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An Integrated Approach for Evaluating Water Quality between 2007–2015 in Santa Cruz Island in the Galapagos Archipelago

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Abstract: Water quality in Galápagos has been deteriorating by increased human impacts over the past few decades. Water quality is a key environmental component and issue in need to be evaluated in the Pelican Bay Watershed, the biggest urban and economic development of Santa Cruz Island, for better management and regulation of water resources. This study assesses coastal and ground water bodies of Pelican Bay by employing a 9-year dataset obtained during a local water quality monitoring program conducted by the Galápagos National Park. Physical-chemical and microbial parameters were evaluated with respect to national and international water quality standards. A statistical integrated approach was performed to calculate environmental background levels of water quality parameters and to explore their seasonal and spatial variation. In addition, a sensitivity analysis was conducted to evaluate the impact of changes in tourism and residents in San Cruz Island in the degradation of water sources. Results highlighted are: (a) water is not suitable for drinking and domestic use at some inland sites; (b) saline water is used for irrigation in the highlands; (c) the presence of parameters of concern at coastal sites represent a risk for human and ecosystem health; (d) background levels may serve for defining site-specific limits to control water quality, and; (e) the influence of population change on water quality conditions varied at each site with a higher effect at coastal sites relatively to inland sites. This study provided valuable information of the water quality status in Santa Cruz Island and can serve as a baseline for effective water management and control of pollution.

Keywords: water quality; spatial and seasonal variability; background levels; coastal waters; groundwater; water uses; Galapagos

1. Introduction

Growing water quality impairment represents a global scale problem threatening human development and ecosystem integrity. Alterations of water can pose a threat to public health and affect human access to safe water for drinking and domestic purposes, food production, and recreation [1]. In aquatic ecosystems, poor water quality can lead to detrimental effects such as the increase in algal blooms, aquatic species mortality, increase in fish disease, among others [2,3]. Within the Galapagos Islands, human activities have contributed to major alterations in coastal and ground water quality [4–6], resulting in public health problems such as a high incidence of respiratory and gastrointestinal parasitic infection in residents and tourists [4]. In addition, as observed in other parts of the world, poor water quality can be impaired further by natural-climate driven processes [7–10]. This study seeks to evaluate coastal and ground water quality on the Pelican Bay watershed in Santa Cruz Island to gain a better understanding of the current status of water quality along with seasonal and spatial variations.

Increasing permanent human population and tourism in the Galapagos exerts a significant pressure over the fragile ecosystem of the islands and enhances water degradation [5,11]. Main groundwater sources for Santa Cruz Island are contaminated due to several factors such as the location of the basal aquifer beneath dense urban settlements, the lack of effective wastewater treatment plants, and seawater intrusion [12]. In fact, seawater may be migrating inland due to overexploitation of the aquifer [5,13,14]. In particular, malfunctioning septic tanks are responsible for most of the fecal contamination in the island [4]. Main sources of fecal contamination for coastal marine waters in Puerto Ayora, the main urban area on Santa Cruz Island, include: land runoff of sewage waters during wet weather, submarine and boat discharges, and overland pipe sewage effluents [5]. Additionally, high levels of *E. coli* in the coastal waters seem to be related to groundwater leachate flowing seaward during low tide [15]. Yet, more specific monitoring is needed to understand the complete picture of potential water impairment in the Galapagos Islands and to identify the implications of basin sensitivity on water quality to increases in tourism and residents.

Besides the anthropogenic factors, water quality can be directly affected by several climate-related mechanisms in both the short and long term. For example, water quality variation in the Huai River Basin in China is significantly correlated with precipitation and strongly affected by air temperature [7]. Other studies [8,9] found that intense rainfalls and runoff make pathogens more susceptible to rise in concentration in superficial waters. Moreover, water temperature increases reduce gases solubility and favors many physical-chemical processes such as dissolution, solubilization, complexation, nitrification, degradation, and evaporation occurring in water bodies, leading to elevated levels of dissolved substances found in temperate and tropical regions [10]. Additionally, mineralization increases leads to a greater release of nitrogen, phosphorus, and carbon from soil that is then transported by runoff [16]. Warmer temperatures may also impact water bodies with long residence times, which would imply eutrophication problems in the future [16]. Regarding precipitation, literature studies have demonstrated that pollutant transport is enhanced by heavy rainfall events, which increase runoff and erosion, and in many cases cause higher levels of turbidity and organic matter [10]. Therefore, similar climate-related processes as those described herein may affect water quality in the Galapagos Islands. Although, other factors, such as the direction of the groundwater flow, the distance from the sea, and changes in altitude, have been observed to influence changes in water temperature, pH, conductivity, and dissolved oxygen (DO) in Santa Cruz Island [13], there is still the need to investigate water quality variability due to seasonal and natural processes in the Galapagos.

Determining environmental background levels constitutes a helpful comparative tool that can be utilized to define thresholds values for specific water bodies [17,18] and defines if water characteristics are influenced by either natural processes or human activities. Background concentration is defined as "a concentration of a substance in a particular environment that is indicative of minimal influence by human (anthropogenic) sources" [19]. Therefore, the environmental background levels can reveal natural conditions unaffected by anthropogenic influence [17]; thus, it enables us to distinguish values of a particular parameter that are product of natural processes from anthropogenic impacts [20–22]. Environmental background levels and the upper limit background levels (or thresholds) have been established worldwide for many waterbodies [17,22]. However, the application of large-scale background values to evaluate local status of water quality can lead to misunderstandings because local background is constrained by local conditions [17,22] such as water–rock interactions, chemical and biological processes, residence time of water, recharge inputs and transport processes [18,21]. For that reason, statistical methods are preferred for the calculation of local background levels.

This study evaluates coastal and ground water status in Pelican Bay, a human-influenced watershed in Santa Cruz Island, using a 9-year (2007–2015) dataset obtained during a local water quality monitoring program conducted by the Galápagos National Park. Physical-chemical and microbiological parameters were used to assess water quality and its suitability for designated purposes at each study site, such as potable water, irrigation and/or recreation based on national and international guidelines. Additionally, environmental background levels were calculated to reveal natural conditions unaffected by anthropogenic contributions within the 9-year study period. To evaluate whether or not changes in tourism and residents are responsible for degradation of the water sources between 2007 and 2015, a sensitivity analysis was conducted. Finally parameters were analyzed to describe their seasonal and spatial variations.

2. Materials and Methods

2.1. Study Area

Water quality parameters at seven sites located in Santa Cruz Island in the Galápagos Archipelago at the equator in the Eastern Pacific Ocean, about 1000 km off the coast of Ecuador, were analyzed in this study. The sites were classified into two groups (Figure 1): (a) Inland sites that measured groundwater in the aquifer: Pozo Profundo (I1), INGALA (I2), Misión San Francisco (I3); and (b) coastal sites: Las Ninfas Lagoon (C1), Academy Bay in (C2), Academy Bay out (C3), and Muelle de los Pescadores (C4). All sites are located within Pelican Bay watershed in Santa Cruz Island. This watershed occupies an area of 43 km^2 including the concentration of the main population and economic development of the island [23]. Water quantity is an issue in this watershed due to the demand for an extensive agricultural area (irrigation and cattle) that occupies 22.5 km^2, and for municipal and domestic supply for the two main towns, Puerto Ayora and Bellavista [23]. In addition, water quality at the study sites, as noted above, is subject to perturbations associated with human activities.

Inland sites (Figure 1) provide access to the basal aquifer water of Santa Cruz, which consists of brackish water resulting from seawater laterally intruding the highly pervious fractured basalt, at least 9 km inland [14]. Water is extracted for different purposes from this aquifer. For example, site I1 is a well built on the area of agricultural lands at 4.7 km from the sea and 157 m.a.s.l. The well has been operated since 2002 by Bellavista municipality, supplying water to the local population of approximately 1721 inhabitants [13]. Water from this source is considered safe for domestic use since no coliform contamination has been detected yet; however, high contamination risk is present due to its proximity to the main road, urban settlements and saline intrusion [23]. Site I2 corresponds to a crevice located in Puerto Ayora's periphery at 1.1 km from the sea and 23 m.a.s.l., and it is surrounded by urban cover and mixed vegetation. It was tapped in the 1980s and provided water for drinking and domestic use to Puerto Ayora until the detection of *E. coli* and other coliforms determined in 2011 [4,14]. Currently, its use is limited to supply water for irrigation and cleaning purposes [13] while it is facing risk of an increase of fecal coliform contamination [24]. Finally, I3 is a crevice within Puerto Ayora urban area, at 0.5 km from the sea and 20 m.a.s.l. Its water was distributed through the municipal water supply and designated for private desalinization until its closure in 2011 due to the presence of extremely high levels of *E. coli* and total coliforms [4,12,13]. Despite that inland sites are located at different elevations, extracted and sampled water belong to the same basal aquifer whose water level is virtually the same as sea level [25].

Coastal sites are located within Puerto Ayora's coastline (Figure 1). Site C1 consists in a small semi-enclosed basin with brackish waters that, due to its salinity and tidal influence it approximates to an estuary. This place was a popular swimming spot for tourists and residents until signs of human fecal contamination were detected [26] which in part was due to an inadequate management of stormwater runoff in the surrounding area [5]. Nowadays swimming and other recreational activities are prohibited since they represent a high potential risk of waterborne disease incidence [26]. Moving seaward from C1 are sites corresponding to Academy bay, a narrow and long indentation of Puerto Ayora' shoreline, where C2 covers the enclosed water and C3 the outlet. On the other hand, C4 site is in the southeast bay and represents the last point of freshwater outflow to the sea. Both, C1 and C4, host surrounding mangroves, though their ecological integrity was disturbed due to urban development.

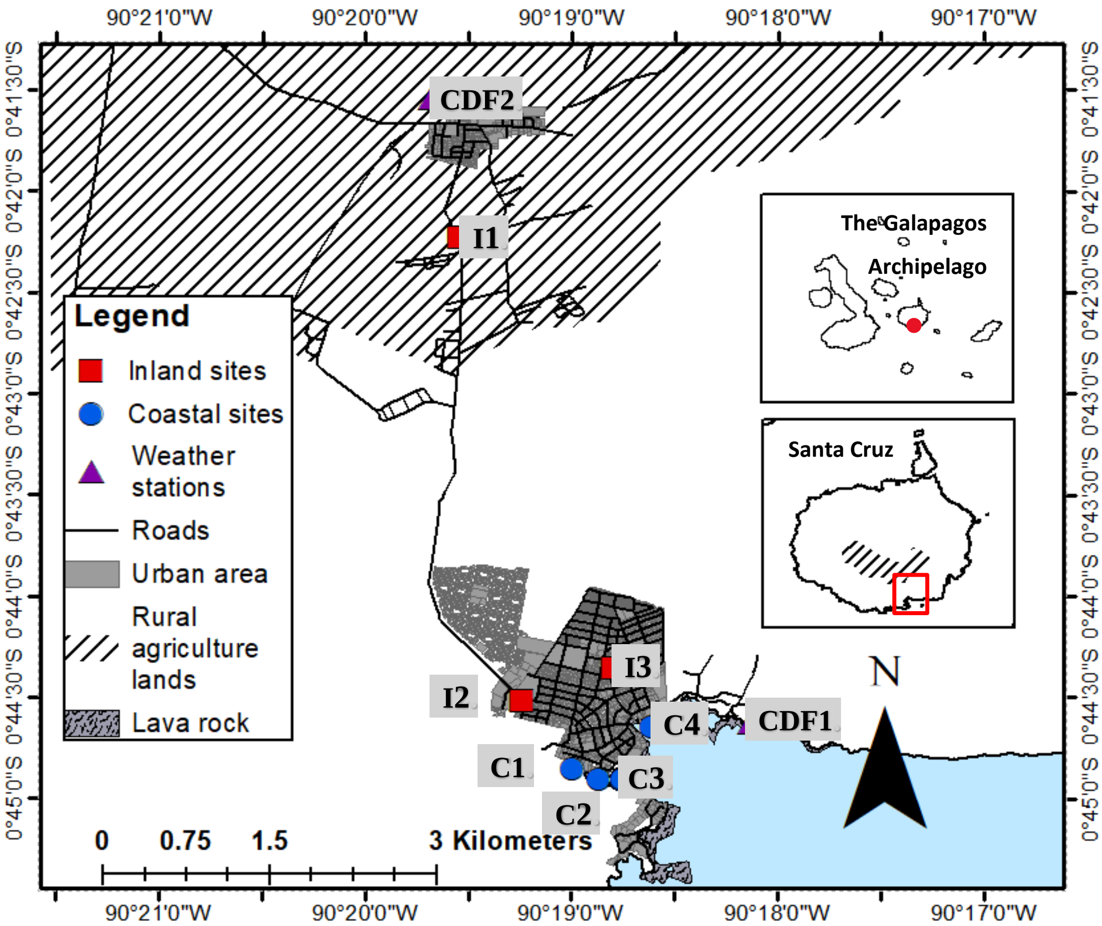

Figure 1. Pelican Bay Watershed: Urban, Rural and Agricultural Areas, Two Weather Stations (purple triangle), Four Coastal Sites (blue circle) and Three Inland Sites (red square). Coastal sites are: Las Ninfas Lagoon (C1), Academy Bay in (C2), Academy Bay out (C3) and Muelle de los Pescadores (C4). Inland sites are: Pozo Profundo (I1), INGALA (I2), Misión San Francisco (I3). CDF1 and CDF2 represent the Charles Darwin Foundation weather stations located in the Charles Darwin Research Station and Bellavista, respectively. Top inset: Galapagos Archipelago. Bottom inset: Santa Cruz Island.

