Estuarine, Coastal and Shelf Science 211 (2018) 217–226

Contents lists available at ScienceDirect

Estuarine, Coastal and Shelf Science

journal homepage: www.elsevier.com/locate/ecss

An integrated approach for the assessment of land-based pollution loads in the coastal zone

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ARTICLE INFO

Article history:
Received 21 February 2017
Received in revised form
1 August 2017
Accepted 18 August 2017
Available online 24 August 2017

Keywords:
Cartagena Bay
Water quality
Pollution loads
Coastal zone management
Land-based pollution

ABSTRACT

The identification and prioritization of pollution sources is essential to coastal zone management. This task is complicated when a variety of pollution sources are found and by limited data availability, which can result in an inconclusive assessment and differing public perceptions, ultimately hindering the progress of management actions. This is the case in Cartagena Bay (Colombia), a Caribbean hot-spot of pollution, which receives large freshwater discharges from the Magdalena River drained via the Dique Canal along with coastal industrial effluents and untreated domestic wastewater from parts of the coastal population. This study presents a methodology for the integrated assessment of anthropogenic pollution sources discharged into the coastal zone by estimating their loads and comparing their relative contributions to receiving coastal waters. Given the lack of available data on discharges and water quality, an integrated approach is applied by combining various methods of load estimation while emphasizing the importance of calculating confidence intervals for each load value. Pollution loads from nearby sources of domestic wastewater, coastal industrial effluents and continental runoff were assessed with respect to their contributions of coliforms, total suspended solids, nitrogen, phosphorus, and biological oxygen demand (BOD). Loads from the canal's surface runoff were calculated with monthly discharge and water quality data. Domestic loads were computed using GIS analyses of population and sewerage coverage in combination with export coefficients of daily load per capita. Industrial loads were estimated based on previous studies. Results show that each type of land-based source is responsible for different pollution impacts observed in Cartagena Bay. Occasionally, inadequate recreational water quality can be attributed to nearby sources of domestic wastewater, which contribute the highest coliform load ($6.7 \pm 3.9 \times 10^{15}$ MPN/day). Continental runoff via the Dique Canal contributes the greatest sediment load ($2.5 \pm 1.9 \times 10^{3}$ t/day) causing the bay's turbid plumes and related ecosystem issues. Hypoxic conditions in the bay can be attributed to all three pollution sources which all discharge significant BOD loads (2–8 t/day), while the highest total phosphorus load comes from the Dique Canal (3.2 ± 2.4 t/day) and the highest nitrogen loads flow from the canal (3.7 ± 3.1 t·NO_3-N/day) and the industrial sector (3.1 ± 4.1 t·N/day). Given that these loads are projected to increase in future years, this study highlights the importance of prioritization and mitigation in coastal pollution management and demonstrates a method that could be applied in other places with similar problems in the Wider Caribbean Region.

1. Introduction

A common challenge in coastal management is to balance the priorities of environmental conservation and economic development. These priorities often create conflicts for the sustainable development of the coastal zone as the growth of human populations and industrial activities generate pollution that leads to

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http://dx.doi.org/10.1016/j.ecss.2017.08.035
0272-7714/

environmental degradation. This conflict is particularly relevant in the Caribbean Region, where the economy is very dependent on tourism (15% of GDP; WTTC, 2017) drawing on the appeal of beaches and clear seawater. However, the growth of coastal populations and tourism in the region has also increased the discharge of wastewater in the Caribbean Sea, about 85% of which is untreated, posing threats to public health (UNEP/GPA, 2006). Moreover, human population growth and pollution are among the principal causes of widespread marine ecosystem change across the Caribbean, where coral reefs have declined drastically since the 1970s (Jackson et al., 2014).

