Relationships between benthic infauna and groundwater eutrophication on a sandy beach in southern Brazil

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Abstract
Urban expansion in Brazilian coastal zones has caused various anthropic impacts on coastal marine ecosystems that have resulted from unorganized use and the lack of infrastructure projects. The inadequate disposal of domestic and industrial effluents in coastal waterbodies is notable, which can cause severe environmental problems. For sandy beaches, the relationships between the contamination of groundwater with domestic sewage and the possible effects on spatial and temporal variations in the density and composition of benthic infauna are still poorly understood. This work aimed to relate variations in benthic infaunal associations with the concentrations of groundwater nutrients in summer and winter on Enseada Beach. The greater concentrations of nutrients in water percolating through the sediment in the summer, increasing of domestic effluents, and periods of intense precipitation increased the contamination of the surface and groundwater. This contributes to an increase in the population density of *Thoracosphelia furcifera*, demonstrating its use as an indicator of eutrophication of the groundwater, allowing monitoring and contribution to actions aimed at improving the environmental quality of sandy beaches.

Keywords Sandy beaches · Benthic infauna · Groundwater · Eutrophication · Domestic effluents · *Thoracosphelia furcifera*

Introduction
Sandy beaches comprise one of the longest ecosystems along coastal Brazil (Amaral et al. 2016), are characterized as transition zones between oceans and continents, and are socially, economically and ecologically important (Defeo and McLachlan 2013; Amaral et al. 2016; McLachlan et al. 2018). They are highly hydrodynamic sedimentary environments, with a physical structure determined mainly by environmental energy from waves, and vary based on the degree of exposure. The interactions between these factors produce types of beaches with morphodynamics that range from reflective to dissipative (Wright and Short 1984; Short 1996; Short 2006). At a local scale, seasonal variation in the sandy beach morphodynamic can rapidly change the population dynamic of organisms in the benthic community (Defeo et al. 2009; Cisneros et al. 2011), which is involved in various ecological functions at multiple trophic levels, such as breaking down organic material in the sediment, substrate aeration, nutrient cycling and transferring energy to animals that feed on them (e.g., birds, reptiles, and fish) (Campanyà-Llovet et al. 2017). Furthermore, these organisms are sensitive to
environmental changes, since they have sessile or sedentary habits, and can be used as bioindicators when evaluating impacts caused by many human activities in aquatic environments (Coutinho and Bernardino 2017).

Coastal waterbodies (i.e., estuaries, bays, lagoons, inlets, tidal rivers, and tidal creeks) normally carry water with domestic and/or industrial effluent to beaches and intense rainfall results in groundwater saturation that causes water to percolate through the sediment of the profiles. Due to the bacterial action in effluent, the percolation water carries nutrients to beaches, which can favor the growth of populations of primary producers. The composition, diversity, biomass, and distribution of species of the phytoplankton community constantly change due to seasonal and temporal variations (Córdoba-Mena et al. 2020). Furthermore, algae overgrows when nutrients are in excess and there are ideal light and temperature conditions (Smith et al. 1999; Van Beusekom 2018; Barletta et al. 2019). This can result in reduced water quality, decreasing the quantity of dissolved oxygen by bacterial action (Halliday et al. 2014), which can affect many organisms in the trophic chain (Douglas et al. 2016; Lecher and Mackey 2018). The main effects of organic pollution on benthic organisms are observed in the structure of communities, with a tendency towards a reduction in the number of species sensitive to environmental changes and an increase in the number of opportunistic species (Dauvin et al. 2016; Cândido and Netto 2020). Additionally, individuals can exhibit morphological and ecological changes when exposed to organic contamination for long periods (Gusmao et al. 2016). This type of pollution in these important coastal environments can reduce the ecosystem and socioeconomic services provided, decreasing the environmental sanitary quality of a region (Amaral et al. 2016).

Thus, the objective of this work was to determine how benthic infauna are affected by eutrophication of the groundwater of a profile of Enseada Beach in the summer and winter. This beach was chosen because it has one of the highest urban occupations among the beaches of São Francisco do Sul, Santa Catarina.

Material and methods

Study area

São Francisco do Sul Island is bordered by the Atlantic Ocean to the east, Babitonga Bay to the north and west, and the Linguado Canal to the south (Possamai et al. 2010) (Fig. 1). The climate of the region is classified as temperate subtropical and humid subtropical, with winds predominantly from the south-southeast and east-northeast quadrants (Alvares et al. 2014). Enseada Beach is near the mouth of Açaraí Lagoon in the northern part of the island, extends approximately 2,260 m along the coast, and has a reflective profile in the summer, intermediary profile in the winter, and sediment with medium- to fine-grained sand (Lorenzi and Baran 2017). It has one of the highest amounts of urban occupation among the beaches in São Francisco do Sul. The beach is heavily used for tourism and recreation, mainly in the summer when the population of residents in São Francisco do Sul (ca. 50,746 inhabitants) (IBGE 2020) increases 8 times, especially in the northeastern part of the island where there are places to bathe (De Lima et al. 2018).

Sampling the benthic infauna

To determine the variability of the benthic infauna and environmental variables, samples were taken in the winter (September 2017) and summer (March 2018) from a profile of Enseada Beach (Fig. 1). In this profile, four of ten transects disposed in a 30 m perpendicular line near the drift line were randomly spaced and oriented perpendicular to the coastline in the intertidal zone (Rosa Filho et al. 2015), with ten points equidistant between themselves in each transect from the drift line (P10) to the low tide water line (P1). At each collection point a biological sample was collected, 15 cm deep, with a 0.05m² steel cylinder. In the field, the samples were washed in bags with a 500 μm opening and the remaining material was placed in plastic bags and fixed in 10% formalin. In the laboratory, the material was sorted with a stereomicroscope and the organisms were identified (Melo 1999; Amaral and Nonato 1996; Melo 1996; Rios 1994).

