10]. Warmer temperatures are conducive for bacterial growth in BW [11,12]. The relationship between salinity and the survival of *Enterococci was* negative [5]. Lower salinity levels and warmer temperatures are favorable for the growth of *V. cholerae* [13]. pH was found to be an additional parameter on the spread of *V. cholera* [14].

1.1. Ballast Water Treatment Systems

To provide a safe, productive, clean sea for our children and grandchildren, international efforts have been initiated towards protecting the marine environment from invasive species. Ballast Water Treatment Systems (BWTS) are designed to remove/inactivate harmful aquatic organisms and pathogens in BW before it is discharged into a new environment. Various techniques are being used in this context, such as:

- **Physical Filtration:** To stop the transfer of species of larger sizes and sediments from the BW using screens or filters.
- **Chemical Treatment:** To kill or neutralize harmful organisms in BW using chemicals (biocides or disinfectants) like chlorine, hydrogen-peroxide (H_2O_2).
- **Ultraviolet (UV) Radiation:** To inactivate or sterilize microorganisms by damaging their DNA by exposing BW to high-intensity UV light.
- **Ozonation:** To kill or inactivate microorganisms and pathogens by injecting ozone (O_3) gas (a strong oxidizing agent) into the BW.
- **Electro chlorination:** To disinfect BW with an electrochemical process to generate chlorine on board the ship using seawater.
- **Advanced Oxidation Processes (AOPs):** To effectively destroy organic contaminants in BW using multiple treatments like UV-radiation, and H_2O_2 or O_3, to create highly reactive hydroxyl radicals.

Each BWTS has advantages and limitations. For example, water chemistry changes with chemical systems generating chlorine, and the removal of oxygen. Less power, less maintenance, and fewer footprints are involved in the EC-system than the UV-system to treat an equal volume of BW. UV light is required to reach each drop of BW, which can be affected by sediments or turbid water. The UV-system is cheaper to install (CAPEX), but operating costs (OPEX) are higher, like a Chemical injection system. However, the installation of the EC-system requiring saline water is more complicated than that of UV or chemical injection systems. For oil and gas tankers, a BWT system involving deoxygenation and heat treatment may not be acceptable due to potential safety concerns and operational challenges. Determination of overall cost and benefit is impossible for each type of BWTS [15]. Thus, researchers undertook a comparison of selected BWTS.

1.2. IMO Conventions

The International Maritime Organization (IMO) established the International Convention for Control and Management of Ships' BW and Sediments (IMO regulations). As per the Ballast Water Management (BWM) Convention adopted by IMO in 2014, ships may conduct BW exchanges with over 95% volumetric efficiency. However, open-ocean exchange showed limited success and failed to stop the invasion of pathogens and exotic species [16]. IMO came out with measures to mitigate the transfer of NIS and pathogens through BW discharge and established the D-2 standard for BW to be discharged after treatment by approved BWTS [17]. The IMO Resolution MEPC. 325(75) (MEPC.325 (75).pdf) included amendments to the BWM Convention with effect from 1st June, 2022. Yards and vessel owners to comply with the mandatory commissioning testing at the initial BWTS commissioning survey. The collection and analysis of representative samples for testing, each with volume ≥ $1m^3$ should be unbiased to the BWTS manufacturer, supplier, and also to the flag administration. However, commissioning testing and compliance testing are two different concepts.

1.3. BWTS and SDG

BWTS aligns well with SDG 14: Life below Water, specifically target 14.2, aiming to sustainably manage and protect marine and coastal ecosystems to avoid significant adverse impacts. It also contributes to SDG 6, "Clean

Water and Sanitation," by improving water quality and promoting sustainable water management practices. It also indirectly supports other SDGs, such as SDG 8: Decent Work and Economic Growth and SDG 15: Life on Land.