A particularly challenging example of such conflicts can be found in Cartagena, Colombia. This coastal city is home to a population of 1 million people, has one of the country's largest ports and industrial zones, and represents Colombia's principal touristic destination, though various environmental issues are evident in the waters of Cartagena Bay (Tosic et al., 2017). Hypoxic conditions are likely related to the drastic reductions in artisanal fisheries observed in recent decades by the bay's rural communities (personal communication with fishermen). Turbidity has been linked with marine ecosystem degradation in the adjacent Rosario Islands Marine Protected Area (Restrepo et al., 2006, 2016a), while findings of high coliform concentrations present a potential risk to the city's beaches.

It is accepted that these environmental issues are due to land-based sources but there are many such pollution sources flowing into Cartagena Bay, including domestic and industrial wastewater along with continental runoff from the Magdalena Watershed discharged via the Dique Canal. To identify which pollution sources are primarily responsible for the bay's degraded water quality, a quantitative assessment of their pollutant loads is required. Such assessments of loads entering Cartagena Bay have been carried out previously (Garay and Giraldo, 1997; Tuchkovenko and Lonin, 2003). However, the comparison and interpretation of their results are limited as these studies did not report estimates of the uncertainty or variability involved in their load calculations, without which a decision-maker cannot confidently reach a conclusion.

In this study, we propose an integrated approach for pollution load assessment with a focus on data uncertainty and variability. The approach combines different methods of load estimation, including effluent monitoring, spatial analyses with geographical information systems (GIS), and previously published results. In order to permit a comparison of the estimates calculated by differing methods, a novel approach is proposed for the approximation of confidence intervals for each load, considering the uncertainty and variability inherent in each value used for load calculation. The application of this approach is demonstrated in Cartagena, where we aim to address the research question of “which land-based sources of pollution are responsible for the issues of hypoxia, turbidity and unsanitary conditions in the waters of Cartagena Bay?” Using this approach, ultimately the decision-makers can confidently identify the primary pollution sources and this could be applied to other coastal zones across the Wider Caribbean Region where data availability and monitoring programs are common limitations.

2. Study area

Cartagena Bay is a micro-tidal estuary located on the north coast of Colombia in the Caribbean Sea (Fig. 1). The bay has a surface area of 84 km^2, a maximum depth of 32 m, and a strong vertical salinity stratification. It receives water from two seaward straits (Bocachica and Bocagrande) and various freshwater sources. Foremost to these freshwater sources is continental runoff from the Magdalena River via the Dique Canal which discharges into the southeastern part of the bay with strong seasonal variability. Other freshwater sources include domestic and industrial wastewater, as well as runoff from a small coastal catchment area around the bay, though this runoff contribution is considered negligible in comparison to that of the Dique Canal.

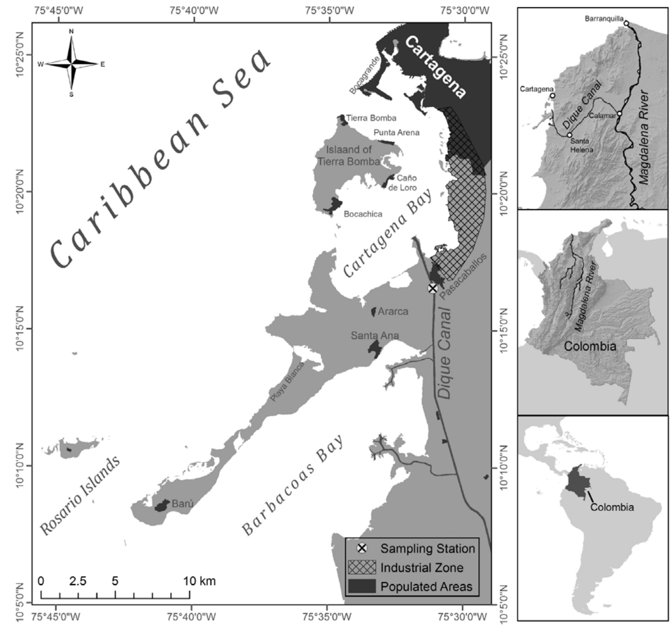

Fig. 1. Study area showing the populated areas and industrial zone around Cartagena Bay along with the Dique Canal, Magdalena River and location in South America and the Wider Caribbean Region.