Sampling the sediment

For the granulometric analysis of the beach profile, sediment samples were collected along one transect and stored in 300mL plastic pots. The samples were dried to determine the percentage of moisture (% moisture), and the percentage of calcium carbonate (% CaCO₃) was determined by the reaction in 10% HCl (Dean 1974). Subsequently, the sediment was sieved to determine the diameters of the sandy fraction (Suguio 1973) and pipetting was conducted to determine the silt and clay fractions (Galehouse 1971). The mean diameter, asymmetry, selection, and kurtosis of the sediment samples from each point in the profile were determined with the software Sysgram 3.0 (Camargo 2006).

Morphodynamics and percolation water sampling

On one of the transects, the following was determined: the slope of the profile, with an automatic level (CST/Berger® 55-SAL24ND 24x) and graduated ruler; the depth of the groundwater, with a graduated tape measure; percolation

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water salinity, with a refractometer; and temperature, with a thermometer in Celsius. Percolation water samples were collected from three transects (according to the distances used to infauna transects randomization in winter and summer), where each point of sediment was drilled with an excavator. Thirty samples were taken, which were stored in 300 mL bottles and cooled in a freezer until the nutrient analysis. The samples were filtered before with a 0.45-μm Millipore membrane, and consecutively, the concentrations of ammonia, nitrate, nitrite, and phosphate (mg/L) were determined with a Lamotte Smart® 3 Colorimeter (Jeffery et al. 1989).

Statistical analysis

Beach morphodynamics

The mean values for groundwater depth, profile slope, moisture and calcium carbonate percentages, mean diameter, asymmetry, selection, and kurtosis of the sediment grains for the seasons (winter, WIN; summer, SUM) and respective profile points (P10 to P1) were submitted to the Kolmogorov-Smirnov normality test ($p$-value < 0.05). Variables that did not meet this assumption were logarithmized and retested. A principal component analysis (PCA) (Legendre and Legendre 2012) was applied to this set of variables to determine the relationships of the clusters of seasons of the year and profile points with the morphodynamic variables.

Groundwater variables

The means for pH, salinity, temperature, groundwater depth, ammonia, nitrate, nitrite, and phosphate for the seasons of the year (winter, WIN; summer, SUM) and the respective profile points (P10 to P1) were submitted to a Kolmogorov-Smirnov (K-S) normality test. The significant differences between the seasons were tested with a parametric t test and Mann-Whitney $U$ test. The differences of the mean values of the environmental variables between the profile points (P10 to

Fig. 1 Location of Enseada Beach, São Francisco do Sul, Santa Catarina, Brazil. Rectangle in black represents the area of the beach where sampling was performed.
The densities of the benthic infauna taxa (ind./0.05 m²), total density, and richness (taxa/0.05 m²) were initially submitted to a K-S normality test. We used a Mann-Whitney U test for the variables that did not meet the normality assumption and a parametric t test for the variables that met this assumption, both for the purpose of comparing the seasons (WIN and SUM). The differences in the infauna density and richness for the profile points were tested with a Kruskal-Wallis ANOVA and post hoc multiple comparisons were applied (Underwood 1997; Vieira 2010). To determine the clusters of infauna taxa, the mean values of the densities for the seasons of the year (WIN and SUM) and profile points (P10 to P1) were submitted to a K-S normality test and, subsequently, a correspondence analysis (CA) (Legendre and Legendre 2012).

**Infauna**

The densities of the benthic infauna taxa (ind./0.05 m²), total density, and richness (taxa/0.05 m²) were initially submitted to a K-S normality test. We used a Mann-Whitney U test for the variables that did not meet the normality assumption and a parametric t test for the variables that met this assumption, both for the purpose of comparing the seasons (WIN and SUM). The differences in the infauna density and richness for the profile points were tested with a Kruskal-Wallis ANOVA and post hoc multiple comparisons were applied (Underwood 1997; Vieira 2010). To determine the clusters of infauna taxa, the mean values of the densities for the seasons of the year (WIN and SUM) and profile points (P10 to P1) were submitted to a K-S normality test and, subsequently, a correspondence analysis (CA) (Legendre and Legendre 2012).

**Groundwater and community interactions**

The normality of the mean values for taxon density, moisture and temperature of the sediment, groundwater depth, pH and nitrate, nitrite, ammonia, and phosphate concentrations in the percolation water for the seasons (WIN and SUM) and profile points (P1 to P10) were tested (K-S) to apply a canonical correspondence analysis (CCA). Subsequently, a Monte Carlo test with 100 permutations was applied to determine which groundwater variables significantly (p-value < 0.05) influence the clusters of benthic infauna taxa (Palmer 1993).

**Results**

**Environmental variables**

The unevenness of the profile varied in topography and length. The most uniform profile was in the winter, with a variation of 1.53m of unevenness and a total length of 60 m (Fig. 2A). In the summer, the topographic variation was greater, with 1.27m of unevenness and a total length of 42 m (Fig. 2B).