Climatic Conditions

Due to its location, Santa Cruz Island is characterized by cool and dry climatic conditions influenced by extreme inter-annual variability and spatial variability between coast and highlands [14]. Two seasons in the island, as well as in all the Archipelago, are clearly defined: the cool garúa season, from June to December, and the hot invierno, from January to May [27]. During the garúa season, average temperatures are 22.6 ± 3.4 °C and the cool air brings a moisture-laden mist above approximately 250 m, whereas below this elevation the lowland areas remain dry [28]. During the invierno season, rainfall is convective; the amount of precipitation is positively correlated with sea surface temperatures [27], the climate is warm (26.0 ± 2.0 °C) with occasional heavy rain showers, and dry spells result in strong evapotranspiration [14]. Spatial variability has also been identified: annual rainfall ranges from 502 mm on the coast to 3068 mm in the highlands [14] whereas the temperature gradient is of −0.8 °C per 100 m of elevation [29]. El Niño Southern Oscillation (ENSO) also induces extreme inter-annual climatic variations.

2.2. Study Approach

2.2.1. Water Quality Parameters

Analyses employed a 9-year (2007–2015) dataset obtained from the routine water quality monitoring program carried out by the Galapagos National Park in Santa Cruz Island to monitor the overall status of inland and coastal waters [30]. Data consisted in a total of 11 water quality parameters presented in Table A1: electrical conductivity (EC), salinity (Sal), dissolved oxygen (DO), water temperature (WT), pH, turbidity (Turb), fecal coliforms (FC), total coliforms (TC), nitrite (NO_2^--N), nitrate (NO_3^--N), and total phosphorus (TP).

Over the 2007–2015 sampling period, monitoring based on field measurements and sampling was done by the Galapagos National Park once a month or a few times in the year between 9:00 and 11:30 am at all study sites [30]. Briefly, field measurements of DO, pH, EC, salinity, temperature, and turbidity were conducted in situ using field portable instruments in triplicates (Table A1). According to Galapagos National Park, nitrate, nitrite, and total phosphorus were analyzed using a spectrophotometer, and fecal and total coliforms were detected by using a portable microbiology laboratory [30]. Overall, sampling, preservation, transportation and analysis of the water samples were as per standard methods [31] as described by Galapagos National Park [30].

The main focus of this study was to complete a cursory analysis of available, but limited, data to evaluate water quality in Santa Cruz Island. We conducted a statistical analysis based on data collected by a third party in order to calculate environmental background levels of water quality variables and to explore seasonal and spatial variations. The analytical techniques applied for data collection and data monitoring were not evaluated in this study. While monitoring was carried out monthly, some parameters, such as pH and DO, may present changes in narrower time-scales like hours or minutes. Therefore, the frequency of the data analyzed herein may not be enough to represent short-term variability. Additionally, data may be impaired by the presence of outliers, missing values and possible measurement limitations that were not appropriately verified when they were reported by the Galapagos National Park [30].

2.2.2. Meteorological Variables

Basic meteorological records from 2007–2015 were obtained from existing long-term manual stations operated by the Charles Darwin Foundation, which are located at 2 m.a.s.l. (CDF1 Charles Darwin) and 180 m.a.s.l. (CDF2 Bellavista), respectively (Figure 1) [25]. Assessed variables include: mid-day air and sea temperatures, and total daily rainfall. Air temperature was recorded daily in the shade 2 m above the ground surface, sea temperature was recorded at the closest coast of CFD1 in a bucket pulled from the sea, and total daily-rainfall was the sum of measurements taken at 06h00, 12h00 and 18h00 from a Hellmann rain gauge 1.5 m above the ground [32].

2.2.3. Evaluating Water Suitability for Designated Water Uses

Suitability of ground and coastal water for different designated uses was evaluated for each parameter considered in this study (Table A1). These parameters were compared to standards of three different guidelines on water quality: (a) Unified Text about Secondary Environmental Legislation of Ecuador 2015 [33], (b) WHO guidelines for drinking-water quality [34] and (c) Hawaii Administrative Rules Title 11, Chapter 54 [35]. Thus, for inland sites, parameters were evaluated comparing Ecuadorian water quality criteria for drinking and domestic uses and criteria for protection of agriculture [33], and WHO drinking water guidelines [34]. For coastal sites, parameters were evaluated with specific criteria for estuaries and embayments from water quality standards of Hawaii Administrative Rules Title 11, Chapter 54 [35]. These standards were chosen due to hydrogeological similarities between

Hawaii and Galapagos established in previous studies [14,36]. Ecuadorian guidelines for preservation of wild and aquatic life in marine waters and estuaries, and for primary and secondary contact recreational waters [33] were also used. Guideline values and criteria considered for the analysis on both inland and coastal sites were those that matched the available data. In order to assess DO data of coastal sites, DO was converted to percent saturation units through Benson and Krause equations [37].

2.2.4. Statistical Techniques for Environmental Background Level Determination

Several different approaches exist to determine environmental background levels of water quality variables in water bodies. For this study, we used two statistical techniques presented by Matschullat et al. [38], using two model-based objective methods to define background levels of water quality: (a) the iterative 2σ technique, and; (b) the distribution function (df) technique. The data was statistically processed using an Excel application developed by the University of Zagreb that uses an algorithm designed to estimate background levels by means of the interative 2σ and the distribution function [20]. Both techniques aimed to define the background by approaching a normal range [20,21,38] so then, anomalous and background subpopulations could be differentiated. For most water quality parameters, background levels are those with lowest values and most frequent occurrence, whereas anomalies due to anthropogenic influence lie separated and are less numerous. After calculating background levels, the Lilliefors test, an adaptation of the Kolmogorov–Smirnov test, was applied for each data series to evaluate the goodness of fit to a normal distribution by generating the t-statistic as suggested by Nakić et al. and Urresti-Estala et al. [20,21]. If the t-statistic value of a parameter is below the critical t, background values are considered to fit a normal distribution with 95% confidence level, suggesting they have been estimated correctly and the utilized technique was appropriate for such parameter [21].

The iterative 2σ and the distribution function (df) techniques estimate the threshold between background and anomalies. The iterative 2σ calculates the threshold as the upper and lower values of the background variation since both high and low values may define anomalies in certain parameters [21]. This technique constructs a normal distributions around the mode of the original dataset and calculates the mean and standard deviation of this normal distribution, then the 2σ range is stablished, corresponding to the background levels, and the values outside this range are removed [38]. The distribution function (df) defines the upper limit of background levels by taking the positive asymmetry of a normal curve as anomalies that may be the result of anthropogenic influence [38]. Specifically, this technique calculates the median of the data and eliminates the values above it, what is left is reflected towards values above the median to stablished a range from which a median and a standard deviation is calculated [38]. Advantages toward utilizing these techniques have been addressed in previous studies. For example, the targeted dataset does not require a specific prior distribution, such as to be normal or lognormal distributed [21]. However, they have been showed to be more successfully applied in unimodal and skewed distributions [20]. Another advantage is that both techniques can be applied to relatively small data populations ($n > 30$) in contrast to other techniques that require hundreds or thousands of data to be successfully applied.

For practical application in water quality control, background levels were calculated for all water quality parameters except for microbial parameters (TC and FC) because the utilized techniques have only been applied to geochemical parameters [20,21,38].

2.2.5. Estimating Sensitivities to Changes Population

To evaluate whether or not changes in population are responsible for the degradation of the water sources between 2007 and 2015, we a conducted sensitivity analysis (*S*) that takes into account changes in population and changes in parameter concentration over the 9-year period of study. We calculated *S* using a simplified approach with linear regression analysis applied to data at the annual time scale to develop a general understanding of the relative sensitivity of water quality parameters to changes in population at each study site. Regression analysis methods to evaluate the significant influencing factors of ambient water quality conditions and estimate the magnitude of their impacts have been applied in other areas [39–44]. However, in reporting the results, we acknowledge that their interpretation is greatly limited by assuming that any interactions across space and time are not fully represented in this analysis.

Changes in population was calculated as the number of permanent residents in Santa Cruz Island and the number of tourists that stay in the island per day. The number of permanent residents was obtained from the last three population census done in Galápagos in 2001, 2010, and 2015 [45]. We first estimated the growth rate between census and then used a regression analysis to estimate the slope of the curve between 2001 and 2010, and 2010 and 2015. Thus, the number of permanent residents between 2007–2015 was obtained. The number of tourists staying on the island was obtained from the Galapagos Tourism Observatory [46]. Tourists landing in Baltra Airport in Santa Cruz Island but not staying in Puerto Ayora overnight, were not considered in our study.

The sensitivity analysis evaluates the strength of relationship between the annual percent change in population and annual percent change in water quality parameters based on the R^2 and the size of the effect of population change on water quality based on the $ß_1$ (slope). Therefore, the sensitivity analysis will also determine whether or not sources of contamination during the 9-year period are due to anthropogenic influences (strong relationship and large effect: high R^2 and $\mathbf{ß_1}$), natural variability (weak relationship and low effect: low R^2 and $\mathbf{ß_1}$) or both (weak relationship and large effect: low R^2 and high $\mathbf{ß_1}$). No relationship ($R^2 < 0.2$) means that any change in parameter concentrations of water quality between 2007 and 2015 is not related with changes in population.

3. Results

3.1. Parameters Exceeding Water Quality Criteria and Guidelines

Parameters at inland sites were evaluated according to values exceeding the WHO guidelines and Ecuadorian criteria of water quality (Table 1). Fecal coliform levels are alarmingly high at I3, and therefore not recommended for drinking nor domestic use. Results suggested that water at inland sites may be not suitable for drinking and domestic use due to its Sal and Turb levels. Salinity levels at I2 and I3 (90% and 100% of values exceeding) exceeded acceptable levels in the WHO water quality guidelines [34]. Site I1 can also be considered unpalatable but in less extent (26%). Turb levels at all inland sites exceeded guidelines, particularly I3 (18% of values exceeding). Furthermore, some values of EC and Sal exceeded irrigation water limits, making its water not recommended for neither drinking nor irrigation. Similar to Sal, site I2 and I3 have more EC values within severe limits relative to I1. Inland sites levels of NO_3^--N, NO_2^--N, are within safe limits of WHO guidelines and Ecuadorian criteria for drinking water, and irrigation water for agriculture and water for livestock, respectively. Therefore, they are not presented in Table 1.

