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Aggregative Indexes as Tools for Assessing Water Quality in Aquaculture: A Case Study from Nayarit, Mexico

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ABSTRACT

Nayarit, is a leading aquaculture state in Mexico, so evaluating the physicochemical characteristics of the water is essential for monitoring the region's aquaculture systems. For this, the objective was to evaluate the hydrological and ecological suitability of water in shrimp production. Physical and chemical variables (dissolved oxygen, pH, temperature, turbidity, and salinity) were measured at 15 pumping water points during the winter and summer seasons. The Hydrological Aptitude Index (HAI) was calculated weighing the parameters from highest to lowest according to their importance for shrimp development. The ecological suitability was assessed following the guidelines of the Canadian Council of Ministers of the Environment (CCME) for Ecological Criteria for Water Quality compliance. The results indicated that the parameters dissolved oxygen (2.2 to 10.3 mg/L), temperature (24 to 35 °C) and pH (7.3 to 9.1) were identified as significant predictors of water quality according to the Mann-Whitney test ($p < 0.05$). Winter offered the best conditions for shrimp; the HAI classified hydrological suitability from requiring little management to having excellent quality (6 - 10) in 66.7 % of the samples. Although, a lack of correlation with shrimp productivity is shown in the Spearman test ($p > 0.05$). According to CCME, ecological conditions rarely or sometimes deviate from desirable levels (65-94) at 53.3% of sites. This research sets a precedent for the current state of aquaculture tributaries in Nayarit and proposes the use of quality indices as a tool for the comprehensive analysis of water suitability for *Litopenaeus vannamei* production.

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INTRODUCTION

Globally, aquaculture has grown significantly, with an average annual growth rate of 10% (Ponce et al., 2018). Mexico, ranks seventh in the world and second in Latin America (Noguera-Muñoz et al., 2021; Flores-Pérez et al., 2023), where >90 % is produced in the coastline of the Pacific, covering Sinaloa, Sonora, Baja California Sur, and Nayarit (Zavala et al., 2022), represented shrimp production of 273,940 tons in 2024 (CONAPESCA, 2024).

Unfortunately, rapid development has brought consequences such as deterioration of soil and seawater quality (Koçer & Sevgili, 2014; Xu et al., 2020). When physicochemical (pH, temperature, dissolved oxygen, and salinity) quality fluctuates frequently, shrimp become

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susceptible to stress and water-borne diseases such as red color, soft shell, tail rot, black gills, and white spots, among others (Ferreira et al., 2011; Hossain et al., 2013; Ahmed et al., 2019; Ahmed & Turchini, 2021; Millard et al., 2021). Losses attributed to water-acquired diseases generate significant economic losses (USD 15 billion) in aquaculture (Gámez-Bayardo et al., 2021), and the case of Mexico is no different.

San Blas coastline, known in the Nayarit state for being the largest *L. vannamei* (whiteleg shrimp) producer, reflects the environmental footprint in terms of abiotic, biotic, and water deterioration left by anthropological activities (González et al., 2020; Noguera-Muñoz et al., 2021). The CESANAY (State Aquaculture Health Committee of the State of Nayarit) annually reports losses of *L. vannamei* due to waterborne diseases, however, information on quality parameters is not publicly available. A better understanding of quality parameters status of water bodies and shrimp farming ponds can help prevent and solve some of the disease problems faced by shrimp farmers in San Blas (Nájera et al., 2021; CESANAY, 2025).

In aquaculture, it is important to determine the relationship between disease susceptibility and abiotic environmental conditions (Millard et al., 2021). The variability of water quality parameters is a threat to shrimp farming and merits inspection of the influents and effluents of shrimp farms (Ahmed et al., 2019; Ahmed & Turchini, 2021). To assess the water quality of marine aquatic systems, many countries have introduced water quality monitoring schemes and predictor indices for the relevance of animal farming and the risk of environmental damage (Mohanty et al., 2018).

The application of aggregative functions indices allows reporting in a simplified way a water suitability level, considering only the critical environmental variables that affect the quality (Beltrame et al., 2006; Ferreira et al., 2011; Mohanty et al., 2018**;** Jamroen et al., 2023). Subsequently, the Canadian Council of Ministers of the Environment (CCME) compares deviations of the water quality parameters that feed the index against environmental guidelines (CCME, 2017; Lin et al., 2018). The indices contribute to the construction of a comprehensive system of support for decision-making (dos Santos et al., 2008) to improve operational efficiency (Ma et al., 2020). This necessity occurs virtually anywhere shrimp is farmed (González-Huerta et al., 2020).

In Nayarit, due to the lack of existing water quality applications for shrimp production, this research pioneers the development of multivariate indices based on critical water descriptors (dissolved oxygen, pH, temperature, turbidity, and salinity) to identify the most favorable conditions for aquaculture. Specifically, a set of hydrological and ecological criteria was applied to samples distributed between winter and summer to represent the suitability level for *L. vannamei* and the temporal and spatial variations of the San Blas-Chacalilla-Chiripa estuarine complex in Nayarit, Mexico.

MATERIALS AND METHODS

Data collection

The samples were collected from the supply system of 15 production units of *L. vannamei* in the municipality of San Blas, Nayarit, Mexico (Table 1) through targeted sampling of sites identified according to selection criteria. The sites had to be close to the coast and localities and/or economic activities, and easily accessible. A total of 30 samples were prorated 15 in January-March (winter) and 15 in August-September (summer) during 2023. Also, metadata of production (t) and survival (%) of *L. vannamei* during 2023 was provided by CESANAY.

Physicochemical analysis of water

For the physicochemical analysis temperature (T) and dissolved oxygen (DO) were measured with SMART SENSOR/AR8210, pH using the HANNA HI8424, salinity (Sal) with a VSA1T/

Table 1. Location of farms in San Blas, Nayarit, Mexico.