The mean values for groundwater depth were significantly higher in the summer (p-value < 0.05). For groundwater depth, pH, and salinity, the differences between the seasons were not different (Table 1). The mean values for groundwater depth were significantly higher in P10 (1.13m), P9 (0.62m), and P5 (0.53m) (Table 2). Salinity (P1: 36.67 PSU; P2: 35.83 PSU; and P3: 35.33 PSU) and pH (P1: 8.45; P2: 8.45; and P3: 8.30) in P1, P2, and P3 were significantly higher (Table 2). The mean values for ammonia were significantly greater in P5 (2.52 mg/L) and P8 (2.30 mg/L) compared to P1 (1.11 mg/L) and P2 (1.02 mg/L). The mean concentrations for nitrite were greater in P7 (0.14 mg/L), P5 (0.09 mg/L), P3 (0.03 mg/L), P8 (0.02 mg/L), and P6 (0.02 mg/L). The mean values for phosphate were greater in P7 (1.93 mg/L), P6 (1.15 mg/L), P2 (1.08 mg/L), P10 (1.06 mg/L), P9 (1.08 mg/L), P8 (0.98 mg/L), and P3 (0.95 mg/L). The differences in the mean values for temperature and nitrate in the profile points were not significant (Table 2). In the results of the PCA, component 1 (PC1) contributed 17.88% of the variance and related the increase in temperature, ammonia, nitrite, nitrate, and phosphate values to the profile points in the summer, with a tendency for an increase in P7 and P5. In the cluster of winter points, the values of these variables were intermediate. The granulometric composition of Enseada Beach was well selected and had a very positive asymmetry. In both seasons, the mean diameters of the grains were composed of fine sand in all the profile points and there was an extremely leptokurtic distribution (Fig. 3, SI. 1).

In the comparisons between seasons of the year, the temperature of the percolation water, ammonia, nitrite, nitrate, and phosphorous were significantly higher in the summer (p-value < 0.05). For groundwater depth, pH, and salinity, the differences between the seasons were not different (Table 1). The mean values for groundwater depth were significantly higher in P10 (1.13m), P9 (0.62m), and P5 (0.53m) (Table 2). Salinity (P1: 36.67 PSU; P2: 35.83 PSU; and P3: 35.33 PSU) and pH (P1: 8.45; P2: 8.45; and P3: 8.30) in P1, P2, and P3 were significantly higher (Table 2). The mean values for ammonia were significantly greater in P5 (2.52 mg/L) and P8 (2.30 mg/L) compared to P1 (1.11 mg/L) and P2 (1.02 mg/L). The mean concentrations for nitrite were greater in P7 (0.14 mg/L), P5 (0.09 mg/L), P3 (0.03 mg/L), P8 (0.02 mg/L), and P6 (0.02 mg/L). The mean values for phosphate were greater in P7 (1.93 mg/L), P6 (1.15 mg/L), P2 (1.08 mg/L), P10 (1.06 mg/L), P9 (1.08 mg/L), P8 (0.98 mg/L), and P3 (0.95 mg/L). The differences in the mean values for temperature and nitrate in the profile points were not significant (Table 2). In the results of the PCA, component 1 (PC1) contributed 17.88% of the variance and related the increase in temperature, ammonia, nitrite, nitrate, and phosphate values to the profile points in the summer, with a tendency for an increase in P7 and P5. In the cluster of winter points, the values of these variables tended to decrease (Fig. 4, SI. 2). PC2 contributed 9.69% of the variance and related the increase in salinity and pH to the lower profile points, which decreased in the direction of the higher points of the beach profile (Fig. 4, SI. 2).

**Benthic infauna**

The total density and richness of the infauna taxa were the same in the winter (13.12 ind./0.05 m² and 1.8 taxa/0.05
m², respectively) and summer (10.9 ind./0.05 m² and 1.57 taxa/0.05 m², respectively). However, the densities of *Donax hanleyanus* (1.32 ind./0.05 m²) and *Hastula cinerea* (0.200 ind./0.05 m²) were significantly higher in the winter (Table 3). In the summer, the densities of a species of Diptera (0.17 ind./0.05 m²) and *Thoracophelia furcifera* (5.20 ind./0.05 m²) were higher (Table 3). The densities of *Hemipodia olivieri*, *Albunea paretii*, a species of Coleoptera, *Excirolana braziliensis*, *Emerita brasiliensis*, *Haploscoplos* sp., *Scolelepis goodbodyi*, and *Orchestia* sp. were the same (Table 3).

The results of the comparisons of mean densities among the profile points had significantly high density (P1: 18.75 ind./0.05 m², P2: 32.87 ind./0.05 m²; and P3: 20.25 ind./0.05 m²) and richness (P1: 2.75 ind./0.05 m², P2: 2.75 ind./0.05 m², and P3: 2.35 ind./0.05 m²) values in the lower mesolittoral (Table 4). In this part of the profile, *Scolelepis goodbodyi* (P1: 14.0 ind./0.05 m², P2: 32.50 ind./0.05 m², and P3: 17.0 ind./0.05 m²), *Haploscoplos* sp. (P1: 1.38 ind./0.05 m², P2: 0.50 ind./0.05 m², and P3: 1.38 ind./0.05 m²), and *Emerita brasiliensis* (P1: 1.0 ind./0.05 m² and P2: 1.0...
Table 1 Results of the t test (t) and Mann-Whitney U test (U) comparing winter (WIN) and summer (SUM), showing the mean values, standard deviation (sd) and comparisons, ns: non-significant difference; *: significant difference with p-value < 0.05. N, sample number; df, degrees of freedom