1.4. BWTS in India

India is yet to sign the BWM Convention. Instead, a Ballast Water Treatment Test Facility (BWTT-TF) is being operated by the National Institute of Ocean Technology (NIOT) in Andhra Pradesh. Thus, ships entering Indian ports are not required to follow IMO regulations regarding ballast water, which is a major threat to India's ecology and ecosystems. As per Circular No. 32 of 2020 of Directorate General of Shipping, Government of India has authorized Recognized Organization (ROs) to issue Statement of Compliance (SOC) to ships operating on Indian coast till India accedes to the IMO Convention, subject to the condition that the vessel meets all other requirements of BWM Convention, including discharging BW and meeting Regulation D-1 of the BWM Convention. Foreign-flagged ships operating in the Indian coast or ports or anchorages with a valid license granted by the Indian Administration, are granted dispensation from the fitment of BWMS meeting Regulation D-2 of the BWM Convention for the period of the license, provided that the following conditions are fulfilled:

- The RO has confirmed that all BW and sediments are removed prior to taking in or discharging BW along the Indian coast; and
- Such a dispensation is granted by the Flag State of the concerned foreign-flagged ship and is informed to IMO as per BWM Convention requirements.

1.5. Comparison of BWTS

Assessment of the effectiveness of BWTS involves the selection of a finite set of indicators focusing on enumeration of number and types of living organisms and microbes per unit volume of treated water, and comparison with the IMO standards (Regulation D-2), where each indicator is in a ratio and observations across samples from the same ballast tank are not additive, like average speed of cars. Computation of the indicators should follow proper sampling followed by a sound method of combining sample observations and defining limit values L_{1i} and L_{2i} such that the average value of *i*-th indicator (μ_i) lies between the limits with say 95% probability. Such limits also provide a minimum deviation from the standard (MDS) to ensure compliance. However, indicator-wise threshold values (limits) are not available. Meaningful computation of L_{1i} and L_{2i} requires knowledge of distribution of the *i*-th indicator; estimates of population standard deviation (SD) and confidence interval around μ_i. Moreover, measurement of μ_i may go wrong due to various reasons like variations in equipment, laboratories, technicians, day-to-day variations, faulty method of combining observations of k-samples $x_{1i}=\frac{C_{1i}}{V_{1i}}$, $x_{2i}=\frac{C_{2i}}{V_{2i}}$, ……$x_{ki}=\frac{C_{ki}}{V_{ki}}$ for the *i*-th indicator. For example, μ_i should be taken as pooled mean= $\frac{\sum_{j=1}^{k} C_{ji}}{\sum_{j=1}^{k} V_{ji}}$ and not as $\frac{\sum_{j=1}^{k} x_{ji}}{k}$. Similarly, pooled SD may be taken for the *i*-th indicator.

Research gaps in assessing effectiveness of BWTS include absence of methodologically sound method of aggregation of all relevant indicators expressed in different units and following unknown probability distributions to a composite index (CI) for assessment of overall quality of treated BW and monitoring of compliance with D-2 standard with unknown limits of MDS, and undertaking statistical inferences.

The paper describes theoretical frameworks for a composite index I_{BW} reflecting overall quality of treated BW by multiplicative aggregation of the chosen indicators facilitating estimates of confidence interval of the index such that ($CI_{Lower\ Limit} \leq I_{BW} \leq CI_{Upper\ Limit}$) implying compliance and water may be allowed to be discharged. Desired properties satisfied by the index are also discussed.

2. Literature Review

Discharges of untreated BW in ports have affected the marine species structure at the global level. In India, around 30 invasive species, including the most harmful Charru mussel (*Mytella strigata*), have been identified due to this practice. The species may experience sexual reversal under certain conditions. It has replaced the Asian green mussel and the edible oyster *Magallana bilineata*. Major INSs found in the South China Sea, include among others*, Penaeus monodon, Caulerpa racemose, Pterois volitans, Perna viridis,* and green crab (*Carcinus maenas*) [18]. The algae *Pseudocochlodinium profundisulcus* has caused algal bloom pollution by BW of vessels traveling between

China and North America's ports [19]. *Eriocheir sinensis* is found on the west coast of North America, damaging the fishery and aquarium industries and thus causing significant economic and ecological losses [20]. The list of dispersal of INS through BW carried by ships goes long [21–23]. The value of economic losses due to invasive alien species in China in 2000 was estimated at 144.5 billion USD [24].