Location	Estuary	Site	Latitude (ºN), Longitude (ºW)
San Blas	San Cristobal	Tsikuri	21.580348º, -105.286359º
Chacalilla	San Cristobal	La Providencia	21.599018º, -105.272304º
Chacalilla	Chacalilla	Gran Nayar	21.614054º, -105.287026º
Chiripa	Papayitos	Camaronai	21.620727º, -105.316175º
Chiripa	La Poma	Venancio Torres	21.624632º,- 105.305837º
Chiripa	Papayitos	Lamosa 3	21.628427º,- 105.341657º
Chiripa	Papayitos	Lamosa 4	21.627143º,- 105.334881º
Chiripa	Papayitos	Callejones	21.621455º,- 105.330929
Chiripa	Papayitos	Isla	21.613304º,- 105.315383º
Chiripa	Papayitos	Plebes	21.606210º,- 105.312713º
Chiripa	Papayitos	Puntilla	21.623487º,-105.322604º
Chiripa	Callejones	Familia	21.629705º,-105.323366º
Chiripa	La Poma	Cocodrila	21.621082º,-105.302625º
Chiripa	Jerónimo	Llorona	21.631937º,-105.310759º
Chiripa	Callejones	Michoacanai	21.643670º,-105.325880º

Table 2. Selected variables suitability estimation for the cultivation of *L. vannamei*.

Weight range	Sal (PSU)	Tb (NTU)	T (°C)	pH	DO (mg/L)
5	30	<10	[25-30]	8	>7
[4,5]	[(20-30)/(30-35)]	[10-20]	[(24-25)/(30-31)]	[(7.5-8)/(8-8.5)]	[6-7]
[3,4]	[(15-20)/(35-40)]	[20-35]	[(23-24)/(31-32)]	[(7-7.5)/(8.5-9)]	[5-6]
[2,3]	[(10-15)/(40-45)]	[35-60]	[(22-23)/(32-33)]	[(6.5-7)/(9-9.5)]	[4-5]
[1,2]	[(5-10)/(45-50)]	[60-100]	[(21-22)/(33-34)]	[(6-6.5)/(9.5-10)]	[3-4]
[0,1]	[(0-5)]	[100-150]	[(20-21)/(34-35)]	[(5.5-6)/(10-10.5)]	[2-3]
Weight	5	4	3	2	1

HAI classes: >8 adequate; 6-8, low restriction; 4-6, medium restriction; 2-4, high restriction; < 2 inadequate.

PRO1001436, and turbidity (Tb) using the HACH 2100. Ecological Criteria for Water Quality guideline (DOF 1989) was used to verify the compliance of the variables.

Hydrological Aptitude Index (HAI)

To assess the suitability classes (Table 2) of pond water quality based on the most critical parameters for *L. vannamei* culture (Sal, Tb, T, pH and DO) proposed, HAI was estimated as described by Mohanty et al. (2018) to adjust the weight range to local environmental conditions, and by Jamroen et al. (2023) who included water temperature in the water quality calculation because of its influence on the metabolism of crustaceans. Weights (β) from 1 to 5, and the ranges (V) from 0 to 5, were assigned to the variables (Table 2). Then, they were multiplied to obtain the value of the variable (W) Eq. (1). Finally, score (S) was obtained by multiplying the five variables Eq. (2).

$$W=\beta \times V \quad (1)$$

$$S= W_{Sal} \times W_{Tb} \times W_{T} \times W_{pH} \times W_{DO} \quad (2)$$

Applying Eqs. (1) and (2), the S can vary between 0.0 and 18,750. To facilitate understanding of the index, these values were recalculated to values from 0 to 10 as follows (Jamroen et al. 2023):

$$HAI = 0.7677 \times (PF)\ 0.2 \quad (3)$$

As suggested by Jamroen et al. (2023), the HAI values are grouped into 5 classes of suitability for shrimp farming (Table 2).

CCME Index

After defining compliance parameters according to the provided guidelines, due to its flexibility regarding the type and number of water quality parameters to be analyzed and the application period, the CCME index was developed to calculate each of the three factors that comprise it. F1 (Scope) represents the percentage of the number of parameters that do not comply with the guidelines at least once during the period considered, about the total number of parameters measured:

$$F1 = \left(\frac{\text{Number of Failed Parameters}}{\text{Total Número of parameters}} \right) x100 \quad (4)$$

F2 (Frequency) represents the percentage of individual tests that do not meet the guidelines:

$$F2 = \left(\frac{\text{Number of failed test}}{\text{Total Number of test}} \right) x100 \quad (5)$$

F3 (Amplitude) represents the amount by which failed test values do not meet the guidelines and is calculated in three steps:

$$\text{excursión} = \left(\frac{\text{Objetive}}{\text{Value of failed test}} \right) - 1 \quad (6)$$

$$\text{nse} = \frac{\sum_{i=1}^{n} \text{excursión}\, i}{\text{No. of test}} \quad (7)$$

$$F3 = \frac{\text{nse}}{0.01\text{nse} + 0.01} \quad (8)$$

Finally, the CCME index is calculated as follows:

CCME=100(√F12 + F22 + F32/1.732) (9)

CCME values are grouped into 5 water quality levels (Table 3).

Data analysis

Non-parametric Kruskal-Wallis tests were used to compare the water profiles between the sampled sites and Mann-Whitney test to determine significant seasonal variation. The parameters were grouped using a multivariate cluster analysis to classify the sites according to their similarity. The Spearman test is proposed to determine productivity correlation betwen the indices with the production (t) and survival (%) data of *L. vannamei*. Minitab (vs.18.1.0) was used, considering a p-value < 0.05 as significant.