| Variables                  | Winter (N=30) Mean (sd) | Summer (N=30) Mean (sd) | t (p-value) | U (p-value) | N= 60 df= 29 Comparisons |
|---------------------------|-------------------------|-------------------------|-------------|-------------|---------------------------|
| Temperature (°C)          | 19.30 (0.47)            | 22.17 (0.46)            | -           | 0.00 (0.000) * | SUM > WIN                |
| Ammonia (mg/L)            | 1.12 (0.61)             | 2.49 (1.02)             | -6.32 (0.000) * | -           | SUM > WIN                |
| Nitrite (mg/L)            | 0.005 (0.007)           | 0.07 (0.09)             | -8.30 (0.000) * | -           | SUM > WIN                |
| Nitrate (mg/L)            | 0.13 (0.17)             | 0.35 (0.28)             | -5.33 (0.002) * | -           | SUM > WIN                |
| Phosphate (mg/L)          | 0.67 (0.27)             | 1.41 (0.71)             | -6.71 (0.000) * | -           | SUM > WIN                |
| Salinity (PSU)            | 29.53 (6.84)            | 31.63 (4.94)            | -           | 389.0 (0.367) ns | ns                      |
| Groundwater depth (m)     | 0.46 (0.35)             | 0.59 (0.27)             | -1.65 (0.104) | -           | ns                       |
| pH                        | 8.18 (0.17)             | 8.14 (0.24)             | -           | 0.61 (0.544) | ns                       |

ind./0.05 m²) were dominant. Donax hanleyanus was dominant in the lower and intermediary parts of the profile (P1: 2.25 ind./0.05 m², P2: 0.75 ind./0.05 m², P3: 1.5 ind./0.05 m², P4: 1.5 ind./0.05 m², P5: 1.12 ind./0.05 m², and P6: 0.62 ind./0.05 m²) and the density of Thoracophelia furcifera (P5: 5.12 ind./0.05 m², P6: 6.25 ind./0.05 m², P7: 7.35 ind./0.05 m², and P8: 7.25 ind./0.05 m²) was significantly greater in the intermediary part and initial part of the upper portion of the beach profile. The differences in the densities of the remaining benthic infauna taxa were not significant among the profile points (Table 4).

The correspondence analysis (CA) produced clusters of benthic infauna by profile point and season, with H. cinerea, Haploscoloplos sp., D. hanleyanus, H. olivieri, and S. goodbodyi corresponding to the lower part (P1 and P3) and initial portion of the intermediary part of the profile (P4 and P5) in both seasons of the year and predominating in the intermediary points (P6, P7, and P8) in the winter (Fig. 5). E. braziliensis, Orchestia sp., and Coleoptera formed a cluster in the upper points (P9 and P10) in the two seasons and only T. furcifera occupied the upper intermediary portion in the summer (P7 and P8) (Fig. 5).

In the results of the canonical correspondence analysis (CCA), the increase in groundwater depth (axis I: related to 76.4%) in the upper part of the profile in the summer and winter significantly influenced the cluster with the highest densities of Coleoptera, E. braziliensis, and Orchestia sp. Furthermore, the decrease of groundwater depth influenced the increase in the density of the cluster of H. olivieri, D. hanleyanus, Haploscoloplos sp., S. goodbodyi, and H. cinerea in the summer and winter, when the pH and moisture values of the sediment increased. In axis II (related to 14%), the increase in the concentration of nitrate significantly influenced the increase in the density of T. furcifera at the border between the intermediary (P5) and upper (P7 and P8) parts of the profile in the summer; the concentrations of the remaining nutrients increased with the percolation

Table 2 Results of the analyses of variance (ANOVARAs) for the environmental variables comparing the sample points (P1 to P10) and showing the mean values, standard deviation (sd), F value of parametric ANOVA, H value of Kruskal-Wallis ANOVA, ns non-significant difference and *: significant difference with p-value < 0.05. N, sample number; df, degrees of freedom