Freshwater runoff from the Dique Canal has a seasonality related to the Magdalena River, with greater discharges from October to December and lower levels from February to April (Molares and Mestres, 2012). The Dique Canal is a man-made distributary channel that diverges from the Magdalena River at Calamar (Fig. 1) and flows along 114 km to Cartagena Bay, where previous studies have reported an approximate discharge of 55–250 m^3/s (Tuchkovenko and Lonin, 2003) and a total sediment flux of 1.9 Mt/y (Restrepo et al., 2016b) which has increased over the past decade (Restrepo et al., 2015). Modelling predictions show these fluxes are intensifying as sediment loads are projected to increase by as much as 317% by the year 2020 (Restrepo et al., 2016b).

The Magdalena watershed has an area of 260,000 km^2, covers approximately 25% of the country's land area, and includes approximately 80% of the national population. It is the main Andean catchment of Colombia as well as the main contributor of fluvial fluxes to the Caribbean Sea (Restrepo and Kjerfve, 2000; Restrepo, 2008). As such a large amount of industrial, agricultural and mining areas can be found in the Magdalena basin, the waters that flow to Cartagena Bay via the Dique Canal carry many potential pollutants along with a significant sediment load.

Domestic wastewater enters the bay from various small populations around the bay without sewerage service. These include the rural communities of Ararca, Bocachica, Caño del Oro, Punta Arena, and Tierra Bomba (Fig. 1) as well as some neighborhoods to the south of the city whose sewage flows to subterranean wells that can be susceptible to seepage or overflow during storm events. The community of Pasacaballos does have a sewage system but it discharges without treatment into the Dique Canal about 2.5 km upstream of its outlet. In previous years, about 40% of the city's sewage system itself (~48,000 m^3/day) was also discharged directly into

Cartagena Bay without treatment via an 800 m submarine outfall (UNDP-UNOPS, 1999; Tuchkovenko and Lonin, 2003), though since 2013 Cartagena's sewage system has been routed to a new outfall sufficiently far north of the city to not affect the bay. However, on occasion the city's sewerage system overflows, particularly during intense rain storms, resulting in direct discharge into the bay through the old submarine outfall and backup outlets along the coast (personal communication with the city water authority, AcuaCar).

Cartagena's industrial zone runs along the east coast of the bay (Fig. 1). While some of these industries discharge to the city's sewage system, the majority of them have their own treatment and discharge directly to the bay or indirectly via small canals (UNDP-UNOPS, 1999). Activities in this zone include a petroleum refinery with multiple distribution terminals, chemical plants, cement factories, aquaculture, electric plants, food processing industries (carbonated beverages, dairy, poultry, fish), production of plastics, leather, and other manufacturers (INVEMAR-MADS, 2011). This industrial zone represents 50% of Cartagena's GDP, of which at least 70% can be attributed to the petro-chemical sector (Cardique & AGD, 2006).

3. Materials and methods

3.1. Load assessments

The land-based sources of pollution leading to the water quality issues of turbidity, hypoxia, and inadequate recreational waters were analyzed by assessing the loads of five water quality parameters: total suspended solids (TSS), nitrogen (various forms), total phosphorus (TP), biological oxygen demand (BOD), and coliforms. TSS loads were analyzed as an indicator of the land-based sources responsible for high turbidity levels in Cartagena Bay, while coliform loads were analyzed to identify sources affecting the bay's adequacy for recreational purposes. To assess the pollution sources responsible for the bay's hypoxia, the loads of BOD, nitrogen and phosphorus were analyzed. BOD is an indicator of hypoxia issues as it measures the amount of dissolved oxygen consumed by the biological decomposition of organic matter. Nitrogen and phosphorus are also indirect indicators of hypoxia issues as the excess supply of these nutrients leads to the primary production of organic matter in the water column that eventually decomposes and consumes dissolved oxygen as well (Newton and Mudge, 2005).