RESULTS AND DISCUSSION

Seasonal Variation

The results of the physicochemical variables (salinity, turbidity, temperature, pH and DO) measured and their medians are shown in Fig. 1. The trend of the profiles of the study sites between the winter and summer seasons can be described. The results of the evaluation of water

Table 3. Classification of the set of ranges for the selected variables in CCME.

Quality	Value	Description
Excellent	95-100	Absence of threat or deterioration; very close to pristine levels.
Good	80-94	Minor degree of threat or deterioration; rarely deviate from desirable levels.
Reasonable	65-79	Occasionally threatened or deteriorated; sometimes deviate from desirable levels.
Marginal	45-64	Frequently threatened or deteriorated; often deviate from natural or desirable levels.
Poor	0-44	It is almost always threatened or deteriorated; deviate from desirable levels.

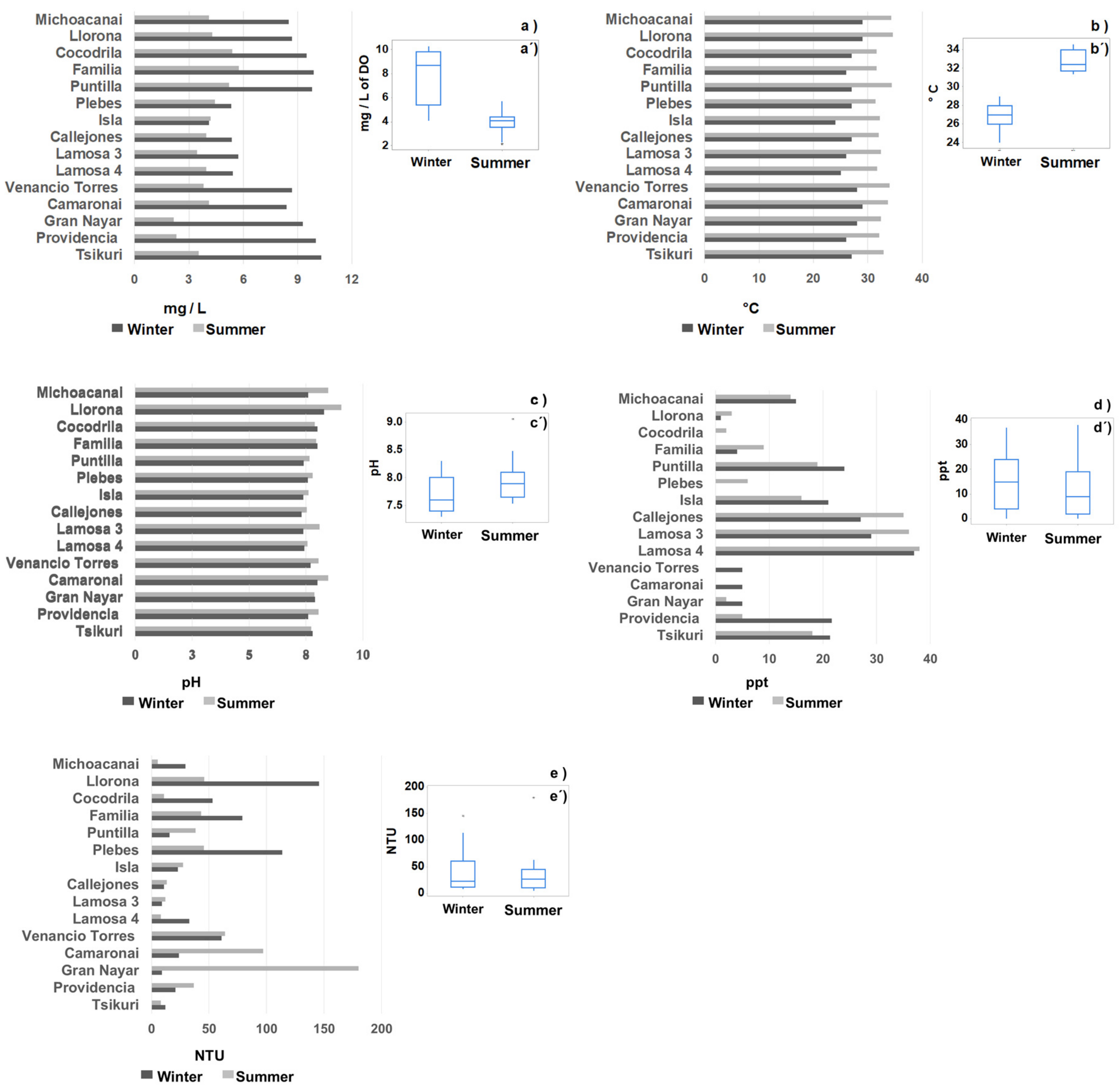

Fig. 1. Variability of DO (a), T (b), pH (c), Sal (d), and Tb (e) parameters among winter and summer seasons. In a′–g′, median values are reported in boxplots. (*) represents an outlier value.

samples from the supply channels show a similar behavior to the San Blas-Chacalilla-Chiripa estuarine complex pursuant to Kruskal-Wallis test ($p > 0.05$). All p-values were found to be non-significant, salinity (0.476), turbidity (0.465), temperature (0.476), pH (0.467) and DO (0.466).

Briefly, DO values ranged from 2.2 to 10.3 mg/L, temperature from 24 to 35 °C, pH from 7.3 to 9.1, salinity from 0 to 38 ppt, and turbidity from 5.4 to 180 NTU (Table 4). The Mann-Whitney test revealed that DO ($p = 0.000$), temperature ($p = 0.000$) and pH ($p = 0.040$) presented

Table 4. Descriptive statistics of physicochemical parameters measured in water samples by production season.