| Variables                  | P1 (N=6) Mean (sd) | P2 (N=6) Mean (sd) | P3 (N=6) Mean (sd) | P4 (N=6) Mean (sd) | P5 (N=6) Mean (sd) | P6 (N=6) Mean (sd) | P7 (N=6) Mean (sd) | P8 (N=6) Mean (sd) | P9 (N=6) Mean (sd) | P10 (N=6) Mean (sd) | F (p-value) | H (p-value) | N= 60 df= 29 Comparisons |
|---------------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------|-------------|---------------------------|
| GW Depth (m)              | 6.23 (0.13)       | 6.57 (0.17)       | 6.29 (0.12)       | 6.42 (0.27)       | 6.57 (0.19)       | 6.53 (0.29)       | 6.55 (0.26)       | 6.14 (0.13)       | 6.82 (0.17)       | 157.16 (0.000) * | -           | -           |                           |
| Salinity (PSU)            | 30.67 (0.82)      | 31.63 (1.17)      | 35.35 (0.52)      | 34.18 (0.357)     | 33.17 (1.94)      | 36.67 (3.12)      | 27.83 (2.08)      | 27.83 (0.87)      | 22.67 (5.44)      | 21.33 (2.94)      | -           | 46.00 (0.000) * |                           |
| pH                        | 8.45 (0.08)       | 8.90 (0.10)       | 8.38 (0.16)       | 8.15 (0.06)       | 8.81 (0.14)       | 7.97 (0.23)       | 8.90 (0.87)       | 8.12 (0.12)       | 8.88 (0.07)       | 7.99 (0.05)       | 16.10 (0.000) * | -           | -           |                           |
| Ammonia (mg/L)            | 1.62 (0.04)       | 1.11 (0.35)       | 1.09 (0.09)       | 2.23 (0.09)       | 1.91 (0.29)       | 2.87 (0.63)       | 2.38 (0.29)       | 1.78 (0.16)       | 1.19 (0.09)       | 3.45 (0.005) *  | -           | -           |                           |
| Nitrite (mg/L)            | 0.99 (0.00)       | 0.62 (0.04)       | 0.63 (0.04)       | 0.17 (0.81)       | 0.09 (0.18)       | 0.63 (0.02)       | 0.14 (0.55)       | 0.62 (0.02)       | 0.82 (0.02)       | 0.41 (0.01)       | 7.24 (0.000) *  | -           | -           |                           |
| Phosphate (mg/L)          | 0.52 (0.25)       | 1.09 (0.25)       | 0.90 (0.53)       | 0.78 (0.07)       | 0.90 (0.41)       | 1.15 (0.51)       | 0.91 (0.42)       | 0.98 (0.46)       | 1.00 (0.31)       | 1.07 (0.49)       | 5.83 (0.000) *  | -           | -           |                           |
| Nitrate (mg/L)            | 0.21 (0.25)       | 0.16 (0.17)       | 0.16 (0.20)       | 0.23 (0.20)       | 0.25 (0.33)       | 0.11 (0.07)       | 0.35 (0.39)       | 0.12 (0.20)       | 0.29 (0.26)       | 0.28 (0.24)       | 1.05 (0.42) | -           | ns                        |
| Temperature (°C)          | 20.57 (0.53)      | 20.59 (1.53)      | 20.57 (1.54)      | 21.17 (2.84)      | 20.63 (1.30)      | 21.13 (1.80)      | 20.58 (1.66)      | 20.67 (1.53)      | 20.50 (1.44)      | 20.58 (1.66)      | -           | 3.65 (0.032) | ns                        |
water temperature. In the opposite direction of the axis, the reduction in the concentration of nitrate significantly influenced the increase in the densities of *H. olivieri*, *D. hanleyanus*, *E. braziliensis*, *H. cinerea*, and *Orchestia* sp. in the upper points of the profile in the winter; the remaining nutrients and the temperature of the sediment also decreased (Fig. 6, Table 5).

### Discussion

The environmental characteristics of Enseada Beach followed the morphodynamic pattern of sandy beaches in southern Brazil (Amaral et al. 2016), where there is an increase in wind from the south, southeast, east, and northeast in winter (Alvares et al. 2014; Lorenzi et al.

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**Table 3** Results of the Mann-Whitney *U* test (*U*) comparing winter (WIN) and summer (SUM), showing the mean values, standard deviation (sd), and comparisons between seasons, ns non-significant difference and * significant difference with *p*-value < 0.05. *N*, sample number; *df*, degrees of freedom

| Variables                  | Winter (*N* = 40) Mean (sd) | Summer (*N* = 40) Mean (sd) | *U* (*p*-value) | *N* = 80 *df* = 39 Comparisons |
|---------------------------|-----------------------------|-----------------------------|-----------------|--------------------------------|
| *Donax hanleyanus* (Philippi, 1847) | 1.32 (1.64) | 0.25 (0.54) | 492.00 (0.003)* | WIN > SUM |
| *Hastula cinerea* (Born, 1778) | 0.20 (0.52) | 0.00 (0.00) | 680.00 (0.011)* | WIN > SUM |
| Diptera (Latreille, 1802) | 0.00 (0.00) | 0.17 (0.59) | 720.00 (0.042)* | SUM > WIN |
| *Thoracophelia furcifera* (Ehlers, 1897) | 0.00 (0.00) | 5.20 (7.61) | 500.00 (0.000)* | SUM > WIN |
| *Hemipodia olivieri* (Orensanz e Gianuca, 1974) | 0.07 (0.35) | 0.00 (0.00) | 760.00 (0.70) | ns |
| *Albunea paretii* (Guérin & Méneville, 1853) | 0.07 (0.27) | 0.00 (0.00) | 740.00 (0.08) | ns |
| Coleoptera (Latreille, 1802) | 0.00 (0.00) | 0.07 (0.35) | 760.00 (0.16) | ns |
| *Exciriana braziliensis* (Richardson, 1912) | 0.30 (0.99) | 0.30 (0.69) | 731.50 (0.29) | ns |
| *Emerita brasiliensis* (Schmitt, 1935) | 0.20 (0.52) | 0.20 (0.61) | 782.00 (0.78) | ns |
| *Haploscoplos* sp. (Verill, 1873) | 0.45 (1.45) | 0.22 (0.73) | 743.50 (0.37) | ns |
| *Scolelepis goodbodyi* (Jones, 1962) | 10.42 (17.11) | 4.45 (9.31) | 665.50 (0.16) | ns |
| *Orchestia* sp. (Leach, 1814) | 0.07 (0.27) | 0.02 (0.16) | 760.00 (0.31) | ns |
| Total density | 13.12 (18.03) | 10.90 (10.27) | 752.50 (0.65) | ns |
| Richness | 1.80 (1.26) | 1.57 (1.13) | 732.50 (0.51) | ns |