The loads of the five water quality parameters were assessed for the three most likely sources: coastal domestic wastewater, coastal industrial wastewater and continental runoff. The sources of domestic and industrial wastewater considered here are those flowing from nearby sources in the coastal zone itself. Continental runoff is considered as the water flowing from the Dique Canal, which also contains other upstream sources of domestic and industrial wastewater, along with agricultural and mining areas. But for the purposes of this study, the three groups of land-based sources will be termed: domestic wastewater (from nearby coastal sources), industrial wastewater (from nearby coastal sources), and continental runoff (from the Dique Canal, which includes a great variety of upstream discharges of wastewater and non-point sources).

These three most likely sources have very different characteristics, requiring different methods of load assessment. To overcome this challenge, the approach presented here integrates different methods for the assessment of each pollutant source (Fig. 2). Methods of effluent monitoring were carried out to characterize continental runoff, GIS analyses of population were employed to assess coastal domestic wastewater, and previously published results were used to estimate coastal industrial wastewater loads. While each of these methods has been previously applied (e.g. McPherson et al., 2002; Tsuzuki, 2006), the novelty of the present approach is in the integration of these different methods and the focus on incorporating confidence intervals into the analysis.

The approximation of confidence intervals is the key to comparing results from different methods. This was done by quantifying the uncertainty and variability inherent in each value used for load calculation, and by carrying these quantities through the load calculation process in accordance with the rules for error propagation (Fig. 3). Qualitative estimates of uncertainty have previously been used to better inform environmental management on target setting of pollutant loads in the rivers of the Great Barrier Reef catchment area (Brodie et al., 2009). By quantitatively approximating confidence intervals, the present study goes a step further to provide environmental management with an idea of the potential range of values above and below each calculated load, allowing for a comparison of results with greater confidence.

3.1.1. Effluent monitoring

Given the complexity and immense variety of pollution sources found in the Magdalena River watershed, the most practical method deemed for the assessment of its pollutant loads was to measure them at the catchment's coastal outlet. This was made possible by an extensive 2-year monthly water quality monitoring program. Water quality and discharge were measured monthly from September 2015 through August 2016 in the Dique Canal at a location upstream of the Pasacaballos community (Fig. 1). The quantification of runoff loads using measured discharge and pollutant concentration data has been well-established in many previous studies (e.g. McPherson et al., 2002; Restrepo et al., 2006; Tosic et al., 2009; Joo et al., 2012).

Water velocity was measured with a Sontek mini-ADP (1.5 MHz) along a cross-stream transect three times on each monthly sampling date and discharge values were subsequently calculated with the Sontek River Surveyor software. The average discharge value of the three repeated transect measurements was used for the monthly calculation of pollutant loads. The sample standard deviation of the three discharge measurements was used in the computation of the confidence interval (Fig. 3). Henceforth, the term “standard deviation” will be understood as the sample standard deviation due to the data's small sample size. Triplicate surface water samples were collected between the hours of 9:00–12:00 (Karydis and Kitsiou, 2013). Samples were stored, cooled, and transported to the CARDIQUE Laboratory for analysis of TSS, BOD, TP, and nitrate-nitrogen (NO_3-N) and as well as to the AcuaCar Laboratory for analysis of fecal coliforms, all by standard methods (APHA, 1985). The average concentration and standard deviation of the three samples were used to calculate the monthly pollutant loads and confidence intervals, respectively.

Monthly loads were calculated as a product of the discharge and pollutant concentration, and converted into tonnes per day (t/d). As the results showed great temporal variability, an annual average was calculated from the 12 monthly measurements in order to compare with the loads of the nearby sources of domestic and industrial wastewater. The confidence interval for the annual average of daily runoff loads was computed by factoring in the uncertainty due to measurement (standard deviations of discharge and pollutant concentration) as well as the temporal variability of loads, which was calculated as the standard deviation of the 12 monthly measurements (Fig. 3).