BWTS differ with respect to the efficiency of microbial inactivation, along with factors such as temperature, pH, and turbidity [25]. The efficiency of BWTS is also influenced by age and size of ships, the holding time of BW, and the filter mesh size. Among several BWTS, only 69 systems have IMO type approval [26]. Different combinations of BWTS were felt needed for improved efficiency in microbial inactivation and treatment of BW [27,28]. Filtration or hydrocyclonic separation, followed by UV radiation or ozonization, appears to be the preferred method. The effectiveness of BWTS is assessed by comparing the number and types of organisms in uptake water (water taken into the ship) with those in treated water before discharge, ensuring compliance with IMO Regulations and operational reliability (the ability to operate under various conditions, including high turbidity and TSS). Comparison of efficiency of BWTS has been investigated with respect to the extent of reduction of concentration of total residual oxidant (TRO) and plankton species, before and after the ballast treatment process, with varying holding times, and also in terms of energy consumption and cost-effective evaluation. Consumption of energy is higher for physical treatment methods than for methods based on chemical treatments. However, chemical treatment methods for BW require additional safety measures, which can be expensive. Findings from studies with non-uniform indicators and a limited number of ships and treatment systems varied and cannot be generalized [29,30].

Additional factors to select BWTS are: size of the vessel, flow rate of BW to be treated, regulatory and standard requirements, and specific environmental conditions of the ship's operating areas. Many countries have adopted regulations and standards for BWT to protect ecosystems from the potential impact of invasive species and pathogens emerging from BW discharge. Based on an arbitrary value for the importance of four key factors, Key Performance Indicators (KPIs) for Dry Bulk carrier and separately for fishing vessels were suggested by Yonsel and Vural [26], who opined that an elaborate investigation was needed to establish the validity of decision-support methods. Data on perspectives of 24 deck side officers and 26 marine engineers on six criteria were analyzed using the Analytic Hierarchy Process (AHP) [31] and found that (i) Rare alarms and malfunctions was most important criterion and (ii) BWTSs using UV-radiations were more preferable when compared to electrochemical (El-Chem) type BWTSs. While use of ozone was most appropriate BWTS from ship designer's point of view, use of filter followed by UV-radiation was most appropriate from the viewpoint of ship owners. Here, evaluation methodology was multi-criteria decision making method (MCDM) involving development of a hierarchy analysis model and finding weights of the items following pairwise subjective comparisons ($\frac{n(n-1)}{2}$ for n-indicators) which suffers from weighting system where weight vector is the principal eigenvector obtained from Principal Component Analysis (PCA) [32]. However, AHP, Fuzzy AHP, and MCDMs with different assumptions suffer from methodological limitations, and no single MCDM performs the best. Moreover, MCDM techniques using subjective preferences and conflicting objectives are computational intensive for optimizations. Six MCDM software products were compared with respect to usability and functionality, and it was found that ranking the MCDM software products is itself a multi-criteria problem [33]. However, improvement in compliance over time was rather insignificant. Outinen et al. [34] opined that compliance testing of ships' BW with the D-2 standard is necessary. For objective and consistent assessment of water quality, geometric mean (GM) is preferred since different indicators in different units and different inter-correlations and different relationships with quality of treated BW do not allow meaningful aggregation of the indicators, and distributions of sensitivities of individual organisms in toxicity tests are more likely to be lognormal [35]. Use of GM in various fields for aggregation, given with numerical illustrations for habitat suitability [36], optimization under environmental uncertainty [37], pharmacokinetics [38], and evaluation of tenders [39].

Indicators and Nature of Data

Details of the Regulation D-2 indicators and IMO targets [40,41] are given in **Table 1**.

Table 1. Indicators and targets of ballast water performance.