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Fig. 4 Result of the principal component analysis (PCA) showing the correlations between the sample points (P1 to P10) during each season (WIN: winter; SUM: summer) and the environmental variables [salinity (PSU), temperature (°C), ammonia (mg/L), nitrite (mg/L), nitrate (mg/L) and phosphate(mg/L)]. Cumulative percentage of variance for principal component 1 (PC1 17.88%) and principal component 2 (PC2 9.69%). See SI. 2 for mean values and components eigenvectors.
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Table 4 Results of the Kruskal–Wallis analysis of variance for the taxa between sample points (P1 to P10). Showing the mean values, standard deviation (sd), $H$ value, and comparisons; ns non-significant differences and *: significant difference with $p$-value < 0.05. N, sample number; df, degrees of freedom

| Variables            | P1 (N=8) Mean (sd) | P2 (N=8) Mean (sd) | P3 (N=8) Mean (sd) | P4 (N=8) Mean (sd) | P5 (N=8) Mean (sd) | P6 (N=8) Mean (sd) | P7 (N=8) Mean (sd) | P8 (N=8) Mean (sd) | P9 (N=8) Mean (sd) | P10 (N=8) Mean (sd) | H (p-value) | NS/df | Comparisons |
|----------------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------|-------|--------------|
| Donax hanleyanus     | 2.25 (2.43)        | 0.75 (0.73)        | 1.98 (1.07)        | 1.50 (0.99)        | 1.12 (0.58)        | 6.62 (1.06)        | 0.12 (0.35)        | 0.00 (0.00)        | 0.00 (0.00)        | 0.00 (0.00)        | 28.35 (0.005) | *P1P2P3P4P5P6P7P8P9P10 |
| Eucelopa brasiliensis | 1.90 (2.10)        | 1.00 (1.07)        | 0.00 (0.00)        | 0.00 (0.00)        | 0.00 (0.00)        | 0.00 (0.00)        | 0.00 (0.00)        | 0.00 (0.00)        | 0.00 (0.00)        | 0.00 (0.00)        | 18.77 (0.001) | *P1P2P3P4P5P6P7P8P9P10 |
| Haplocladus sp.      | 1.57 (2.59)        | 0.50 (0.78)        | 1.73 (2.15)        | 0.00 (0.00)        | 0.12 (0.06)        | 1.00 (0.00)        | 0.00 (0.00)        | 0.00 (0.00)        | 0.00 (0.00)        | 0.00 (0.00)        | 20.60 (0.006) | *P1P2P3P4P5P6P7P8P9P10 |
| Scoliepis goodbodyi  | 14.0 (24.14)       | 32.50 (25.26)      | 17.00 (11.59)      | 6.75 (6.02)        | 4.50 (4.47)        | 1.50 (1.69)        | 1.00 (0.00)        | 1.00 (0.00)        | 1.00 (0.00)        | 1.00 (0.00)        | 52.00 (0.006) | *P1P2P3P4P5P6P7P8P9P10 |
| Thoracophilia furcierea | 0.00 (0.00)       | 0.00 (0.00)        | 0.00 (0.00)        | 0.00 (0.00)        | 0.00 (0.00)        | 0.00 (0.00)        | 0.00 (0.00)        | 0.00 (0.00)        | 0.00 (0.00)        | 0.00 (0.00)        | 27.62 (0.001) | *P1P2P3P4P5P6P7P8P9P10 |
| emptied                | 2.75 (1.03)        | 2.75 (1.03)        | 2.75 (1.03)        | 1.75 (0.87)        | 1.75 (0.87)        | 2.25 (2.34)        | 1.75 (0.89)        | 1.12 (0.44)        | 0.00 (0.00)        | 0.00 (0.00)        | 31.69 (0.006) | *P1P2P3P4P5P6P7P8P9P10 |
| Total Density         | 19.75 (14.78)      | 34.87 (25.26)      | 20.25 (13.11)      | 8.75 (6.99)        | 18.75 (8.26)       | 8.75 (7.83)        | 8.12 (1.12)        | 7.25 (1.23)        | 0.00 (0.00)        | 0.00 (0.00)        | 52.90 (0.000) | *P1P2P3P4P5P6P7P8P9P10 |
| Coleoptera            | 0.00 (0.00)        | 0.00 (0.00)        | 0.00 (0.00)        | 0.00 (0.00)        | 0.00 (0.00)        | 0.00 (0.00)        | 0.00 (0.00)        | 0.00 (0.00)        | 0.00 (0.00)        | 0.00 (0.00)        | 8.10 (0.123)   | ns    |              |
| Díptera               | 0.40 (0.10)        | 0.00 (0.00)        | 0.00 (0.00)        | 0.00 (0.00)        | 0.00 (0.00)        | 0.00 (0.00)        | 0.00 (0.00)        | 0.00 (0.00)        | 0.00 (0.00)        | 0.00 (0.00)        | 21.43 (0.010) | ns    |              |
| Excireolina braziliensis | 0.40 (0.00)      | 0.00 (0.00)        | 0.00 (0.00)        | 0.00 (0.00)        | 0.00 (0.00)        | 0.00 (0.00)        | 0.00 (0.00)        | 0.00 (0.00)        | 0.00 (0.00)        | 0.00 (0.00)        | 15.82 (0.070) | ns    |              |
| Hemileuca cebrensis   | 0.00 (0.00)        | 0.00 (0.00)        | 0.00 (0.00)        | 0.00 (0.00)        | 0.00 (0.00)        | 0.00 (0.00)        | 0.00 (0.00)        | 0.00 (0.00)        | 0.00 (0.00)        | 0.00 (0.00)        | 11.25 (0.236) | ns    |              |
| Hemipodia olivieri    | 0.40 (0.00)        | 0.25 (0.35)        | 0.00 (0.00)        | 0.12 (0.35)        | 0.12 (0.35)        | 0.25 (0.40)        | 0.00 (0.00)        | 0.00 (0.00)        | 0.00 (0.00)        | 0.00 (0.00)        | 7.18 (0.018)   | ns    |              |
| Heteropoda paretii    | 0.12 (0.35)        | 0.12 (0.35)        | 0.00 (0.00)        | 0.00 (0.00)        | 0.00 (0.00)        | 0.00 (0.00)        | 0.00 (0.00)        | 0.00 (0.00)        | 0.00 (0.00)        | 0.00 (0.00)        | 11.43 (0.247) | ns    |              |
| Thoracophilia furcierea | 0.00 (0.00)       | 0.00 (0.00)        | 0.00 (0.00)        | 0.00 (0.00)        | 0.00 (0.00)        | 0.00 (0.00)        | 0.00 (0.00)        | 0.00 (0.00)        | 0.00 (0.00)        | 0.00 (0.00)        | 11.43 (0.247) | ns    |              |