3.1.2. GIS analysis of population

Spatial analyses were applied using GIS to assess the population of inhabitants without a connection to the city's sewage system. Spatial coverages of the inhabited areas within the bay's coastal

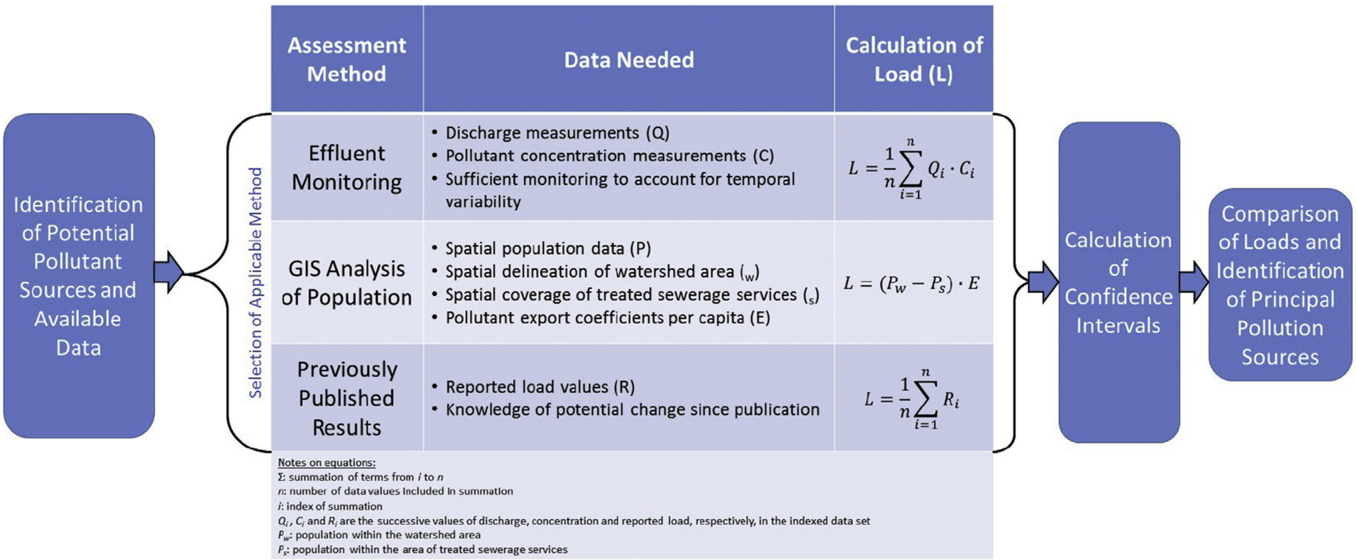

Fig. 2. Framework of the integrated approach for pollutant load assessment.

watershed were obtained from the online geoportal of Colombia's National Administrative Department of Statistics (DANE, 2017a). Population values for each inhabited sector were also obtained online from the same department (DANE, 2017b) and associated with corresponding sectors of the spatial coverage of inhabited areas in order to create a spatial coverage population. A map of the city's sewage network was obtained from Cartagena's water authority (AcuaCar, 2016) and digitized into a single polygon of the sewage system's coverage area. This area was then overlaid with the population coverage in order to identify the populations without connection to the sewerage service. The populations of these areas without sewage services were then summed and termed the "non-serviced population."

The loads of these nearby sources of domestic wastewater were estimated for the non-serviced population using export coefficients, which approximate the load of a given pollutant generated by each non-serviced habitant per day. This approximation method has been used in previous studies (Tsuzuki, 2006), including research at the national level in Colombia (INVEMAR, 2009) and at the regional level in the Wider Caribbean Region (UNEP-UCR/CEP, 2010). Among the available export coefficients, the values proposed by INVEMAR (2009) were ultimately selected for this study based on the criteria that they have been previously applied in Colombia and were near the average values of all of the reviewed references.