Paramete r [Unit]	Winter				Summer				
	Minimum	**Mean**	**Maximum**	**Median**	**Minimum**	**Mean**	**Maximum**	**Median**	**p value**
DO [mg/L]	4.12	7.94	10.30	8.70	2.15	4.05	5.74	4.10	0.000
T [ºC]	24	27	29	27	31	33	35	32	0.000
pH	7.3	7.7	8.3	7.6	7.5	8.0	9.1	7.9	0.040
Sal [PSU]	0.00	14.40	37.00	15.00	0.00	13.53	38.00	9.00	0.756
Tb [NTU]	9.00	42.60	145.50	23.70	5.40	36.60	180.00	27.30	0.590

significant variations among seasons. Salinity (p = 0.756) and turbidity (p = 0.590) were ruled out as seasonal predictors (Table 4).

The spatial relationship of environmental variables in the estuarine complex shows comparable anthropogenic patterns occurring near the region and flowing toward the coast. Aquaculture and land-use changes in the coastal plain are potential anthropogenic processes in Nayarit that have become a constant in the natural environment and, in many cases, describe local climate changes, variations in the hydrological cycle, and the nature of the coastal environment (Nájera et al., 2021; Noguera-Muñoz et al., 2021). The significant influence of climate variability on the quality and availability of surface water impacts aquaculture operations and requires robust monitoring and statistical analysis frameworks (Al-humairi et al., 2023).

The changes inherent in temporal dynamics govern the water behavior of the ecosystem. A significant level indicates a correlation between water quality parameters in the rainy and dry seasons, which can oscillate if there are fluctuations in the same variables (Ariadi et al., 2023). The variation and perturbation of the parameters in these samples infers the influence on the survival of *L. vannamei*.

Regulatory compliance

According to the Ecological Criteria for Water Quality guideline, 86.7 % (13/15) and 93.33% (14/15) of the water samples evaluated in winter and summer exceed the salinity limit, 27 ppt and 35 ppt, respectively (Fig. 2). Also, 73.3 % (11/15) of the sites analyzed in winter and 60.0 % (9/15) of the samples in summer exceeded the maximum turbidity limit (15 NTU) (Fig. 2). For DO compliance (6 mg/L), 33.7 % (5/15) and none of the sites evaluated in winter and summer complied with the limit, respectively (Fig. 2). Likewise, 86.7 % (13/15) of the samples analyzed in winter and none of the samples in summer remained within the permissible temperature range (26 - 30 °C) (Fig. 2). Finally, 33.3 % (5/15) and 6.7 % (1/15) of the samples analyzed in winter and summer exceeded the pH reference range (75-8.8), respectively (Fig. 2).

Two main groups of environmental profiles stand out with high similarity in winter (10 sites) (a) and in summer (14 sites) (b). The colors red (does not comply) and yellow (yes complies) indicate the agreement with the reference standards. Limits are specified for each parameter. The tons (t) harvested and the % survival were provided by the Nayarit State Aquaculture Health Committee (CESANAY).

The multivariate analysis of the physicochemical variables discriminated two groups (71.18 %) in winter and two groups (61.62 %) in summer (Fig. 2). Regulatory compliance warns about the relevance of the use of the water resource belonging to the municipality of San Blas in shrimp production (Fig. 2). The analysis reveals that the non-optimal parameter profile was defined by DO and temperature in summer. This means that the emergence of out-of-specification parameters could be a consequence of natural conditions.

The sensitivity of the crustacean to oxygen variation is directly related to salinity and temperature (Ariadi et al., 2019). High temperatures increase appetite, accelerating the growth rate and consumption of available oxygen, and therefore, a drop in ATP levels and possible

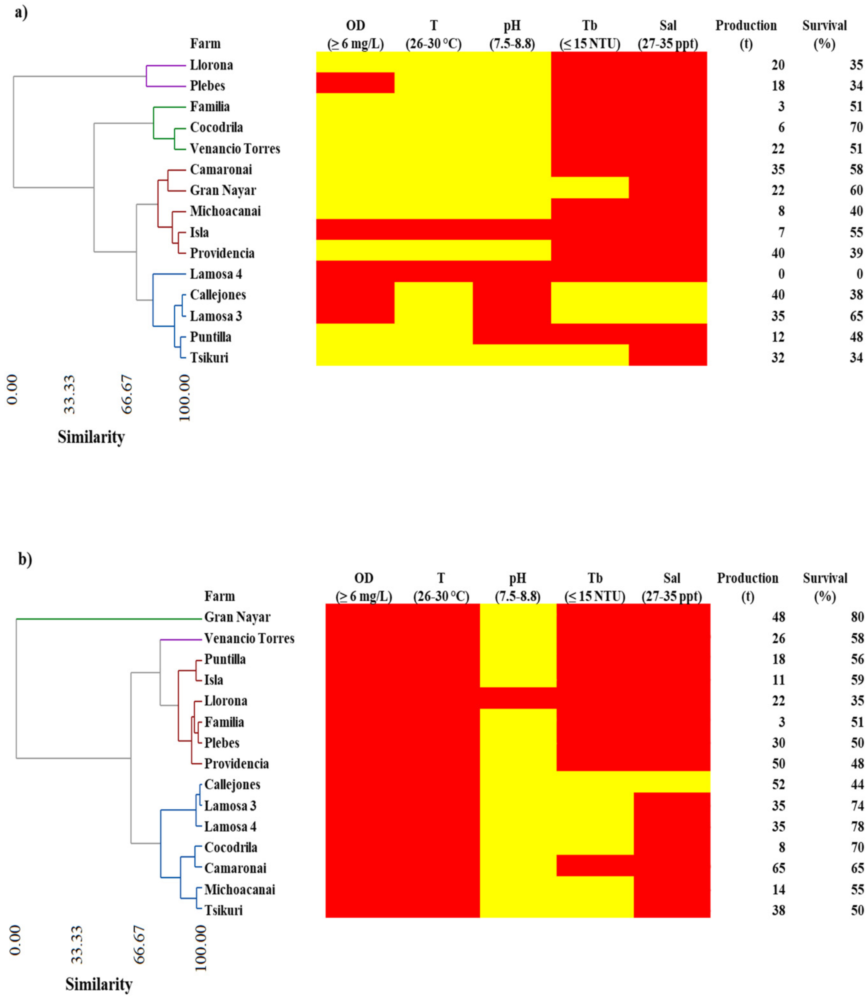

Fig. 2. Regulatory compliance and similarity of environmental variable profiles.