Indicator	Target
Viable organisms:	
#Organisms ≥ 50 µm (X_1)	<10 per m^3
#Organisms ≥ 10 µm and < 50 µm(X_2)	<10 per ml
Specific microbes:	
Toxicogenic Vibrio cholera (X_3)	<1 colony-forming unit (CFU)/100 ml
Escherichia coli (X_4)	<250 CFU per 100 ml
Intestinal Enterococci(X_5)	<100 CFU/100 ml

Each of the above said indicators is influenced by the following physical and chemical factors, for which specific IMO targets are not there.

- Temperature(X_6): Temperature of BW can influence the survival and activity of organisms.
- Salinity(X_7): Salinity levels can also affect the viability of organisms.
- pH (X_8): pH measured in (-) log of the hydrogen ion concentration of seawater is not additive. For example, 100 ml of an acid with pH = 3 when mixed with 400 ml of another solution with pH = 1, the resulting pH is 1.10. pH can impact effectiveness of certain BW treatment methods. pH of a seawater sample is affected by temperature and loss or gain of CO_2 on contact with the atmosphere.
- Dissolved Oxygen (DO) (X_9): DO levels are important for the survival of some organisms.
- Turbidity (X_{10}): Indicates water clarity (transparency) measured in Nephelometric Turbidity Units (NTU). High turbidity does influence effectiveness of BWTS like UV disinfection.
- Total Suspended Solids (TSS) (X_{11}): Indicates mass of solid particles suspended in one liter of water, measured in (mg/L). High TSS also impact treatment effectiveness.
- Total Oxidant Concentration (TRO) (X_{12}): Indicates amount of chlorine or chlorine-containing compounds present in water sample. IMO limit of TRO is < 0.1 mg/L of Cl_2.
- Residual Biocides(X_{13}): Indicates concentration of biocides in water after disinfection or other treatment processes ($\frac{\text{mg}}{\text{L}}$ or ppm). For systems using biocides, monitoring residual biocides is vital to ensure compliance with regulations and prevent potential environmental impacts.

Issues:

- There could be situation where $X_i \leq$ corresponding D-2 standard but X_i exceeds the corresponding target for $i, j = 1,\ 2,\ \ldots .5$ and $i \neq j$.
- Addition is not admissible for indicators in different units. Consideration of different volumes of BW across samples for an indicator in ratio further adds to the problem of addition.
- Distributions of the indicators are different and unknown.
- Assessing and monitoring compliance with D-2 standard requires well defined limits indicating MDS is not known to accept compliance.
- Sum of scores of two indicators $X_{1_i} +\ X_{2_j} = Z_j$ is not meaningful since the joint distribution of Z_j is unknown when X_{1_i} and X_{2_j} follow two different distributions. Lack of knowledge of probability distribution of Z_j does not allow finding $P\left(Z_j = z\right) = P\ (X_{1_i}=\text{x}, X_{2_j}=\text{z - x}) =\ \int_{-\infty}^{\infty}(\int_{-\infty}^{z} f_{X,Y}(x,\ t-x)dt)\ dx.$
- Computation of confidence interval around μ_i requires knowledge of probability distribution of the i-th indicator.
- Sample mean $\pm$ sample SD is routinely indicated in empirical investigations of viable organisms and/or specific microbes. However, interpretation of sample mean $\pm$ SD is problematic since estimate of population SD reflecting consistency of outcomes or lack thereof is not known and precise statement about the probability of a data point falling within a certain range around the mean cannot be made. Moreover, small sample size can result in inaccuracies in the confidence interval reflecting the range where population mean is most likely to fall with a certain level of confidence.