2021), which contributes to more waves. The waves remobilize the deposited sediment, resulting in a destructive profile. The opposite occurs in the summer, when the intensity of wind and waves decreases, promoting deposition in the intertidal zone and an increase in the topographic variation that characterizes a constructive profile (Short 2006). These patterns corroborate the work of Lorenzi and Baran (2017), where in previous years the profile of Enseada Beach varied from reflective in the summer to intermediary in the winter and sediments composed of fine to medium sand grains predominated. Both works conducted on this beach identified the tendency

Fig. 5 Result of the correspondence analysis (CA) showing the correlations between the sample points (P1 to P10) in each season (WIN: winter; SUM: summer) and the benthic infauna (H. cinerea, Haplocladus sp.; D. hanleyanus; H. olivieri; S. goodbodyi; E. braziliensis; Orchestia sp.; Coleoptera, T. furcierea). Percentage of inertia on dimension 1 (44.79%) and dimension 2 (25.29%)
of greater unevenness in the upper portion of the profile in the summer, a pattern that was also observed by Pinto and Borzone (2018) on Barrancos Beach in Pontal do Paraná. Thus, the effects of seasonality on the profile morphology of beaches in the South Region of Brazil are evident (Amaral et al. 2016). As expected, the upper

Table 5 Monte Carlo test results with the proper values of the axis, cumulative percentage of variance of the axis and correlations between nutrients and environmental variables. sd, standard deviation

| Variable                  | Mean (± sd) | p-value | F-ratio |
|---------------------------|-------------|---------|---------|
| GW depth (m)              | 0.36 (± 0.21) | 0.019*  | 2.81    |
| Ammonia (mg/L)            | 1.34 (± 0.59) | 0.584   | 0.68    |
| Nitrite (mg/L)            | 0.049 (± 0.07) | 0.96    | 0.28    |
| Phosphate (mg/L)          | 0.78 (± 0.43) | 0.96    | 0.14    |
| Moisture (%)              | 1.85 (± 0.30) | 0.118   | 1.61    |
| pH                        | 8.33 (± 0.15) | 0.703   | 0.45    |
| Temperature (°C)          | 20.15 (± 1.25) | 0.366   | 1.01    |

*Variables that influenced biological groups (ind./0.05 m²) in the slope points (P1 to P10) and seasons (WIN, winter; SUM, summer)
mesolittoral of the profile was characterized by the greater slope and depth of the groundwater and greater sediment moisture; in the lower mesolittoral the slope of the profile was less, with greater sediment moisture and saturation of the groundwater and greater salinity, pH, and calcium carbonate (Lorenzi and Baran 2017; McLachlan et al. 2018).

The nutrient concentrations of the percolation water increased in the middle and upper mesolittoral in the summer, which coincided with greater precipitation events in this season (Alvares et al. 2014; Lorenzi et al. 2020, 2021) when there is groundwater saturation and contaminated water drains into the ocean (Coffey et al. 2018). When the water reaches the sediment surface, the nutrients are used by benthic algae, which increases primary production (Tappin 2002; Defeo et al. 2009; Schlacher and Hartwig 2013) and bacterial density (Halliday et al. 2014). In the case of Enseada Beach, the increase in the concentrations of nutrients can be attributed to the summer vacation season (De Souza et al. 2018) that, according to data from the municipality, attracts around 400 thousand people to the city of São Francisco do Sul, representing an increase of up to 8 times the resident population (IBGE 2020).

Since there is no collection and treatment of sewage in the municipality, the domestic effluents are dumped directly into the rainwater drainage system (which goes to waterbodies) or into septic systems. In the second case, due to the systems not being watertight, the permeability of the sandy soils and the increase in rainfall, contaminated water moves from the septic systems to the groundwater, which contributes to saturating the sediment surface of the beach profile.

According to Resolution no. 369 of the National Environmental Council (Conselho Nacional de Meio Ambiente; CONAMA 2008), which provides the environmental classification and guidelines for groundwater, parameter concentrations most likely to occur are nitrate > 10 mg/L and nitrite > 1 mg/L. At these concentrations, the nutrients cause severe environmental impact in underground waterbodies and, according to Douglas et al. (2016), high concentrations of ammonia (> 1.5 mg/L) and phosphate (> 0.5 mg/L) indicate that the sediment could be hypoxic, which is related to the discharge of sewage with an elevated organic load. Under alkaline conditions, there is a tendency for ammonia to predominate that, in excess, is toxic to various aquatic organisms (Smith et al. 1999). The nitrogen cycle relies on the intense participation of bacteria in the nitrification process, with the bacterial oxidation of ammonia (NH₃) to nitrite (NO₂) and the oxidized form of nitrate (NO₃) (Couturier et al. 2017; Glasl et al. 2017). Nitrogen and phosphorous are the most important nutrients for algae and macrophyte growth and are easily assimilated in the forms of ammonia and phosphate (Fricke et al. 2016).