Parameters at coastal sites were evaluated according to values exceeding Hawaiian rules and Ecuadorian criteria (Table 1). Coastal site C1, frequently exceeded the guidelines for: DO, EC, FC, the sum of nitrogen $[NO_3^-+NO_2^-]$-N and TP. Levels of DO exceeded under the three criteria considered though exceedance was higher at C1 when compared to Ecuadorian criteria of recreational waters (77% of values exceeding). For this criteria, high levels of fecal coliforms at C1 (88% of values exceeding) were also reported. Nutrient levels as $[NO_3^-+NO_2^-]$-N and TP often exceeded the Hawaiian rules (99–100% of the data) at both C1 and C4. However, the concentrations of NO_3^--N and NO_2^--N comply with the Ecuadorian criteria (13 and 0.2 mg/L, respectively) for the preservation of wild and aquatic life in marine waters and estuaries. Levels of Turb at C4 were also high for an embayment (99% of values exceeding). Finally, levels of TC fell below Ecuadorian criteria for secondary contact waters (2000 MPN/100 mL) in C1.

Table 1. Percentage of parameter measurements from study sites that exceed water quality guidelines. Percentage (%) of exceedance represents the fraction of a certain parameter that exceed a specified water quality criteria value. FC: fecal coliforms; Turb: turbidity; Sal: salinity; EC: electrical conductivity; DO: dissolved oxygen; TP: total phosphorus; WT: water temperature.

Parameters	Guideline/Criteria Values	% of Exceedance			
		I1	I2	I3	
	(A) Drinking and domestic use				
FC [a]	1000 MPN/100 mL	-	-	53	
pH [a]	6–9	-	-	2	
Sal [b]	Unpalatable: >1 g/L	26	90	100	
Turb [b]	<1 NTU	18	6	4	
	(B) Irrigation water [c]				
pH	6–9	-	-	2	
FC	1000 MPN/100 mL	-	-	53	
EC	Moderate: 0.7–3 mS/cm	83	51	33	
	Severe: >3 mS/cm	17	49	67	
Sal	Moderate: 0.45–2 g/L	99	76	6	
	Severe: >2 g/L	0	24	94	
Parameters	**Guideline/Criteria Values**	**% of Exceedance**			
		C1	**C2**	**C3**	**C4**
	(A) Preservation of wild and aquatic life in marine waters and estuaries [d]				
DO	>60% saturation	15	3	3	1
pH	6.5–9.5	2	-	1	1
Turb	Shall not deviate more than 5% from background levels	4	16	7	14
	(B) Primary and Secondary contact recreational water [e]				
FC	200 MPN/100 mL	88	n.d.	n.d.	n.d.
TC	2000 MPN/100 mL	4	n.d.	n.d.	n.d.
DO	>80% saturation	77	27	15	8
pH	6.5–8.3 (primary)	3	2	3	1
	6–9 (secondary)	2	-	-	1
	(C) Specific criteria for estuaries and embayment [f]				
$[NO_3^-+NO_2^-]$-N	25 µg/L (estuaries)	100	100	99	-
	20 µg/L (embayments)	-	-	-	99
TP	50 µg/L	97	100	86	99
Turb	3 NTU	8	20	40	99
pH	7-8.6 and shall not deviate more than 0.5 units from background levels	10	-	-	-
	shall not deviate more than 0.5 units from 8.1	-	32	20	18
DO	>75% sat.	69	14	10	6
WT	shall not deviate more than 1 °C from background levels	5	2	1	1
Sal	shall not deviate more than 10% C from background levels	13	15	9	9

Note: [a] Acuerdo 097-A, Anexo 1 del Libro VI del Texto Unificado de Legislación Secundaria del Ministerio de Ambiente, Tabla 1, 2015; [b] Guidelines for Drinking-water Quality; 4th ed.; World Health Organization, 2011; [c] Acuerdo 097-A, Anexo 1 del Libro VI del Texto Unificado de Legislación Secundaria del Ministerio de Ambiente, Tabla 4, 2015; [d] Acuerdo 097-A, Anexo 1 del Libro VI del Texto Unificado de Legislación Secundaria del Ministerio de Ambiente, Tabla 2, 2015; [e] Acuerdo 097-A, Anexo 1 del Libro VI del Texto Unificado de Legislación Secundaria del Ministerio de Ambiente, Tabla 6, 2015; [f] Specific criteria for estuaries and embayment from water quality standards of Hawaii Administrative Rules Title 11, Chapter 54.

3.2. Environmental Background Levels

Environmental background levels of the physical-chemical parameters were determined using two techniques: (a) the iterative 2σ and (b) the distribution function (df) as described in Section 2.2.5. The outer thresholds of background values for the parameters considered are reported in Table 2.

Best estimations are indicated in bold and shaded in grey according to the nature and distribution of original data, and recommendations proposed in previous studies [20,21,38]. Variables that passed the Lilliefors statistic test are also indicated (*) which means that the data fits a normal distribution and that the techniques applied herein are appropriate for such parameters. Overall, results demonstrated that: (1) background levels calculation fit better for coastal sites than for inland sites; (2) the techniques applied herein performed different for each parameter and study site, and; (3) while some parameters exceeded water quality criteria, background levels suggested that those parameters have been varying naturally since 2007.

As demonstrated by coastal sites (C1–C4), background ranges yielded a greater number of parameters that passed the Lilliefors test with at least one of the techniques considered suggesting a better fit for coastal sites relative to inland sites.

In most cases, both the iterative 2σ and distribution function (df) techniques produced similar results, however, differences in their performance was observed. In general, results suggested that: (a) the iterative 2σ technique usually produced the best estimations for EC, Turb and Sal; (b) both techniques were equally suitable for TP, NO_2^--N, and NO_3^--N, and; (c) none of the techniques are a good fit for WT, pH, and DO. Performance differences depend primarily on the frequency distribution of the evaluated datasets. These differences might be provided by the degree of human disturbance, along with the hydrodynamic and hydrochemical characteristics of the water body [21]. Parameters on which the iterative 2σ worked well (EC, Turb, and Sal) presented unimodal or skewed distributions in which background values are calculated around this unique mode and they follow a normal distribution (Figure A1a), thus making them suitable for the application of this technique [20]. In contrast, background values for EC, Turb, and Sal calculated using the df technique fails Lilliefors test because positive anomalies in data cannot be distinguished and thus upper thresholds are overestimated, making backgrounds to not follow a normal distribution (Figure A1b). On the other hand, parameters that showed overlapping polymodal distributions, which may include right skewness, with prevailing lower values representative of background levels (NO_3^--N, NO_2^--N, and TP), were suitable to apply the distribution function technique (Figure A2b) [20,38]. When the distribution of the original dataset is dispersed and has larger number of small values that may represent background levels, the df technique seems to work remarkably good relative to the iterative 2σ technique (Figure A2). The parameters WT, DO, and pH did not present any of the mentioned distributions in most cases, therefore most of the calculated background values across study sites did not pass the Lilliefors test. In the case of WT and DO, distributions different from normal and skewed were documented on these parameters previously [47].

Differences in the range of the background values were also observed between study sites. Background values for parameters such as Turb, Sal, and EC were higher in coastal sites, which may be associated with its proximity to the sea. In contrast, TP background is higher among inland sites which could be a result of land human activities. For NO_3^--N and NO_2^--N ranges of background values were very similar.

Levels for Sal, EC, Turb, $[NO_3^- + NO_2^-]$-N, and TP exceeded water quality criteria at some study sites. However, levels of these parameters are considered to be varying naturally according to background values calculated for the 9-year time period studied herein. For example, EC and Sal levels make water at inland sites unsuitable for irrigation, however, those levels fall mostly within calculated background levels (Table 2) suggesting that have been varying naturally since 2007, reflecting natural brackish conditions. High levels of Turb at coastal sites largely exceeded Hawaiian criteria. However, according to the background levels, is subject to natural increases that surpasses Hawaiian specific criteria for estuaries (3 NTU). Finally, while $[NO_3^- + NO_2^-]$-N and TP largely exceeded Hawaiian criteria for coastal waters, background levels of these parameters show higher natural-occurring values than the limit set for coastal waters in Hawaii. This suggests that the use of Hawaii's water quality rules for evaluating our coastal study sites may lead to misunderstandings about the degree of anthropogenic water quality alteration.

Table 2. Background levels at Inland Sites (I1, I2, I3) and Coastal Sites (C1, C2, C3, C4) using the iterative 2σ technique (2σ) and the distribution function (d.f.) technique.

(a) Inland Sites

Parameters	I1		I2		I3	
	2σ	d.f.	2σ	d.f.	2σ	d.f.
WT (°C)	22.4–24.3	18.8–28.0	23.4–24.2	23.0–24.6	23.8–24.4	22.9–25.5
Turb (NTU)	0.2–0.7	0.2–0.8	0.1–0.6 *	0.1–0.6	0.1–0.6 *	0.1–0.7 *
Sal (g/L)	0.7–1.2 *	0.7–1.1	1.1–1.8	0.8–2.0	2.1–2.6	2.0–2.6
DO (mg/L)	7.2–8.3	6.6–9.0	7.6–8.3	7.2–8.8	7.6–8.3 *	7.2–8.8
EC (mS/cm)	2.1–3.2 *	2.0–3.3	2.2–3.7 *	2.2–3.7 *	2.0–4.7 *	1.9–5.1 *
pH	7.0–8.3	6.8–8.6 *	7.4–8.2	7.2–8.4	7.5–8.2	7.5–8.2 *
NO_3^--N (mg/L)	0.0–0.1 *	0.0–0.1 *	0.0–0.1 *	0.0–0.1 *	0.1–0.4 *	0.1–0.4 *
NO_2^--N (μg/L)	2.6–8.1	3.2–6.8	2.6–8.0	2.9–7.1	2.9–7.4 *	2.7–7.3
TP (mg/L)	0.0–1.3 *	0.0–1.4 *	0.0–1.6 *	0.0–1.7 *	0.0–1.1 *	0.0–1.3 *

(b) Coastal Sites

Parameters	C1		C2		C3		C4	
	2σ	d.f.	2σ	d.f.	2σ	d.f.	2σ	d.f.
WT (°C)	23.1–26.5	21.7–27.7	21.8–27.2 *	21.5–27.9 *	21.7–27.3 *	21.3–27.9 *	21.9–27.6 *	21.3–28.3 *
Turb (NTU)	0.0–2.3 *	0.1–2.3 *	0.3–2.9 *	0.4–3.2 *	0.0–4.7	0.0–5.2	1.2–7.5 *	1.2–8.4 *
Sal (g/L)	16.4–21.6 *	13.3–25.1	16.8–24.1 *	16.7–25.9 *	32.4–33.2 *	28.0–37.6	32.4–33.2 *	28.0–37.6
DO (mg/L)	4.7–7.4	4.5–7.9	6.5–7.8	5.5–8.5	7.5–8.3	7.5–8.3 *	7.5–8.2	6.1–9.5
EC (mS/cm)	21.0–29.4 *	20.2–30.3	26.4–31.7 *	25.6–33.5 *	47.1–53.9 *	39.5–61.1	46.8–55.0 *	39.5–61.1
pH	7.0–8.1 *	6.4–8.6	7.4–8.2	7.1–8.5	7.5–8.2 *	7.2–8.4	7.5–8.2	7.1–8.5
NO_3^--N (mg/L)	0.0–0.1	0.0–0.1 *	0.0–0.1	0.0–0.1 *	0.0–0.1 *	0.0–0.1 *	0.0–0.1 *	0.0–0.1 *
NO_2^--N (μg/L)	3.9–9.1 *	3.7–10.3 *	3.5–8.8 *	3.9–8.1 *	3.3–9.5 *	3.4–10.6 *	3.4–10.0 *	3.7–10.3 *
TP (mg/L)	0.0–0.2 *	0.0–0.2 *	0.0–0.2 *	0.0–0.3 *	0.0–0.5 *	0.0–0.6 *	0.0–0.5 *	0.0–0.6 *

Note: The * indicates variables that passed the Lilliefors test. Values shaded in grey represent the best estimations according to the nature and distribution of data which means that the data fits a normal distribution and that the techniques applied herein are appropriate for such parameters.