3. Proposed Method

Let the observations on the five indicators relating to viable organisms and specific microbes in treated BW are $X_{1t},\ X_{2t}$, ….., X_{5t} for which D-2 standards (targets) are $X_{10},\ X_{20}$, ….., X_{50} where X_{i0} denotes the minimum value for the *i*-th indicator. The ratio $\frac{X_{it}}{X_{i0}} \leq 1$ indicates compliance with D-2. Index of overall status of treated BW (I_{BW}) is proposed as GM of the ratios:

$$I_{BW} = \sqrt[5]{\frac{X_{1t}X_{2t}\ \ldots..X_{5t}}{X_{10}X_{20}\ \ldots..X_{50}}} \tag{1}$$

or equivalently as

$$I_{BW} = \frac{X_{1t}X_{2t}\ \ldots..X_{5t}}{X_{10}X_{20}\ \ldots..X_{50}} \tag{2}$$

As per Equation (2), $0 < I_{BW} \leq 1$ implies compliance across all the indicators. $\frac{X_{it}}{X_{i0}}>1 \Longrightarrow$ non-compliance of the *i*-th indicator and also of I_{BW}.

Properties

– The proposed index takes unweighted GM giving equal importance to the chosen indicators.
– I_{BW} is a monotonically increasing continuous variable and can accommodate all indicators in different units, irrespective of their score ranges, distributions and sample size. I_{BW}*100 may be considered to reflect percentage changes.
– I_{BW} avoids skew and outliers and produces no bias.
– The index reduces substitutability among the indicators significantly and produces no bias for regions and satisfies:
  - Time reversal test since $I_{BW_{t0}} * I_{BW_{0t}} = 1$
  - Formation of chain indices since $I_{BW_{20}} = I_{BW_{21}} * I_{BW_{10}}$
– $I_{BW_{t(t-1)}} > 1$ will give progress of overall impact of BW-quality in successive years. Plot of such progress/decline across time facilitates comparison based on longitudinal data.
– $\frac{X_{it}}{X_{i0}}>1$ indicates criticality of the *i*-th indicator requiring corrective action. Identification of critical indicator is important for monitoring BWTS.
– 1% increase in $\frac{X_{jt}}{X_{j0}}$ implies 1% improvement in $I_{BW_{t0}}$ keeping all others unchanged.
– From Equation (2) $\log(I_{BW}) = \sum_{i=1}^{5} logX_{it} - \sum_{i=1}^{5} logX_{i0}$ i.e., an additive model following lognormal distribution for large sample size [42].
– For lognormal samples, mean and variance of sample GM (SGM) derived by Vogel [43] are:

$$E(SGM) = \exp\left(\overline{\log(X)} + \frac{[SD(\log X)]^2}{2n}\right)$$

and

$$Var(SGM) = \exp\left(2\overline{\log(X)}\right)[\exp\left(\frac{2[SD(\log X)]^2}{n}\right) - \exp(\frac{[SD(\log X)]^2}{n})].$$

– Confidence interval around $E(SGM)$ can be obtained as $E(SGM) \pm 1.96\sqrt{\frac{Var(SGM)}{6}}$. Here, the upper and lower limits indicate maximum deviations allowed for D-2 standard compliance.
– I_{BW} can be decomposed to indices for viable organisms and specific microbes like $I_{VO} = \frac{X_{1t}.X_{2t}}{X_{10}.X_{20}}$ and $I_{Microbes} = \frac{X_{3t}.X_{4t}.X_{5t}}{X_{30}.X_{40}.X_{50}}$ such that $I_{BW} = I_{VO}.I_{Microbes}$. Here, relative importance of viable organisms and specific microbes are given by $\frac{\Delta I_{BW}}{\Delta I_{VO}}$ and $\frac{\Delta I_{BW}}{\Delta I_{Microbes}}$ respectively which can be used to compare treated BW from two different ships.
– Relative importance of X_j on I_{BW} is given by $\frac{\Delta I_{BW}}{\Delta X_j}$. The variables with high value of relative importance merit more attention of the planners and monitoring authorities.