damage to physiological and biochemical processes (Lobato et al., 2020). The decrease in available oxygen in the water has been described as causing an imbalance in the system as crustaceans are often unable to reach the oxygen levels required for metabolism and respiration (Meidiana et al., 2023). In contrast, other authors report a functional DO concentration for *L. vannamei* of 3.5 mg/L (Lien et al., 2020), and even adaptability to 3 mg/L (Ferreira et al., 2011; Lobato et al., 2020). Different rates of oxygen consumption in the metabolic system at each stage of organismal growth are predicted as a form of physiological and behavioral adaptation responses (Wafi et al., 2021).

Temperature is the abiotic factor that responds directly to seasonal changes and is one of the notable external agents that can influence the survival of crustaceans as they are subject to thermal variations in the habitat with a direct effect on their metabolic pathways (Rahman et al., 2021; Jamroen et al., 2023).

In the aquatic ecosystem, temperature also can mediate the stability of other variables such as pH. This synergy is transcendent in the nutrition of *L. vannamei* because it has been confirmed that in summer consistently high levels of temperatures and pH improve the solubility of nutrients (Ariadi et al., 2023), which is relevant for our research. The permissible pH levels, established by the Ecological Water Quality Criteria (DOF, 1989), in waters for aquaculture are 7.5–8.8. In our study, although the values were not met in 33.33% of the samples in winter and only one in the summer, pH was the most consistent variable and within the safe limit with medians of 7.6 and 7.9, in winter and summer, in the order given.

Thermal variability has a direct and indirect synergistic and intrinsic effect on shrimp survival. However, *L. vannamei* has processes at the protein level such as the Unfolded Protein Response that give it the potential to adapt to a certain level of temperature fluctuation through self-regulation, and to repair itself since it has been shown that damage at the histopathological level derived from a drop in temperature (13°C) have been remitted during the process of returning to optimal levels (28°C) (Wang et al., 2019).

On the other hand, although the salinity and turbidity variables did not present statistical significance as references for temporal changes, they also play an important role in the survival of the crustacean. Regarding salinity, the variability observed in the estuarine complex can cause hypertonic alterations in the osmoregulatory system of the shrimp. It has been stipulated that low concentration activates energy expenditure in response to osmotic homeostasis (Ariadi et al., 2019). However, being a euryhaline species, *L. vannamei* tolerates a wide range of salinity (0.5 - 40 ppt) (Lobato et al., 2020). It has been shown that proper acclimatization in low and even no ionic conditions at an early stage of cultivation can mitigate the negative effect on its survival (Rahi et al., 2021). Studies on the response to low salinity at transcriptomic and proteomic levels exposed the crucial physiological processes in the metabolic pathways involved in the rapid adaptive and acute stimulation response to stress (Lu et al., 2023). The ability to go from sublethal low salinity to acute extremely low salinity demonstrates a remarkable ability of *L. vannamei* to adapt and survive.

In the case of turbidity, the levels found in the area in question are presumed to be derived from suspended solids and phytoplankton, which in turn causes obstruction of sunlight in the water column, preventing the photosynthetic process and favoring microbial proliferation (Lien et al., 2020; Warren et al., 2021). Such a condition can negatively affect reproduction and osmoregulation in *L. vannamei* by reducing the rate of oxygen exchange and increasing water temperature. In addition to the fact that particles with a high degree of turbidity cause gill blockage as a compensatory reaction to the alteration of the osmotic and ionic balance, concluding that water turbidity can cause immunological and metabolic changes in shrimp (Kathyayani et al., 2019). The implication of turbidity in the survival of the organism has been previously proven by Bommireddy et al. (2020), who observed a significant inverse correlation between productivity and turbidity. In contrast, Kathyayani et al. (2019) propose values <30 NTU as suitable for cultivation and point to phytoplankton as a desirable form of turbidity by inducing the production of DO and the elimination of potentially toxic compounds such as ammonia, and therefore improving water conditions of the culture tanks.

Although it is essential to monitor those ecosystem factors that are most critical in the shrimp farming system, which can be harmful if they are not efficiently monitored and controlled, it is impractical to assert the success of a production cycle based on a parameter. In this way, water quality indices are a support tool that integrates critical parameters for the survival of *L. vannamei* into a single number that assigns a level of suitability for water use (from suitable to unsuitable) (Beltrame et al., 2006; Ferreira et al., 2011; Carbajal-Hernández et al., 2013; Mohanty et al., 2018; Jamroen et al., 2023), and useful in the selection of potentially productive sites and for making operational decisions (dos Santos et al., 2008).