3.3. Relative Influence of Population Change on Water Quality Parameters

The sensitivity analysis provided useful information about the significant influence of population change on water quality conditions over the 9-year study period. Results highlighted that (a) the strength of the relationship and the influence that changes in population has over water quality parameters varied at each site; (b) the strength of the relationship was stronger at coastal sites relatively to inland sites, and; (c) anthropogenic influence on nutrients (TP, NO_3^--N and NO_2^--N) seems to be higher the closer they get to the coast (C2, C3, and C4).

Higher sensitivity to anthropogenic activities was observed at coastal sites relative to inland sites between 2007 and 2015. Changes in water quality parameters at inland sites exhibited relative weak relationship with percent change in population, based on the low R^2 (Table 3). For example, a large change in population size at I3 resulted in a small change (low $ß_1$, small effect) in FC concentrations. Thus, results suggested that changes in the number of habitants at inland sites has a small impact on water quality parameters. On the other hand, based on the large number of high R^2 found at coastal sites (Table 3), results suggested a strong relationship between changes in population and water quality parameters at these sites. However, the size of the effect of anthropogenic activities varied between parameters, based on the high or low $ß_1$ coefficient (slope). For example, at C4, a small change in population (high R^2) resulted in a big change in Turb values (high $ß_1$, large effect) and a small change in NO_3^--N concentrations (low $ß_1$, small effect). Results also highlighted that the strength of the relationship between population changes and nutrients ([NO_3^- + NO_2^-]-N and TP) increases the closer the site is to coastal waters.

Table 3. Sensitivity Analysis for Inland and Coastal Sites: Represented by the Strength of the Relationship (R2) and the Size of the Effect (slope, **ß$_1$**) between water quality parameters and forcing variables for number of habitants in the island taking into account both, number of tourists and local population.

Inland Sites					Coastal Sites				
Site	**Parameter**	**ß$_1$**	**ß$_o$**	**R^2**	**Site**	**Parameter**	**ß$_1$**	**ß$_o$**	**R^2**
I1	TEMP	−0.92	0.04	0.29	**C1**	TEMP	0.14	0.03	0.01
	EC	0.10	0.03	0.16		EC	0.05	0.03	0.07
	PH	0.20	0.03	0.02		PH	0.58	0.03	0.58
	TURB	0.00	0.32	0.00		TURB	0.02	0.03	0.19
	SAL	0.07	0.04	0.06		SAL	0.19	0.03	0.24
	DO	−0.47	0.04	0.25		DO	0.10	0.03	0.13
	NO_2-N	0.02	0.03	0.00		NO_2-N	0.10	0.04	0.17
	NO_3-N	−0.01	0.03	0.01		NO_3-N	0.00	0.03	0.00
	TP	−0.03	0.02	0.07		TP	0.01	0.03	0.00
	TC	0.00	0.03	0.03		TC	0.01	0.03	0.03
	FC	0.00	0.03	0.03		FC	0.06	0.03	0.29
I2	TEMP	0.04	0.03	0.00	**C2**	TEMP	0.08	0.03	0.00
	EC	0.15	0.04	0.30		EC	0.19	0.04	0.72
	PH	0.70	0.03	0.21		PH	0.84	0.03	0.43
	TURB	0.36	0.03	0.14		TURB	0.08	0.04	0.38
	SAL	0.00	0.03	0.00		SAL	0.09	0.03	0.05
	DO	0.87	0.04	0.47		DO	0.20	0.03	0.46
	NO_2-N	0.01	0.03	0.01		NO_2-N	0.08	0.03	0.08
	NO_3-N	0.01	0.03	0.00		NO_3-N	0.04	0.03	0.38
	TP	0.02	0.03	0.02		TP	0.02	0.04	0.72
	TC	0.01	0.03	0.04		TC	NA	NA	NA
	FC	0.00	0.32	0.00		FC	NA	NA	NA
I3	TEMP	0.60	0.03	0.02	**C3**	TEMP	0.28	0.03	0.09
	EC	0.09	0.04	0.11		EC	0.02	0.03	0.10
	PH	0.45	0.03	0.03		PH	1.58	0.03	0.21
	TURB	0.04	0.04	0.30		TURB	0.03	0.03	0.02
	SAL	0.11	0.03	0.09		SAL	3.28	0.04	0.79
	DO	0.42	0.03	0.04		DO	0.23	0.04	0.22
	NO_2-N	0.09	0.03	0.12		NO_2-N	0.05	0.03	0.30
	NO_3-N	0.02	0.03	0.29		NO_3-N	0.07	0.04	0.52
	TP	0.17	0.04	0.26		TP	0.08	0.03	0.42
	TC	0.05	0.04	0.21		TC	NA	NA	NA
	FC	0.10	0.04	0.34		FC	NA	NA	NA
					C4	TEMP	0.35	0.04	0.14
						EC	0.02	0.03	0.09
						PH	0.57	0.03	0.15
						TURB	0.16	0.05	0.46
						SAL	0.47	0.03	0.05
						DO	0.50	0.04	0.22
						NO_2-N	0.04	0.03	0.13
						NO_3-N	0.08	0.04	0.49
						TP	0.02	0.03	0.02
						TC	NA	NA	NA
						FC	NA	NA	NA

Note: Values with the strongest relationships are highlighted in dark gray, values with weak relationships are highlighted in light gray.

3.4. Seasonal Variations

Data variability within invierno and garúa seasons differed for each parameter suggesting that some of them may be influenced by seasons. While WT, EC, Sal, Turb, NO_3^--N, TC, and FC present seasonal variations (Figure 2), DO, pH, TP, and NO_2^--N did not show any important differences between seasons (Figure A3). In general, higher variation happened during the garúa season relative to the invierno season with the exception of TC and FC in which higher variability happened during invierno. Results for WT, Turb, NO_3^--N, and TC are shown in Figure 2, and results for EC, Sal, and FC are presented in Figure A4.

Variations observed in pH are within normal pH levels of coastal water and coastal aquifers and may not be a problem for ecosystems health and recreational activities [48]. However, a 10% exceedance was found at C1 (Figure A3) which still falls within estuarine pH levels that generally average from 7.0 to 8.6 [48]. Literature suggests that pH anomalies may be caused by bacterial activity, chemical constituents in runoff and sewage overflows which can greatly stress most aquatic plants and animals [48]. However, further analysis needs to be done to better understand the possible causes of the anomalies found in our results.

Seasonal analysis shows that coastal WT variability is consistent with seasonal changes, where higher WT concurred with the hot invierno season and the lower temperatures fell during the garúa season (Figure 3). However, differences between WT observations and measurements of air and sea surface temperatures from the Charles Darwin Foundation (CDF) stations were observed within study sites. Water temperature at coastal sites (Figure 3a–d) behaved similar to air and sea surface temperature between January to May. However, it appears to be one month lag between high peaks for air temperature and coastal water temperature. High peak for air temperature is in March whereas high peak for coastal water is in April. From September through December, a steep rise of WT would be expected according to the seasonal variation seen for air and sea surface temperature; however, the high temperature in September compared to the neighboring months breaks this pattern since unusual high water temperature were reported for this month at many years of the study period. Water temperature regime at inland sites (Figure 3e–g) presented a weaker seasonal variation (also seen in Figure 2b) and only I3 which is Misión San Francisco (Figure 3e) seems to receive seasonal influence that affects its temperature. Periodic annual fluctuation of these inland sites has a noticeable amplitude less than 1 °C.

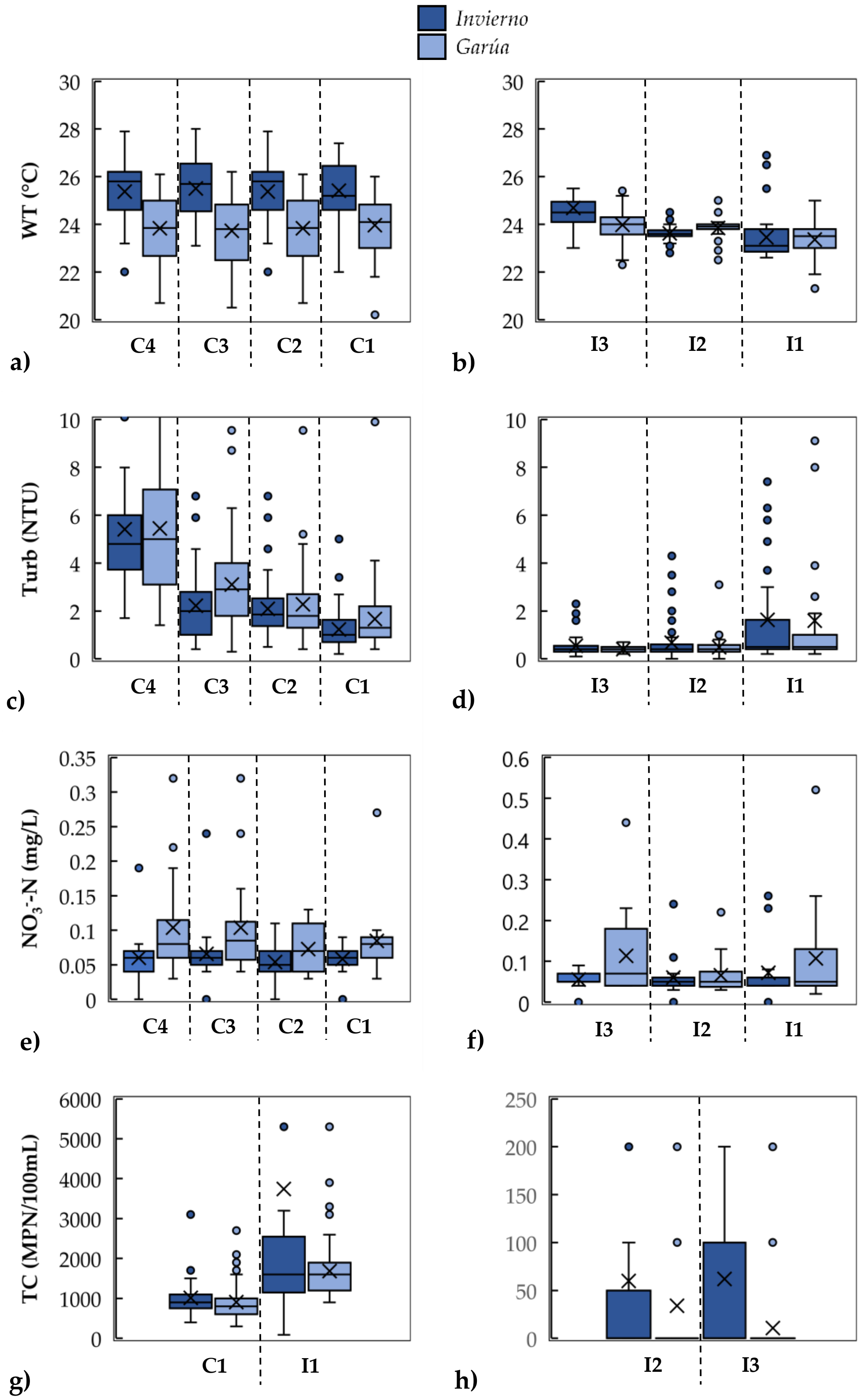

Figure 2. Seasonal variation. Invierno (January–May) and garúa (June–December) variations for (**a**) WT coastal, (**b**) WT inland, (**c**) Turb coastal, (**d**) Turb inland, (**e**) NO_3^--N coastal, (**f**) NO_3^--N inland, (**g**) TC coastal (left) TC inland (right), and (**h**) TC inland. The scale at coastal sites for NO_3^--N and TC differ from the scale at inland sites.