Following similar approach, another index of physical and chemical factors, $(X_6,\ X_7,\ \ldots\ldots X_{13})$ can be computed as $I_{Phy.\&\ Chem} = \frac{X_{6t}X_{7t}\ \ldots\ldots X_{13t}}{X_{60}X_{70}\ldots\ldots X_{13,0}}$ where $X_{60},\ X_{70},\ \ldots\ldots,\ X_{13,0}$ denote pooled average values of the physical and chemical factors of water where treated BW is to be discharged. Multiple linear regression equation can be fitted with each of the indices $I_{BW},\ I_{VO},\ I_{Microbes}$ as dependent variable and $\frac{X_{it}}{X_{i0}}\ \forall i$ =6, 7, ...13 as independent variables where β-coefficients can be interpreted as influence of the chosen independent variable to predict the proposed indices like $I_{BW},\ I_{VO},\ I_{Microbes}$.

4. Limitations

- -Empirical illustration of the proposed indices, along with comparison with other approaches, is suggested to be taken up in future studies.
- Missing values of data are not considered. Treatment of missing data is beyond the scope of the present paper.
- Introduction of a new indicator, say nuclear contamination in BW, with two major components, viz. diffusion velocity, and thickness of the surface mixed layer [44], may make the index I_{BW} non-comparable. To ensure comparability, the value of a new indicator and its components must be estimated for the base period and subsequent periods.

5. Discussion

The proposed index I_{BW} is a function of GM, giving equal importance to the chosen indicators. Sensitivities of individual organisms in toxicity tests are more likely to be lognormal, for which GM is the natural parameter to estimate, since the log of GM is the same mean for normal random variables. Weighted GM is usually taken when one indicator significantly limits the overall result, which cannot be compensated for by other indicators, which is unlikely for the indicators of BW performance.

The index I_{BW} avoids the transformation of original variables and restores the distributional characteristics of the indicators. The index reflects overall status of treated BW in terms of D-2 standards and satisfies many desired properties, including statistical testing of H_0: $\overline{SGM}_1 = \overline{SGM}_2$ against H_1: $\overline{SGM}_1 \neq \overline{SGM}_2$ using logarithm of the indicators and usual t-test. The generalized confidence interval approach based on t-values, also works well, but requires simulation of the sampling distribution [45].

However, computation of the indices $I_{BW},\ I_{VO}, I_{Microbes}$ must take care of original values (avoiding any transformation) of the eight physical and chemical factors $(X_6,\ X_7,\ \ldots\ldots X_{13})$ and water holding time (X_{14}) which can influence values of each of $X_1,\ X_2,\ \ldots\ldots,\ X_5$ and hence, the indices. For example, number of bacteria may increase many folds from the starting bacterial number after a passage of time [38].

6. Conclusions

The paper provides a simple way to find an index I_{BW} reflecting the overall quality of treated ballast water, along with monitoring of compliance with D-2 standard in a multivariate setup. Computation of upper and lower limits of compliance such that $(CI_{Lower\ Limit} \leq I_{BW} \leq CI_{Upper\ Limit})$ implying compliance is a novelty of the paper. The limits are obtained as a confidence interval around the mean (SGM) across all the indicators. The importance of compliance testing will increase as more and more ships will become subject to the D-2 standard.

The index I_{BW} is obtained as multiplicative aggregation of indicators in different units like number of organisms per m^3 or mL, specific microbes in $CFU/100$ mL, irrespective of their score ranges and distributions. Intercorrelations I_{BW} is expressed as a monotonically increasing continuous variable where log (I_{BW}) follows lognormal distribution for large sample. Value of $I_{BW_{t(t-1)}} > 1$ indicates progress of overall impact of BW-quality in successive time periods. Multiplicative aggregation is preferred for significant reduction of substitutability among indicators, and additional features like time reversal test, easy identification of critical areas and contribution of the indicators, estimation of population parameters, and testing statistical hypothesis.

For a better understanding of the salient features of the proposed indices, along with a comparison of the efficiency of the proposed approach with different existing methods associated with BWTS, future numerical investigations with multiple datasets or simulations may be initiated.

Funding

This work received no external funding.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

No datasets were generated or analyzed in the study.

Conflicts of Interest

The author declares that there is no conflict of interest.

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