Index Performance

Using HAI, the majority (66.6 %) of the samples showed hydrological quality suitable for use in *L. vannamei* culture ponds during the winter period: “adequate” (5/15, 33.3%) and “low restriction” (5/15, 33.3%). Only Venancio Torres was classified with a quality with “medium restriction” (4 - 6) in 1/15 (6.66%), while the Plebes, Familia, Cocodrila and Llorona farms presented an “inadequate” quality (0 - 2) (26.66%) (Fig. 3). These farms are provided by the Papayitos, Callejones, La Poma and Jerónimo estuaries located in the vicinity of the town of La

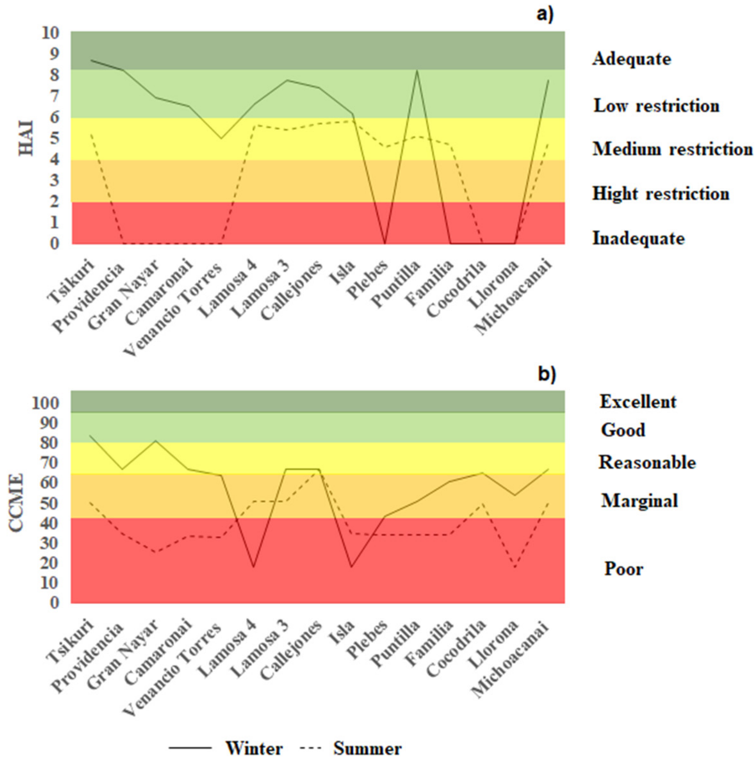

Fig. 3. Hydrological (a) and ecological (b) suitability of pumping canal water for *L. vannamei* cultivation during winter and summer.

Chiripa. About summer, hydrological suitability alternated between "low restriction" in 3/15 (20%), with "medium restriction" in 6/15 (40%) and "inadequate" in 6/15 (40%) of the places. The HAI of 0 corresponded to the water that supplies the production units of Providencia, Gran Nayar, Camaronai, Venancio Torres, Cocodrila and Llorona, supplied by San Cristóbal, Cahacalilla, Papayitos, La Poma and Jerónimo.

For its part, CCME summarizes the ecological character fluctuating between classes below "excellent" (Fig. 3). This index similarly differentiated better water quality throughout most of the winter growing period (Fig. 3). Quality levels ranged from "good" (80-94) in 2/15 (13.33%) of the sites, "reasonable" (65-79) in 6/15 (40%) and "marginal" (45-64) in 4/15 (26.66 %). While Lamosa 4, Isla and Plebes were classified as "poor" (0-44) quality, supplied by water from the Papayitos estuary located in the town of La Chiripa. In the summer season, most of the parameters were found within the ranges of less suitable in the ecological context for shrimp, with the "poor" category predominating (9/15) (60 %) and "marginal" 5/15 (33.33 %). At this time of year, the estuarine complex that supplies the monitored area showed compromised water quality, except for Callejones estuary, which was classified as "reasonable."

In our case study, the HAI and CCME models were established as descriptors of suitability quality for shrimp farming, seasonality as an environmental load factor, and sampling points as water distribution channels to stipulate their relationship with production from *L. vannamei*. The estimated ecological level is due to the degree of compliance with the recommended standards. In the summer, non-compliance profiles of 4-5 of the parameters were identified in 9 of the scenarios (Fig. 2) leading to the low value of water quality, which is essentially due to the low concentration of salinity and DO and to the excess of temperature and turbidity.

In the literature, different works that used the CCME index to study the behavior of the ecological trend in various production scenarios of *L. vannamei* in northwestern Mexico reported coincidences with our observations. Similar behavior can be explained under the space-time context; the observations were recorded in the summer and in similar environmental conditions locations. These studies highlight the effect of seasonal change on seasonally dependent predictors, such as DO and temperature, and the influence of climatic variability on water quality and availability for aquaculture (Carbajal-Hernández et al., 2013; Carbajal-Hernández and Sánchez-Fernández, 2017). The inclusion of different parameters and the variability in the consideration of their limits, imposed by local and/or international legislation, gives this equation adaptation and persistence as a descriptor of the quality of marine water bodies for white shrimp farming (Lin et al., 2018; Longhini et al., 2022; dos Santos Mendonça et al., 2022). CCME index is based on calculating the frequency of the parameter values that are outside of optimal, compensating those low or high concentrations and therefore influencing the final score when the non-critical are evaluated as critical (Carbajal-Hernández et al., 2013). In this case, the analysis is compensated with a complementary discussion focused on suitability indicators for shrimp survival and growth.

In this context, the application of HAI also revealed a lower hydrological suitability for the development of white shrimp *L. Vannamei* culture during the summer. Aptitude hydrological focuses on 60% as "medium restriction" and 40% as "inadequate". The results indicate that in summer water management must be intensified because it is not the best season for water pumping. The unacceptability of water is defined especially by salinity, because its concentration is lower than the minimum required in 93.33% of the samples and because of its critical and direct influence on shrimp production (Table 2) (Jamroen et al., 2023). The nature of the seawater in the municipality of San Blas is conditioned by the contribution of fresh water from the mouth of the Rio Grande de Santiago and by the dilution effect of precipitation during summer rains, providing variability in the concentration of salinity (CONAGUA, 2018).