The overgrowth of algae, caused by eutrophication (Coffey et al. 2018; Barletta et al. 2019; Córdoba-Mena et al. 2020), was investigated on Central Beach in Balneário Camboriú, Santa Catarina. There was an increase in concentrations of nutrients in the water column in the summer that promoted considerable growth of bryozoans and phytobenthos (Rööig et al. 2017), which are an important source of food for the polychaete T. furcifera (Otegui et al. 2012). In this sense, and because it is in a more sheltered place on the coast, Enseada Beach predominantly has sediment with fine sand, which contributes to the population growth of T. furcifera in the summer, a pattern also found by Barros et al. (2001) on sandy beaches near Guaratuba Bay (Paraná). Polychaetes in the family Opheliidae inhabit the intertidal zone of sandy beaches throughout the world (Souza and Borzone 2007; Cisneros et al. 2011; Defeo and McLachlan 2013) and dominate the middle mesolittoral of beaches in the South Region of Brazil (Neves et al. 2007; Lorenzi and Baran 2017), which confirms the distribution pattern of T. furcifera on Enseada Beach. This species digs in the sediment, is a non-selective feeder (Barros et al. 2001; Otegui et al. 2012), and acquires carbon by ingesting sediment with bacteria and other microbes. It is one of the main benthic species responsible for cycling nutrients in this ecosystem (Kemp 1986) and a significant increase in population density can indicate an environmental disturbance (Seike 2008; Bergamin et al. 2009; Otegui et al. 2012). The environmental conditions combined with the organic increment in the summer, notably nitrate, resulted in high densities of T. furcifera in the middle mesolittoral on Enseada Beach, reinforcing the role of this species as a bioindicator of eutrophication on sandy beaches. This contamination compromises ecosystem services (Amaral et al. 2016) of Enseada Beach, reducing the economic, ecological, and social values provided by this important coastal ecosystem (Defeo and McLachlan 2013; McLachlan et al. 2018). In a study conducted on Casablanca Beach (Morocco), Daief et al. (2014) confirmed that sources of sewage influenced the composition of taxa of benthic fauna and are potential causes of eutrophication in urbanized coastal systems. Additionally, Córdoba-Mena et al. (2020) found algae that produce biotoxins, such as domoic acid, which can impact public health.

Another important association related to an increase in the total density and richness of the infauna comprises S. goodbodyi, D. hanleyanus, H. olivieri, H. cinerea, and Haploscoloplos sp. in the lower mesolittoral and initial middle mesolittoral. S. goodbodyi is known for dominating the upwelling zone of sandy beaches in southern Brazil (Borzone et al. 1996; Barros et al. 2001; Neves et al. 2007; Neves and Bemvenuti 2009). The relationship of this association with an increase in concentrations of nutrients in the percolation water was small. Instead, this association is more
related to an increase in sediment moisture, and the species were dominant in both seasons, except for *D. hanleyanus* and *H. cinerea* that were only dominant in the winter.

Worldwide, around 2.3 billion people live in coastal areas and less than half of this population has basic sanitary services (WHO and UNICEF 2017), resulting in the generation and release of tons of effluents into coastal ecosystems. A good proportion of these effluents are improperly discharged into waterbodies, including those associated with sandy beaches, and this may have serious or even irreversible consequences in the coming years, compromising ecosystem services. Using organisms as environmental quality indicators is extremely important since they can be help monitor impacts in a realistic and economically viable way. Installing sewage collection systems that are spread out and far from the coastline, preferably in areas with high environmental energy, can contribute to mitigating the effects of domestic sewage (Roberts et al. 2010; Puente and Diaz 2015; Cândido and Netto 2020). Despite the evidence presented here, long-term studies are still needed to better understand the effects of eutrophication of groundwater on the biological communities of sandy ecosystems.

**Conclusions**

This study provides the first results of the effects of increased concentrations of nutrients in the groundwater on benthic infauna communities on Enseada Beach, in São Francisco do Sul, Santa Catarina. When domestic effluent disposal is associated with a lack of proper treatment and appropriate destination, increase in population density during the summer vacation season and increase in rainfall, the domestic effluents are transported to adjacent marine areas by surface runoff and contaminate the groundwater. Consequently, there is an increase in the population density of the polychaete *Thoracophelia furcifera* that is related to an increased concentration of nutrients in the percolation water in the sediment of the beach profile. This event indicates that domestic effluents near sandy beaches need to be controlled and demonstrates to public managers the need to implement basic sanitary projects and monitoring. Thus, it will only be possible to improve the socio-environmental quality of coastal marine areas of São Francisco do Sul if sanitary criteria are met. In future studies, we hope to relate biological and physical (waves, currents, rainfall) parameters, with the goal of increasing what is known about these processes.

**Data availability** All data is available in tables along the manuscript and supplementary material.

**Author contribution** LL planned the sampling design, collected the data, conducted the statistical analyses, supervised the laboratory work, and wrote the article. DGM collected the data, conducted laboratory work, and wrote the article. BCR collected the data, conducted laboratory work, and wrote the article. PRPA analyzed and discussed the results and conducted a technical revision of the article. DVD analyzed the results and conducted a technical revision of the article. EG analyzed the results and conducted a technical revision of the article. VGT analyzed the results and conducted a technical revision of the article.

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**Declarations**

**Ethics approval and consent to participate** Not applicable.

**Consent for publication** We consent for the publication of identifiable details, which can include to be published in the above Journal and Article. I understand that all Springer Nature journals may be available in both print and on the internet, and will be available to a broader audience through marketing channels and other third parties.

**Competing interests** The authors declare no competing interests.

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