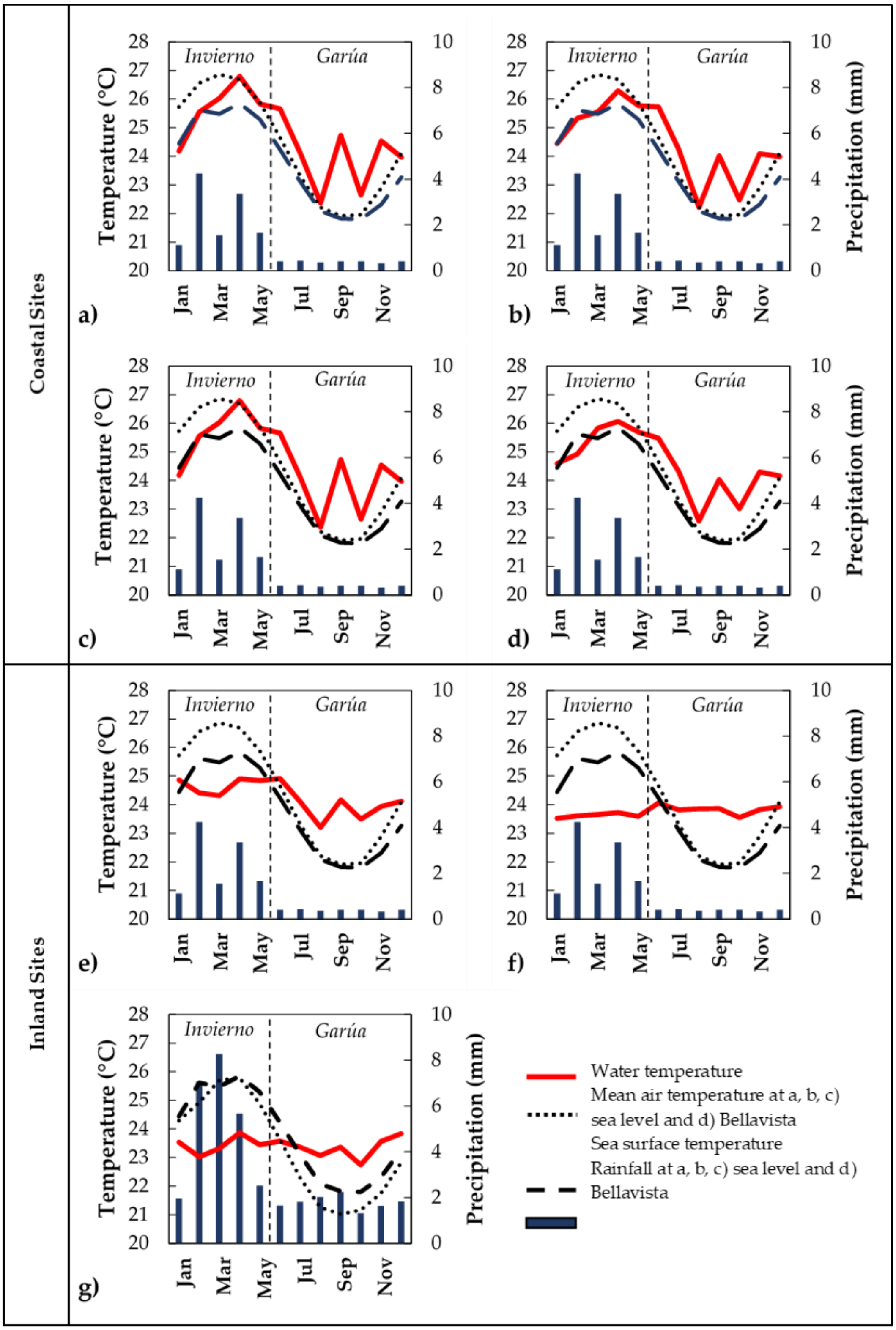

Figure 3. Mean water temperature (WT) from 2007 to 2015 (solid gray line), mean air temperature (dotted line), sea surface temperature (dashed line), and rainfall (bars) at coastal sites: (**a**) Muelle de los Pescadores (C4), (**b**) Academy Bay out (C3), (**c**) Academy Bay in (C2), and (**d**) Las Ninfas (C1); and inland sites: (**e**) Misión San Francisco (I3), (**f**) INGALA (I2), and (**g**) Pozo Profundo (I1).

3.5. Spatial Variations

Physical and chemical parameters were analyzed to explore patterns of spatial variations within Pelican Bay water quality. For WT, EC, Sal, Turb, and TP, important differences between coastal and inland sites were observed (Figure 4) and higher variability was observed in coastal sites relative to inland sites, with the exception of TP. For DO, pH, NO_3^--N, NO_2^--N, TC, and FC no clear spatial pattern was found (Figure A5).

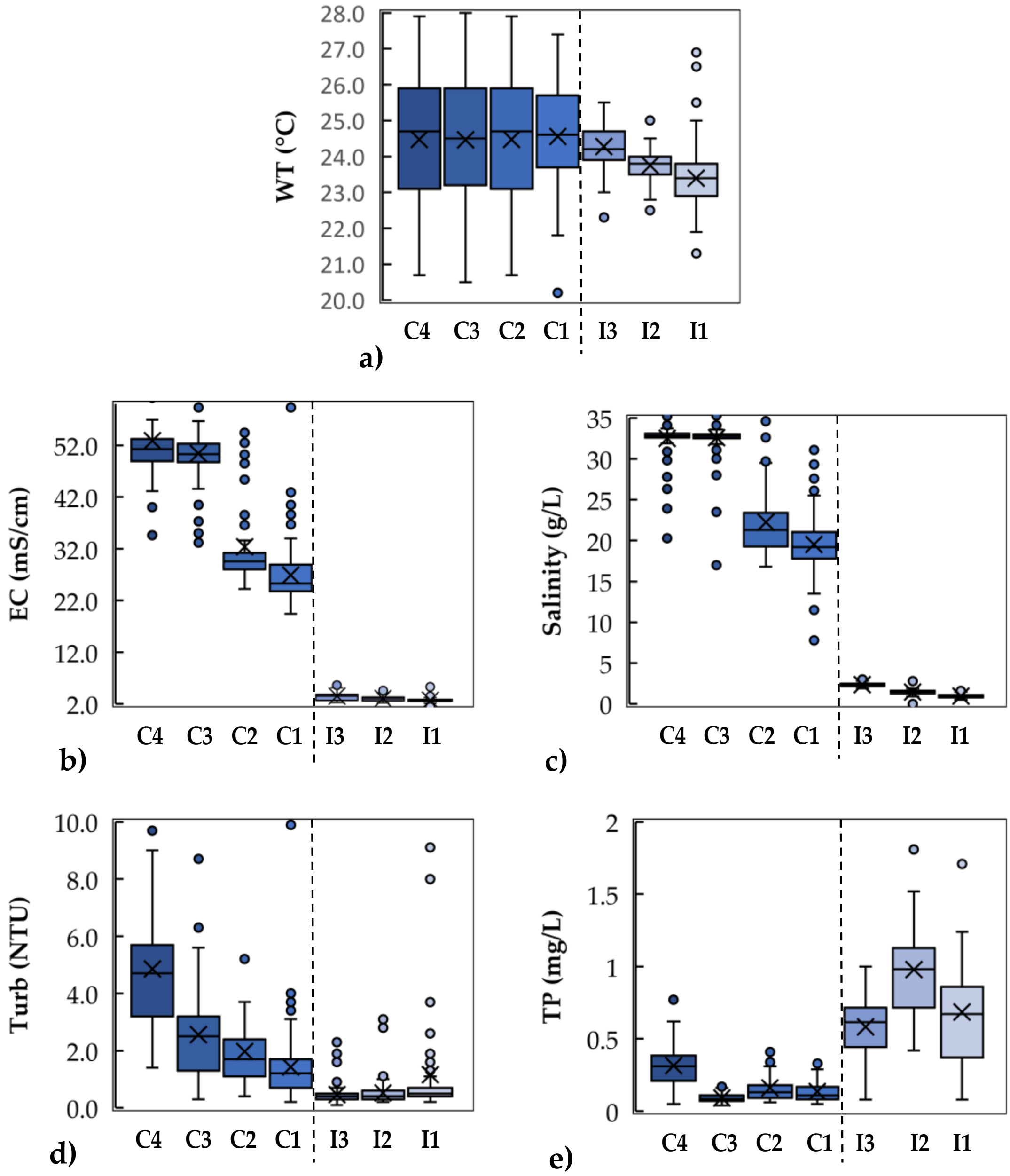

Figure 4. Spatial variation for (**a**) WT, (**b**) EC, (**c**) Sal, (**d**) Turb, and (**e**) TP. Study sites are ordered by proximity to the sea, being C2 the closest to the sea and I2 the furthest. The upper and lower quartiles are represented by the ends of the box, the median is the horizontal line between box ends, the mean is marked by "x", the whiskers indicate variability outside the upper and lower quartiles and, finally, points outside whiskers are considered as outliers.

Results demonstrate that coastal sites are subject to a higher variability of WT than inland sites with seasonal and spatial components (Figures 3a and 4a, respectively). These differences in WT are likely to be attributed to the distance since water is at 20, 28, and 180 m below ground surface at I3, I2, and I1, respectively. While coastal WT variations happen because they correspond to surface water that receives higher heat fluxes driven by seasonal fluctuation [49], inland WT variation may be associated to its distance below the ground level rather than seasonality, which concurs with Kurylyk et al. study [50] that reported that low groundwater temperatures are related to higher topographic areas and higher groundwater temperatures are derived from high air temperatures in sites near coastal areas. However, our results at I2 differ with Szczucińska and Wasielewski [51] which demonstrated that seasonal fluctuations in temperature can affect a depth of 20–30 m in soils depending on the heat transfer ability of the upper soils or rocks.

As expected, higher variability was also observed for EC, Sal, and Turb at coastal sites relatively to inland sites. For EC (Figure 4b), a relatively big difference with distance from the sea was seen with decreases in the mean of 52.9 mS/cm and 26.9 mS/cm from C4 to C1 at coastal sites, and 3.49 mS/cm and 2.74 mS/cm from I3 to I1 at inland sites. Something similar occurred for Sal (Figure 4c), with decreases in the mean of 32.5 g/L and 19.5 g/L from C4 to C1, and 2.4 g/L and 1.0 g/L from I3 to I1. Turb levels (Figure 4d) also showed to be significantly higher and more dispersed among coastal sites, being C4 the one with the highest turbidity (IQR: 3.2–6.4 NTU). While Turb levels seem to decrease with proximity to the sea at coastal sites, they are likely to increase at inland sites.

In contrast, TP presented higher levels and wider variation in inland sites relative to coastal sites, being I2 the one with the highest TP (IQR: 0.7–1.1 mg/L) (Figure 4e). However, those levels may not represent any harm for human health in waters intended for drinking and domestic purposes. Higher inland TP levels relative to coastal TP levels suggests that inland might be a source of phosphorus to coastal waters. This was suggested in previous studies [52] in which TP might migrate from the aquifer to the coasts by processes involved in inland water discharges into the sea. Nonetheless, this cannot be confirmed by this study and further research should be made.

4. Discussion

Water quality monitoring is an essential part of effective water management at local and regional level. Our results demonstrated that data from the 9-year local monitoring program of Santa Cruz Island provided valuable information that allowed the characterization of physical-chemical and microbial properties of study sites and the analysis of water suitability for designated water uses as described in detail in the sections below. To the best of our knowledge, this is the first study that has investigated water quality variability due to seasonal, anthropogenic and natural processes in the Galapagos Islands.

4.1. Suitability Analysis for Drinking and Domestic Use

Results suggested that water at inland sites may be not suitable for drinking and domestic use due to its Sal, EC, Turb, and FC levels (Figure 5).