The variability between the distribution of hydrological suitability classes (Fig. 3) is robustly influenced by the methodology adopted. The HAI is a weighting method that has been deliberately harsh to recognize polluted areas as well as the natural characteristics of the coastal system (Beltrame et al., 2006). The restriction on the suitability of water use is based on the weights assigned to the variables, their ranges in the methodology used and the participation of biogeochemical processes (Ferreira et al., 2011).

The hierarchization of the estuarine complex, according to the restriction that the sum of selected descriptors offers to the cultivation of *L. vannamei* in Nayarit, represents an indicator of areas subject to variability in their hydrographic characteristics. The discrepancy among the indices discussed here and those reported in the literature lies in the type of procedure applied to evaluate specific water bodies. The development of the Analytical Hierarchy Process has evolved among authors to provide solutions to the biogeochemical differences of aquatic ecosystems and contribute to shrimp farming (Mohanty et al., 2018; Jamroen et al., 2023).

The proposed indices have been developed to be adaptable, easy to understand and implement in any aquaculture environment. New avenues for advanced remote sensing techniques, such as those leveraging Sentinel-2 imagery and the NDWI spectral index, applying automated, highly accurate, and computationally efficient in-situ monitoring, have proven effective at large water body scales, supporting the need for integrative approaches to aquaculture management (Abrahim et al., 2025; Mahmood et al., 2025).

The practical implications of the indices for shrimp production in Nayarit include aspects such as comprehensive local monitoring tools and decision support to improve site selection, productivity, and sustainability. Furthermore, government agencies can design evidence-based zoning and standards that reflect the unique variability of Nayarit's and Mexico's estuarine systems, thereby promoting aquaculture growth and environmental protection.

Implications for Management

Regarding the quality-productivity analysis, it was found that winter showed more appropriate ecological conditions, between “good” and “reasonable” in 53.3 % of the sites, for regulatory compliance of water quality parameters within the optimal range for the cultivation of *L. vannamei*, and a hydrological suitability categorized as “adequate” and “low restriction” in 66.7 % of the samples indicating better quality for use (Fig. 3).

While the productivity data of the region (CESANAY, 2023) showed that the summer harvest presented higher yields (survival of 58% and 455 t harvested) (Fig. 2). In Fig. 4, the distribution of suitability classes obtained by the indices proposed in this case study does not agree with the characterization of the productive potential of crop farms. In the same sense, the Spearman coefficient revalidated the lack of correlation ($p > 0.05$), since the farms with the least variation in the production rate are not precisely located in the areas with low water quality restriction in both production cycles. In parallel, the evaluation of the correlation of productivity with environmental parameters showed a negative association ($p < 0.05$) of *L. vannamei* production with turbidity (-0.357, $p = 0.039$) and DO 0.736, $p = 0.002$), in winter and summer, respectively.

Our results are consistent with what was reported by Ferreira et al. (2011) point out that winter provides better conditions for the health of the stocked shrimp and attribute the success to the prevention of diseases (Madusari et al., 2022). The growth of the aquaculture industry is hampered by unpredictable mortalities, many of which are caused by pathogenic microorganisms (*Vibrio*, *Streptococcus* sp., *Nautella italica*, and *Pseudoalteromonas piscicida*) pose threats to crustaceans (Chen et al., 2019).

A good water quality in winter can ensures a healthy and consistent start for juveniles, and also enhances their size and health into summer, when temperature and photoperiod conditions dramatically increase growth rates. This combination improves the immune status and ensure higher stocking density without compromising survival as a basis for significantly higher productivity in the warmer months (Ariadi et al., 2023), like is shown in the Fig. 4 dynamic.

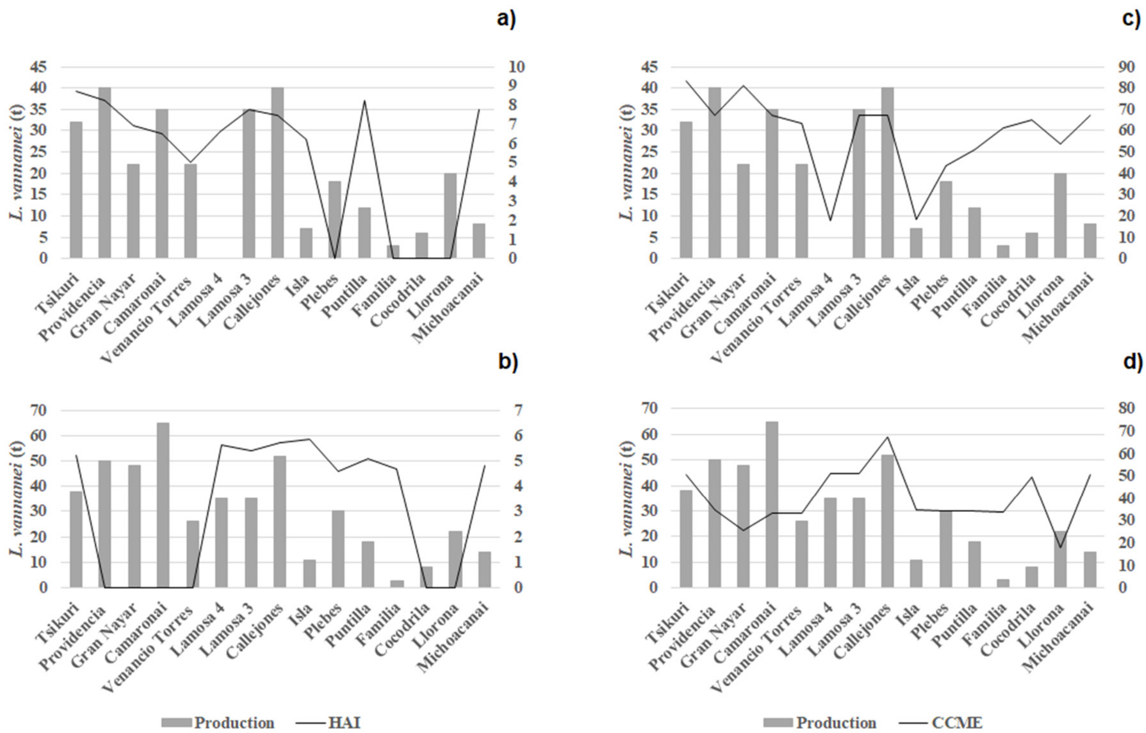

Fig. 4. Relationship between the hydrological (a and b) and ecological (c and d) water quality and shrimp productivity expressed in tons (t) during the winter (a and c) and summer (b and d) seasons.