Sal and EC levels at inland sites reflect seawater intrusion in the basal aquifer of the island. Seawater intrusion has been reported previously [14] with linkages to human over-pumping of the aquifer. This relationship is not uncommon and has been documented in other places [21,53,54]. However, while it is true that human overexploitation of water induces seawater intrusion, there are other factors involved such as dispersive mixing, tidal effects, surface hydrology, and geological characteristics [53] that needs to be evaluated to elucidate seawater intrusion processes in the island. According to the sensitivity analysis, anthropogenic activities at these sites have limited effect on these parameters between 2007 and 2015 (Table 3). Results also suggested that the variability of these parameters may be related to seasons. Both parameters showed higher variabilities during the garúa relative to invierno season at most sites, and variability in garúa surpassed upper thresholds of background levels. These results suggest that garúa may be influencing EC and Sal parameters and could be a direct consequence of Humboldt current influence, producing higher concentrations than those considered to be natural.

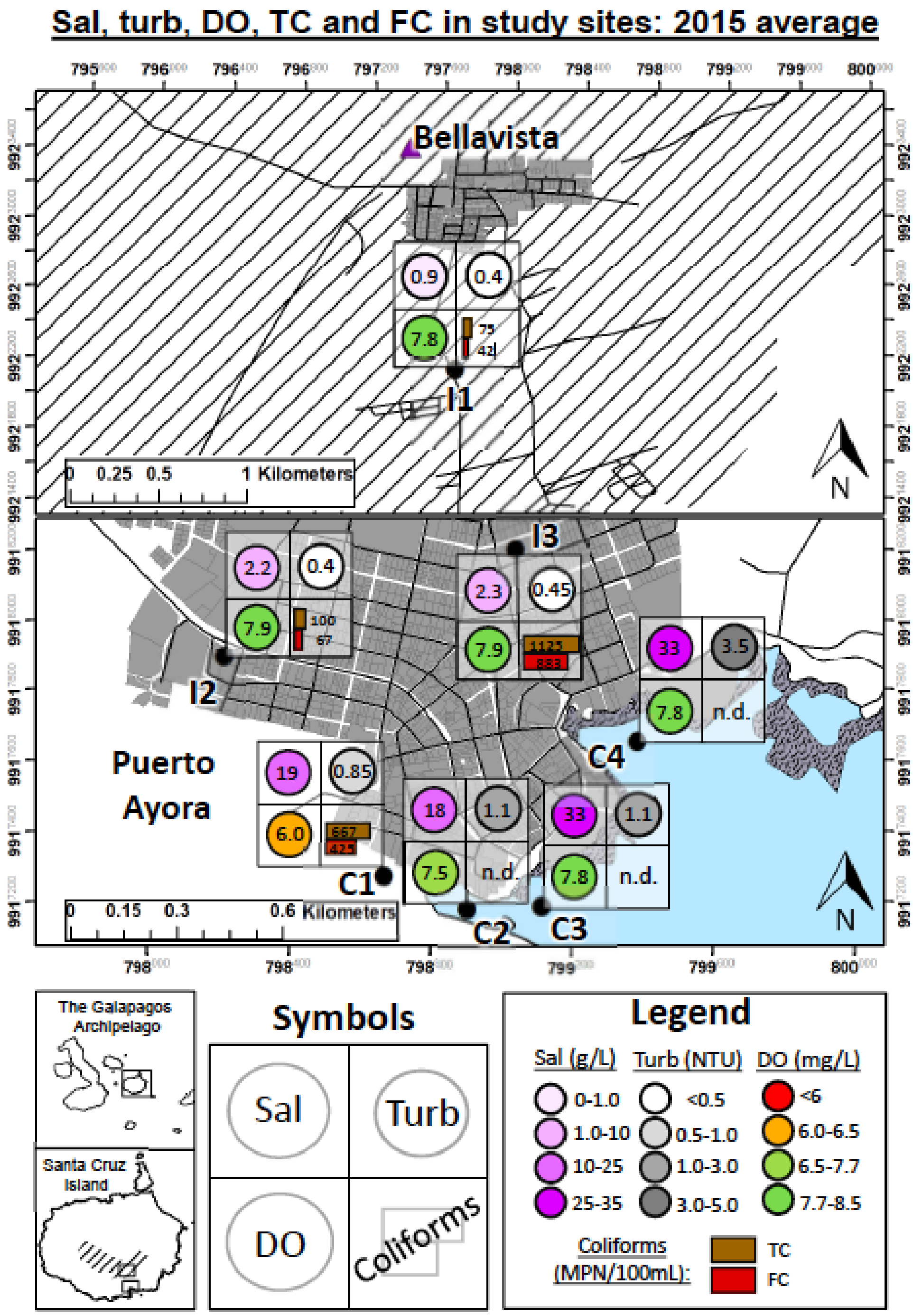

Figure 5. Parameters exceeding guidelines criteria at inland sites (I1, I2, I3) and coastal sites (C1–C4). Bottom left inset: Santa Cruz location in the Galápagos Archipelago (top) and study areas location in Santa Cruz Island (bottom). Bottom middle inset: Location for each parameter within the inset figures showing the results inside the map: Sal—Salinity in the top left side (circles in purple tones), Turb—Turbidity in the top right side (circles in grey tones), DO—Dissolved Oxygen in the bottom left side (circles with multiple colors), TC—Total Coliforms (brown rectangle) and FC—Fecal Coliforms (red rectangle) in the bottom right side. The range of values and color tones are described in the figure legend in the bottom right inset.

According to WHO guidelines for drinking-water quality [34], increases in Turb levels may affect negatively effective disinfection processes, representing a critical issue if these waters come to get polluted by pathogenic bacteria. Fortunately, at I1 (Pozo Profundo) in which Turb values exceed the 1 NTU limit of WHO guidelines during the invierno season (Figure 2), no coliform contamination has been detected yet. While high contamination risk at I1 is present due to its proximity to the main road, urban settlements and saline intrusion [23], results from the sensitivity analysis suggested that anthropogenic activities has no effect on Turb levels at this site (Table 3). Heavy rainfall events can lead to higher Turb levels due to increased runoff and erosion [10]. This might be the case for I1 since this site is prone to receive the highest infiltration of water originated from rainfalls [13].

FC levels are alarmingly high at I3 (Misión San Francisco), which concurs with previous research [4,12] that indicated that I3 has the highest load on fecal indicator bacteria contamination among all crevices operated by Puerto Ayora's Municipality for water extraction [4]. This site was originally distributed through the municipal water supply and designated for private desalinization [4,13,26]. Nowadays, I3 is closed for extraction [4]. It was suggested that this contamination is related to its proximity to urban areas and an inefficient sanitary infrastructure that generates leakages from the septic tanks to the basal aquifer [4]. However, our results suggested that population increases in this area between 2007–2015 has a relatively small influence on FC concentrations (Table 3). Nevertheless, effective wastewater management practices for Puerto Ayora are still needed.

4.2. Suitability Analysis for Irrigation

EC and Sal levels (Figure 5) make inland sites unsuitable for irrigation and they seemed to be enhanced during the garúa season. However, these levels are considered natural according to background values calculated for 2007–2015 period (Table 2) with no significant influence from changes in anthropogenic activities (Table 3). High salinity water is responsible for altering soil properties with negative impacts on crops [53]. Since saline water has been used for irrigation at these sites for at least a decade, long term use of saline water for irrigation needs to be addressed. Using a proper irrigation schedule with saline water to ensure sustainability and adoption of salt-tolerant crops (such as quinoa) has been recommended [47]. However, while water management strategies would further facilitate the use of saline waters for irrigation [55], there is the need to understand how exactly salinity affects soils, and thus crops while constantly monitoring salinity levels to ensure they stay within the acceptable range.

4.3. Suitability Analysis for Wild and Aquatic Life in Coastal Waters and Estuaries

In coastal sites, DO, FC, [NO_3^- + NO_2^-]-N, TP, and Turb are parameters of concern for its different usage purposes (Figure 5). While [NO_3^- + NO_2^-]-N, TP, and Turb largely exceeded Hawaiian criteria for coastal waters, background levels of these parameters between 2007 and 2015 show higher natural-occurring values than the limit set for coastal waters in Hawaii. This indicates that the use of Hawaii's water quality rules for evaluating coastal study sites in Galápagos may lead to misunderstandings about the degree of anthropogenic water quality alteration. However, results from the sensitivity analysis suggested that increases in anthropogenic activities strongly influenced changes in the concentration of these parameters in coastal areas and, the closer it gets to the coast, the higher the effect is (Table 3). The influence of human activities on the mentioned parameters is possible since diffuse pollution sources such as agricultural runoffs may be causing some enrichment of nutrients in water and FC. Furthermore, higher concentrations of nutrients (NO_3, NO_2, and TP) and FC in coastal areas may be related with feces contamination due to untreated wastewater discharges and/or the presence of animal feces. Therefore, results from this analysis suggest that outer thresholds of background levels along with the sensitivity analysis of parameters to changes in population, may serve for defining site-specific limits to control water quality.

Concentrations of DO maintain similar levels across study sites, and those concentrations also reflect prevailing aerobic conditions in the water. However, C1 (Las Ninfas Lagoon) is an exception to this because DO concentrations at this site were lower and highly variable compared to the rest of the study sites (Figure A3a). Low levels of DO may represent a problem for ecosystem preservation, threatening flora and fauna of the estuary, as well as recreational activities [33]. In estuaries, particularly, they lead to stressful conditions for benthic macrofaunal [56]. Additionally, many outliers were observed for DO, which could be a result of simultaneously rapid DO decreases and increases processes derived from bacterial degradation and oxygen release from phytoplankton, respectively [57].

Evidence of high fecal contamination was also found at C1 through the presence of fecal coliform bacteria (Figure A3f). This site was a popular swimming spot for tourists and residents until recreational activities were prohibited due to the presence of human fecal contamination [2,9]. Changes in FC concentrations between 2007–2015 are related with increases in anthropogenic activities at this site (Table 3). It was also observed that higher variability of FC happened during invierno relative to garúa (Figure A4e). This concurs with previous studies that showed evidence of fecal contamination at this site originated from discharges of sewage and agricultural runoff [2,9]. Higher concentration of coliform bacteria proceeding from heavy rainfall events have been reported in other studies [8,9] suggesting that stormwater runoff can be a primary source of coliform bacteria. Furthermore, FC concentrations at C1 largely exceeded Ecuadorian criteria for recreational waters (88% of values exceeding), representing high potential risks of waterborne illness [58]. Additional management practices should be adopted to attenuate fecal contamination at recreational coastal sites.

At coastal sites, NO_3^--N have higher variability and reach higher values during the cool and dry garúa season (Figure 3) suggesting that rainfall runoff during invierno may tentatively be producing a dilution effect of NO_3^--N. Increased NO_3^--N levels were reported previously at Academy bay waters (C2 and C3 area) and Cartago Bay in San Cristobal Island [59]. Human activities such as agriculture, combustion, and sewage discharges may be causing higher-than-natural enrichment of NO_3^--N, especially at coastal sites. For example, Howarth et al. [52] reported high levels of NO_3^--N in the U.S. coastal waters resulting from natural origin, and other sources such as that from native fauna, fossil fuel combustion, and N-compounds from fertilizers. Bacteria action on nitrogenous matter concentrated in sewage can also increase concentrations of NO_3^--N [57]. While our results suggested a strong relationship between anthropogenic activities and NO_3^--N concentrations during the 9-year period (Table 3), further research needs to be done to be able to explain the processes causing NO_3^--N enrichment at these sites.

4.4. Environmental Background Levels

Background levels are a useful tool that serves as a reference to assess the level of water affectation since values outside the range of the background can occur due to atypical events. Our results showed that while some parameters (Sal, EC, Turb, [NO_3^- + NO_2^-]-N, and TP) exceeded water quality criteria, those levels were considered to be varying naturally since 2007 according to the calculated background values. However, our data only captures the 2007–2015 period. Therefore, to reveal real natural conditions unaffected by anthropogenic contributions, data should be compared with historical water sources data and data from pristine sites. Since data for that period is not available, these findings provide valuable information on the water quality status in Santa Cruz Island over the 9-year period analyzed herein and can be used as a baseline for future analysis. Thus, the importance of maintaining long term water quality monitoring to keep track of water status and assess whether alterations are due to impacts of human-induced activities or natural climate-driven processes is clearly highlighted.

Additionally, our results suggested that background levels calculation worked better with parameters at coastal sites than inland sites suggesting that processes underlying coastal sites provide more suitable conditions for the application of the techniques applied herein. While previous research addressed the use of the iterative 2σ and the distribution function techniques in groundwater bodies only, our results suggested that these techniques can also be considered for evaluating coastal water bodies.

Finally, results highlighted the importance of calculating background values for specific sites since the conditions and distribution of the parameters may be different and could lead to misinterpretations when assessing the degree of water alteration [17,22]. This was the case for coastal TP levels that exceed almost 100% with respect to the limits of Hawaii while background calculations suggested that levels were subject to natural increases that surpasses Hawaiian specific criteria for estuaries (3 NTU). Thus, the application of large-scale background values to evaluate local status of water quality is not recommended since local background is constrained by local conditions [17,18,21,22].

4.5. Relative Influence of Population Change on Water Quality Paramertes

Results suggested that the regression analysis method applied for this study could potentially serve as an effective tool to evaluate the significant influence of population change on water quality conditions and estimate the magnitude of its impacts. However, the temporal and spatial correlations are not fully represented in this analysis. To identify the sources of pollutant loads from point and non-point pollution sources (e.g., agriculture, rural domestic, industries, municipal waste, or animal waste), spatial regression methods have been proposed as possible effective methods [60] and should be considered for future analysis. Nevertheless, results from the sensitivity analysis not only supports information obtained from background levels analysis, but provides valuable information that may serve as a scientific basis for water quality management, future research, and decision making [39,40,43] for Santa Cruz Island.

5. Conclusions

A nine year dataset was successfully evaluated providing valuable information of the water quality status in Santa Cruz Island that could serve as a baseline for effective water management in the Pelican Bay watershed. The influence of human activities such as discharges of untreated sewage, combustion, stormwater and agricultural runoffs could cause some enrichment of parameters such as nutrients and coliforms posing a risk for human and ecosystem health. Additional management practices should be considered for recreational coastal sites with high concentrations of coliforms as well as drinking and domestic water with high concentrations of Sal, EC, Turb and FC. Long term use of saline water for irrigation also needs to be addressed. Our results have elucidated that outer thresholds of background levels along with the sensitivity analysis of parameters to changes in population, may serve for defining site-specific limits to control water quality and to distinguish values that are a product of natural processes from anthropogenic activities. However, more specific monitoring is needed to understand the potential water impairment in the Galapagos Islands. Finally, the establishment of long-term water quality monitoring programs in the Galapagos island is a milestone contribution to the preservation and conservation of water resources in the Archipelago.

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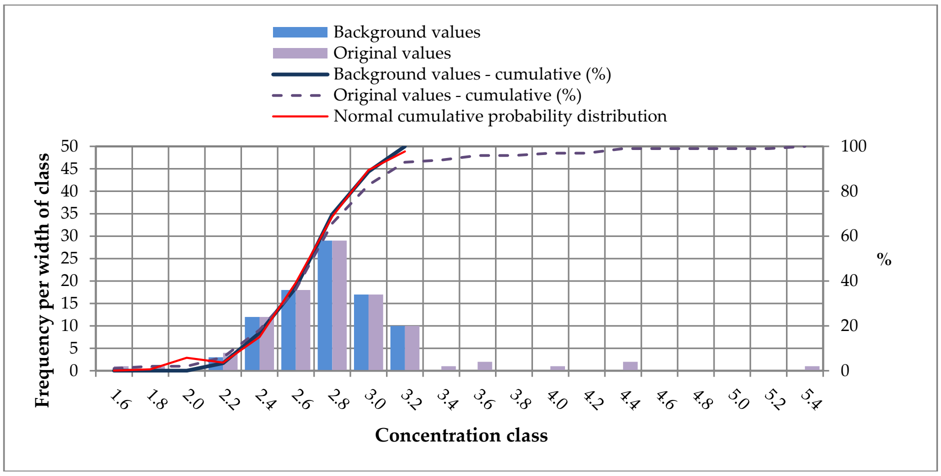
Appendix A

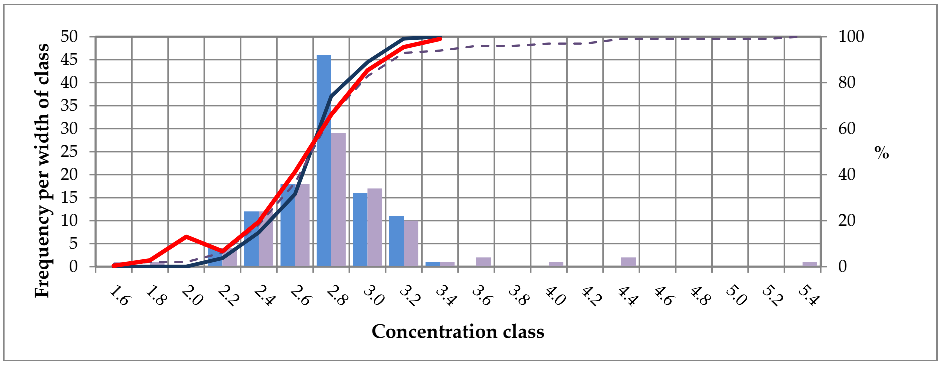
Table A1. Water quality parameters measured by Galapagos National Park during 2007–2015 at all study sites, including their abbreviations, units, analytical methods, and data availability [1].

Parameters	Abbreviations	Units	Time Coverage						
			I1	I2	I3	C1	C2	C3	C4
Water temperature	WT	°C	✓	✓	✓	✓	✓	✓	✓
Turbidity	Turb	NTU	✓	✓	✓	✓	✓	✓	✓
Total Coliforms	TC	MPN 100 mL^{-1}	✓	✓	✓	✓	n.d.	n.d.	n.d.
Fecal Coliforms	FC	MPN 100 mL^{-1}	✓	✓	✓	✓	n.d.	n.d.	n.d.
Salinity	Sal	g L^{-1}	✓	✓	✓	✓	✓	✓	✓
Dissolved oxygen	DO	mg L^{-1}	✓	✓	✓	✓	✓	✓	✓
Electrical Conductivity	EC	mS cm^{-1}	✓	✓	✓	✓	✓	✓	✓
pH	pH	pH unit	✓	✓	✓	✓	✓	✓	✓
Nitrate	NO_3^--N	mg L^{-1}	*	*	*	*	*	*	*
Nitrite	NO_2^--N	µg L^{-1}	*	*	*	*	*	*	*
Total Phosphorus	TP	mg L^{-1}	*	*	*	*	*	*	*

Note: [1] Retrieved from the original planning document [30]. ✓ 91% time coverage: No data for March 2008 and February, March, May, June, July, September, October, and November 2009 (n = 99). * 30%—time coverage: Available data for January, April, August, and December of each year (n = 36). n.d.: no data.



(a)



(b)

Figure A1. Background concentrations for EC at I1 using: (**a**) the iterative 2σ technique (background levels: 2.1–3.2 mS/cm; Lilliefors test statistic [α = 0.05]: Tcrit. = 0.094, T = 0.058), and; (**b**) the distribution function (background levels: 2–3.3 mS/cm; Lilliefors test statistic [α = 0.05]: Tcrit. = 0.085, T = 0.130).

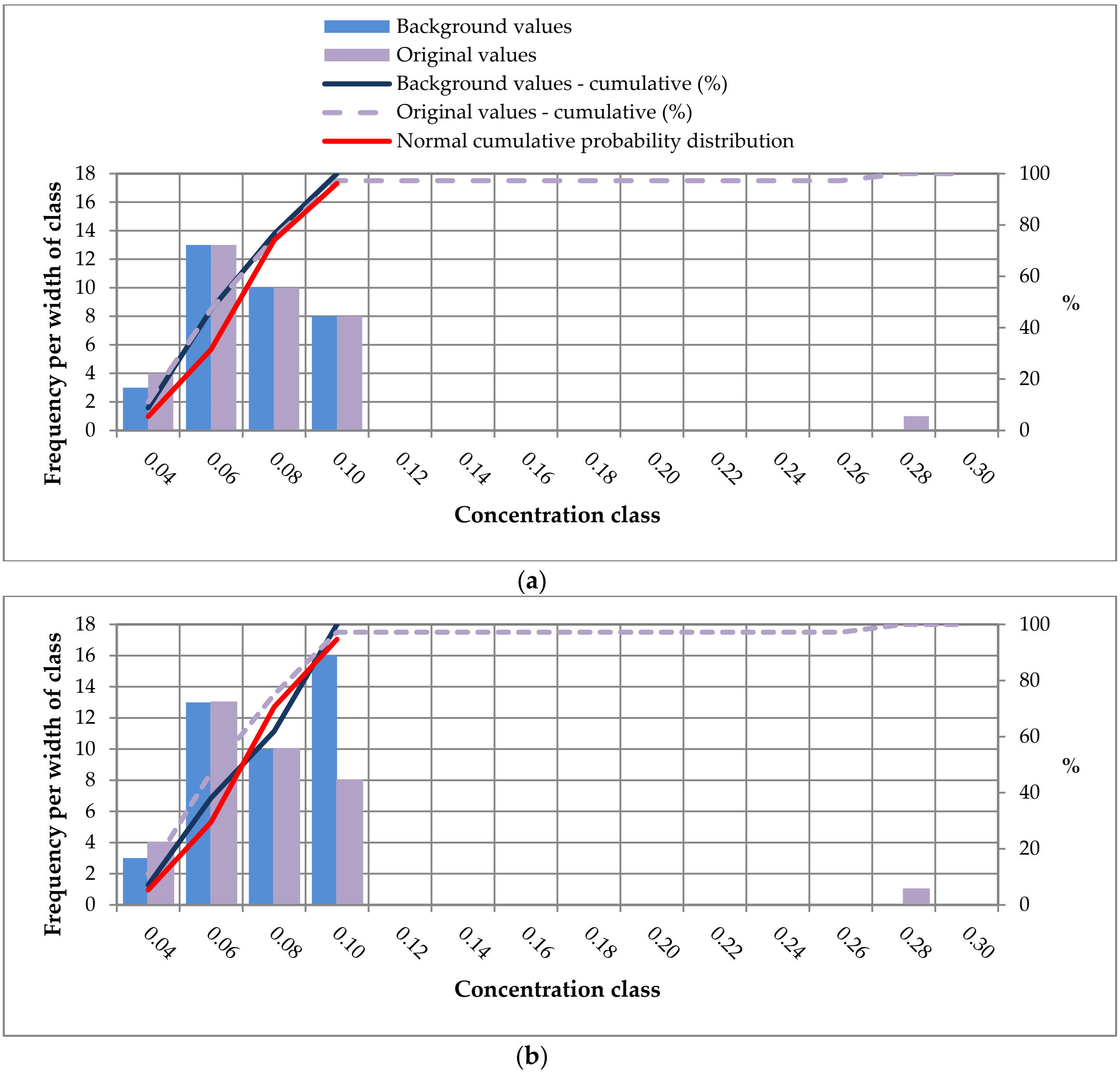


Figure A2. Background concentrations for NO_3^--N at C1 using: (**a**) the iterative 2σ technique (background levels: 0–0.1 mg/L; Lilliefors test statistic [α = 0.05]: Tcrit. = 0.152, T = 0.155), and (**b**) the distribution function (background levels: 0–0.1 mg/L; Lilliefors test statistic [α = 0.5]: Tcrit. = 0.137, T = 0.086).