The dynamics of abiotic factors have a close relationship and indirect influence on the growth rate and productive capacity of *L. vannamei* (Chen et al., 2019). In our findings, the correlation of DO is particularly evident, since its autochthonous dynamics show a downward trend when the production cycle is greater in the northwest Pacific (Fig. 2). Even though, concentrations greater than 5 mg/L in water have been established as optimal for the survival and performance of the crustacean (Mohanty et al., 2018); Ariadi et al., (2019) demonstrated the low influence (4.4%) on its growth, given that it has a greater involvement in its physiological response than in its reproductive rate, while nutrients have a greater influence on the growth rate (75%) and the increase in temperature, which intensifies the shrimp's metabolic rate, resulting in much more efficient feed intake and conversion to biomass in summer (Al-Masqari et al., 2022).

The optimal development of crops includes different physiological and environmental factors. As an intrinsic factor, the intricate metabolic processes that *L. vannamei* possesses give the species adaptability, rapid growth and greater resistance to diseases. Which makes this a cultivable and reproducible species at a higher density under adversity (Yang et al., 2021). As extrinsic factors, Madusari et al. (2022) emphasize that the choice of feeding rate has a very significant effect on the weight and productivity rate. Cross-cuttingly, water management is a notable factor in productivity, since it is an indicator with a high requirement in water exchange, which, while addressing sustainability, provides greater biosecurity, minimizes the organic, nutrient and toxic metabolites, induces molting and promotes growth, and therefore survival rate and yield (Mohanty et al., 2018).

In the face of any adversity, Nayarit producers have managed to be leaders in the shrimp sector. This is possible thanks to the correct feeding rate, and the timely use of techniques such as Good Aquaculture Production Practices to maintain the health of the crops (González et al., 2020). Unquestionably, and despite the variability of the nature of the San Blas-Chacalilla-Chiripa estuarine complex, the production of white shrimp *L. vannamei* has high economic potential in the municipality of San Blas, and accounts for approximately 70% of the gross annual production of marine species cultivation in Nayarit (Ponce et al., 2018). Production in 2019 in the state was 11,740 t, which represents 8% of the total production of this species in Mexico (Noguera-Muñoz et al., 2021). The entity stands out nationally in the extraction and cultivation of Pacific white shrimp, forming part of the most important mono-specific fishery, whose production is widely marketed in the national and international market (Rodríguez-Camacho et al., 2014).

Finally, assess seasonal patterns and balance the effects of extreme events with long-term monitoring is considerable (Longhini et al., 2022). As well as the inclusion of physicochemical, microbiological, oceanographic and hydrochemical descriptor and shrimp variables (weight gain, specific growth rate, feed conversion rate and survival rate) to complement the analysis panel. The pathogen, environmental and nutritional challenges, from a metabolic perspective, help increase the reproduction and growth of organisms cultivated in Nayarit.

CONCLUSION

According to the values of the quality parameters measured in this case study, the water for aquaculture uses from San Blas, Chacalilla and Chiripa in the state of Nayarit presents similar anthropic management. Environmental variables were identified as factors inducing ecological stress for *L. vannamei*, particularly in the summer, and seasonal dynamics as subject to the temporal patterns of the ecosystem. Greater attention is recommended during the period of extreme hydrochemical conditions.

The coexistence of "adecuated-good" composite indices with sub-optimal individual variables reflects both the mathematical design of water-quality scores and the *L. vannamei* specific sensitivity to different environmental factors. Water quality indices are useful for identifying trends of improvement or deterioration before severe biological effects are detected. Even expanding the inspection parameter panel of CCME and standardizing HAI according to needs, purposes and/or other characteristics of the Pacific water ecosystem would address a more effective interpretation of the quality of the resource and promotes comparability across studies.

Both in terms of suitability and of ecological behavior of water, the estuarine complex offers a better characterization of the potential use of water by *L. vannamei* farms in winter. The improved summer production in San Blas is attributed to variables related to the crustacean's metabolism and growth, such as temperature. Furthermore, periodically validating composite indices against direct biological endpoints (mortality rates, immunological biomarkers) can align index thresholds with the health of the organism and not just with numerical targets.

The use of mathematical models is a profitable way, since the water parameters are measurable *in situ* and are data that are easy and quick to interpret, useful in the selection of potential sites and in the sustainable development of *L. vannamei* when associated with other descriptors relevant to the environment. This study provides a first scenario of the relevance of water for aquaculture use in Nayarit and the basis for optimizing performance in shrimp farming, while expertise in water management could be adapted to minimize operating costs.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest for this article.

DATA AVAILABILITY STATEMENT

The authors confirm that data supporting the findings of this study are available in the article.

AUTHORS CONTRIBUTION

All authors contributed to the conception and design of the study. K.S.A.N Development, conceptualization and writing G.M.C.R. Development, conceptualization and organization M.J.E. Development, conceptualization F.J.V.G. Development, conceptualization.

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