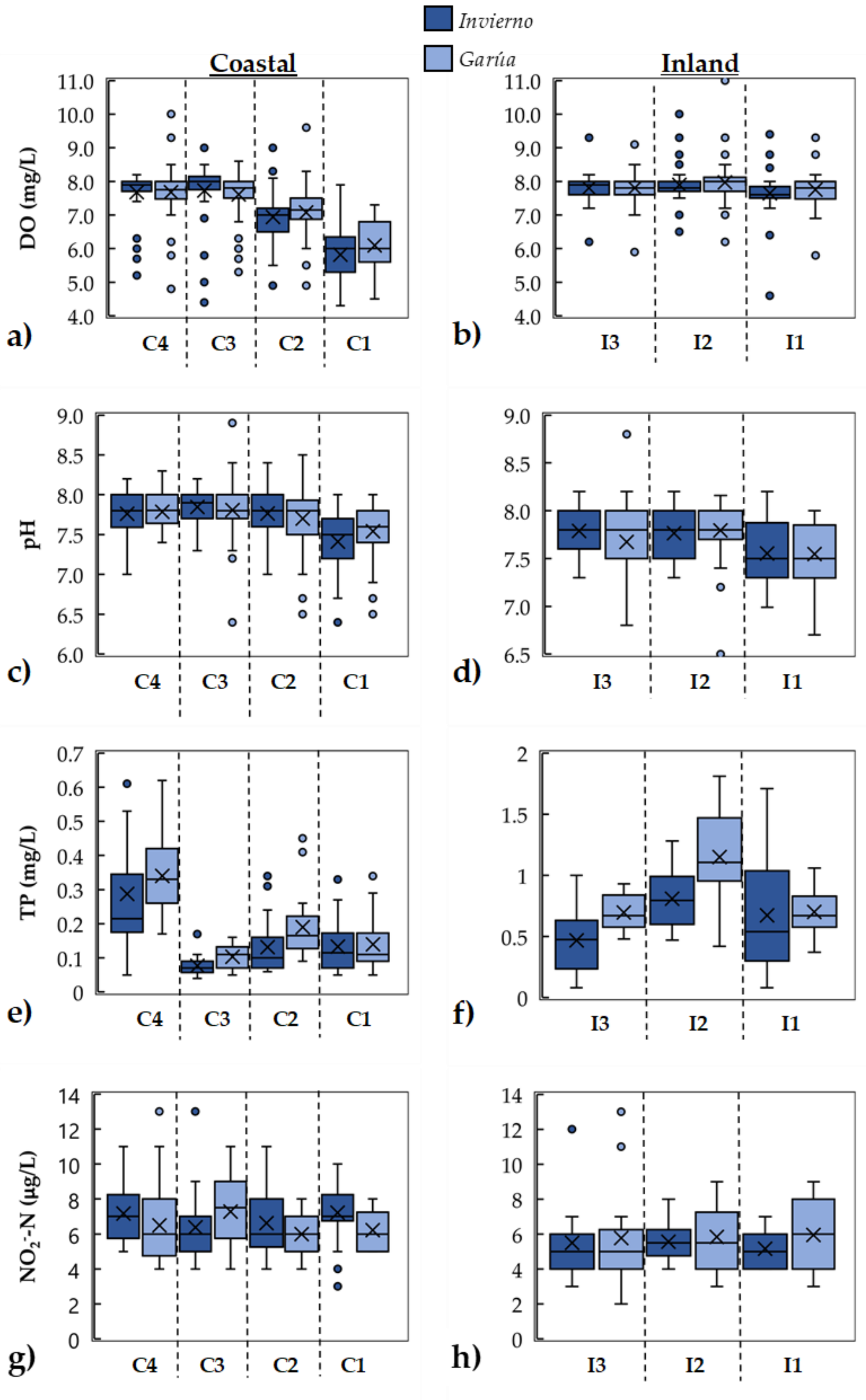


Figure A3. Seasonal variation: Invierno (January–May) and garúa (June–December) variations for (**a**) DO coastal, (**b**) DO inland, (**c**) pH coastal, (**d**) pH inland, (**e**) TP coastal, (**f**) TP inland, (**g**) NO_2^--N inland, and (**h**) NO_2^--N coastal. The scale for coastal TO (C1, C2, C3, and C4) differs from the scale for inland TP (I1, I2, and I3).

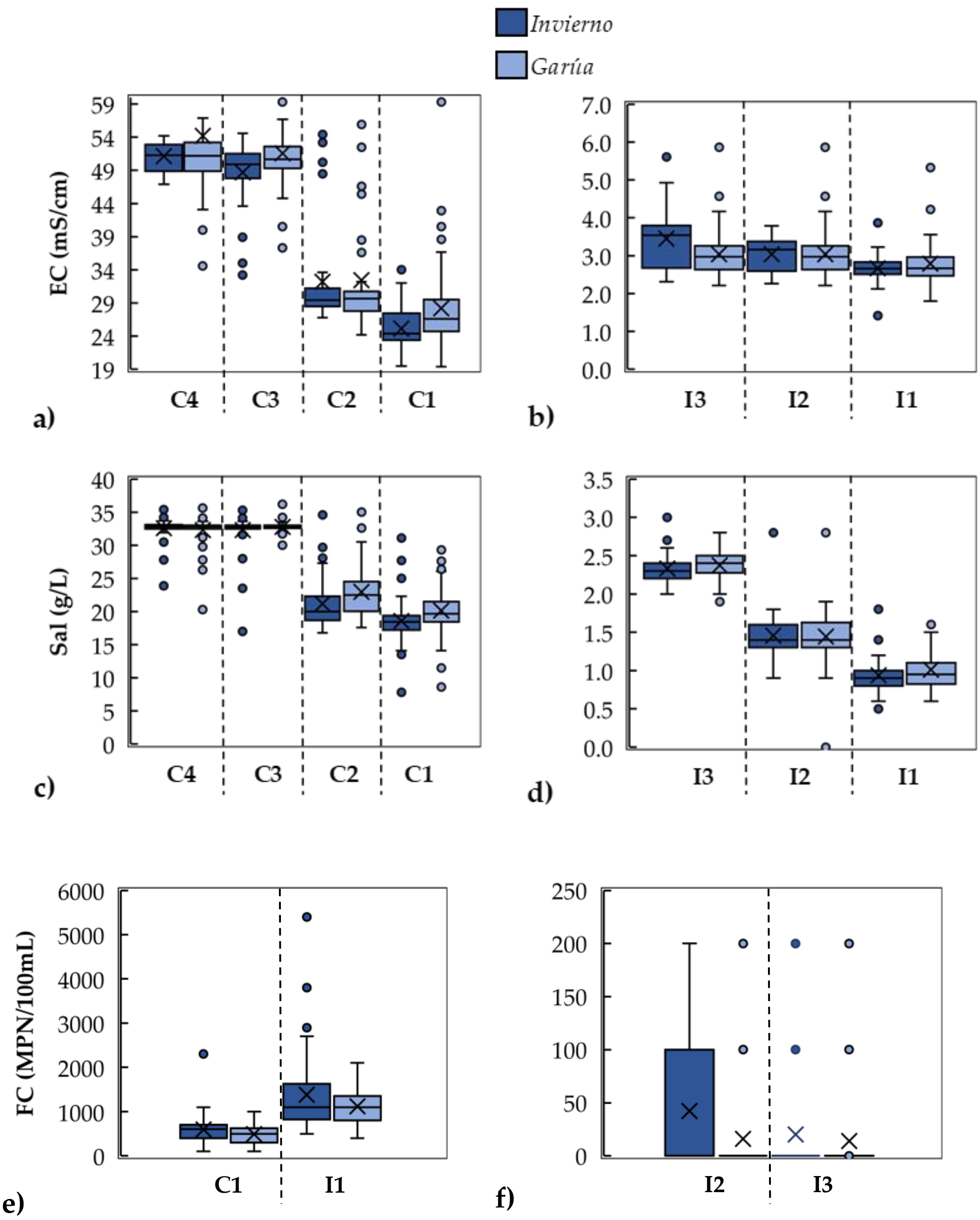


Figure A4. Seasonal variation. Invierno (January–May) and garúa (June–December) variations for (**a**) EC coastal, (**b**) EC inland, (**c**) Sal coastal, (**d**) Sal inland, and (**e**) FC coastal (left) TC inland (right), and (**f**) FC inland. The scale at coastal sites differs from the scale at inland sites.

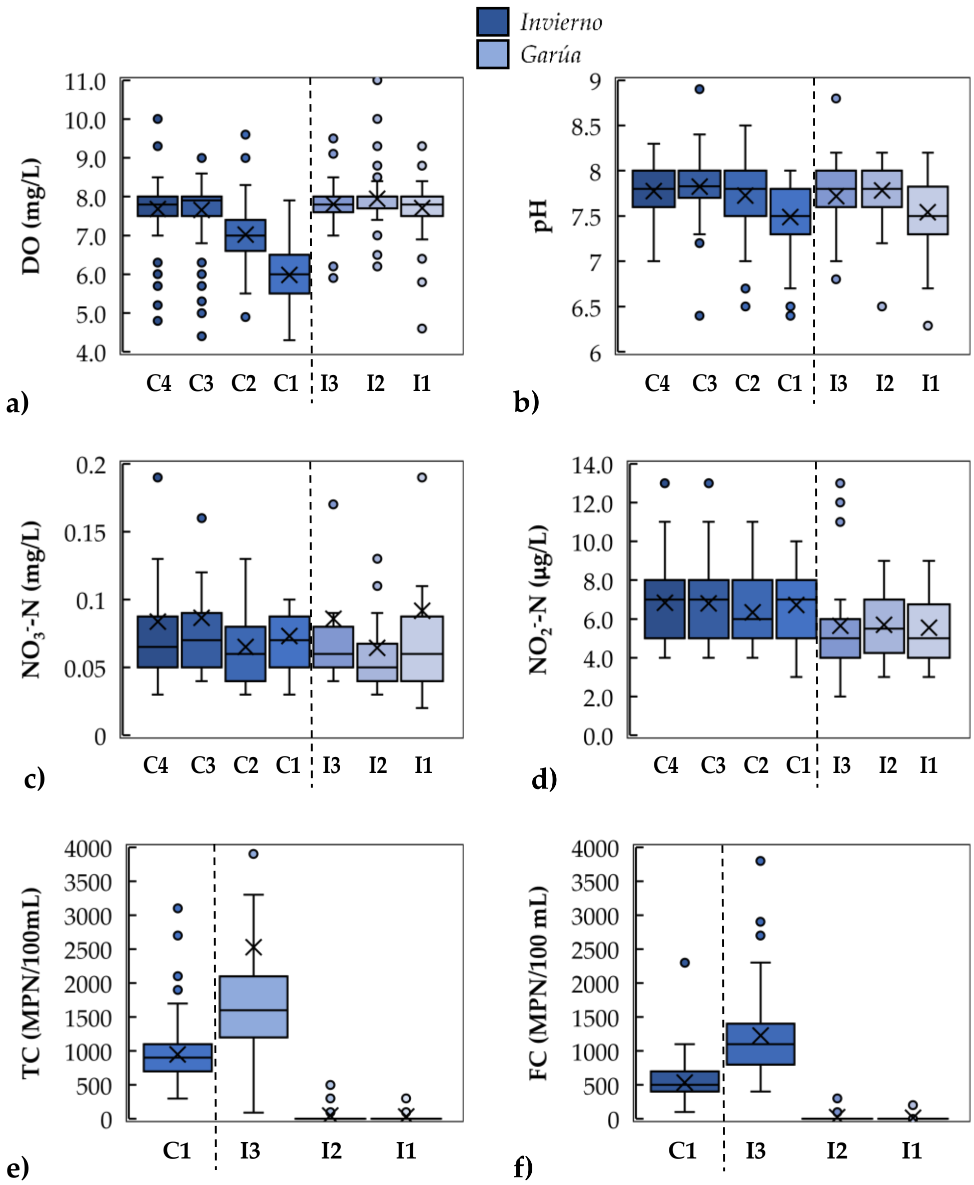


Figure A5. Spatial variation for (**a**) DO, (**b**) pH, (**c**) NO_3^--N, (**d**) NO_2^--N, (**e**) TC, and (**f**) FC. Study sites are ordered by proximity to the sea, being C2 the closest to the sea and I2 the furthest. The upper and lower quartiles are represented by the ends of the box, the median is the horizontal line between box ends, the mean is marked by "x", the whiskers indicate variability outside the upper and lower quartiles and, finally, points outside whiskers are considered as outliers. TC and FC data only exists for C1 at the coastal sites.

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