To approximate confidence intervals for the domestic wastewater loads, the sources of uncertainty and variability were considered for the values of population and the export coefficients (Fig. 3). For the total value of the non-serviced population, two sources of uncertainty were considered: the potential error of measurement in the original census reported in the year 2005, and the change in population between 2005 and 2016. The calculation of a confidence interval for the potential error of measurement is reported by the census itself as ±13.7% (DANE, 2008). A confidence interval for the change of population between 2005 and 2016 was approximated as ±15%, based on the projections of the census that predict a population increase of 13% in the urban parts of Cartagena and a decrease of 17% in the rural parts of Cartagena over this time period. To approximate the confidence interval of the export coefficient values, the standard deviation of the coefficient values reported in the reviewed references was used (Tchobanoglous et al., 2003; Tsuzuki, 2006; INVEMAR, 2009; UNEP-UCR/CEP, 2010). However, in the case of the total coliforms parameter, only one coefficient value was reported and so half of this value was used as an approximation of its confidence interval.

3.1.3. *Previously published results*

The industrial sector located along the eastern coast of Cartagena Bay was characterized through the identification and classification of the different industries currently operating. As data about the pollutant loads discharged from Cartagena's industrial sector was either not available or incomplete, for the present study we used the average value of the total loads reported by previous works of Tuchkovenko and Lonin (2003), Ramírez et al. (2006), and INVEMAR (2009). For the approximation of confidence intervals, the uncertainty in the individual loads reported as well as the variability among reported loads were considered (Fig. 3). As the previous publications did not report confidence intervals with the reported loads, a robust approximation of 50% uncertainty was assumed for each reported load value. The standard deviation of the reported loads was then calculated to account for the variability among reported values. However, in the case of the total coliforms parameter, only one total load was reported (Ramírez et al., 2006) and so half of this value was used as an approximation of its confidence interval. In consideration of the changes that may have occurred in this industrial sector since the time of these previous reports, an additional ±50% was aggregated to the confidence interval. This ±50% is used as a rough compensation of the increased industrial activity that has been developed in this growing industrial sector, as well as possible reductions in pollution loads due to improved wastewater treatment that may have been introduced to some industries since the previous reports.

4. Results

4.1. *Continental runoff via the Dique Canal*

Discharge measured near the coastal outlet of the Dique Canal is shown in Fig. 4. Monthly discharge ranges from 22 to 177 m^3/s, which is lower than previous measurements of 55–250 m^3/s reported for the canal's outlet (Tuchkovenko and Lonin, 2003). These lower values are likely because the period from 2015 to early-2016

Assessment Method	Estimates of Uncertainty or Variability	Calculation of Confidence in Values	Calculation of Load Confidence Interval (δL)
Effluent Monitoring	• Triplicate discharge measurements (δQ) • Triplicate pollutant concentration measurements (δC) • Temporal variability among 12 monthly loads (δL_T)	$\delta Q = S.D.(Q_{1-3})$ $\delta C = S.D.(C_{1-3})$ $\delta L_T = S.D.(L_{1-12})$	$\delta L_i = L_i\sqrt{\left(\frac{\delta Q_i}{Q_i}\right)^2 + \left(\frac{\delta C_i}{C_i}\right)^2}$ $\delta \bar{L} = \frac{1}{12}\sqrt{\sum_{i=1}^{12}(\delta L_i)^2}$ $\delta L = \delta L_T + \delta \bar{L}$
GIS Analysis of Population	• Fraction of uncertainty in reported population value (α) • Fraction of change in population over time since report (β) • Variability of available pollutant export coefficients (δE)	$\delta P = P \cdot (\alpha + \beta + \alpha \cdot \beta)$ $\delta E = S.D.(E_{1-n})$	$\delta L = L\sqrt{\left(\frac{\delta P}{P}\right)^2 + \left(\frac{\delta E}{E}\right)^2}$
Previously Published Results	• Fraction of uncertainty in each reported load value (γ) • Variability of loads reported (δR_V) • Fraction of potential change in loading over time since report (θ)	$\delta R_i = \gamma \cdot R_i$ $\delta R_V = S.D.(R_{1-n})$ $\delta R_t = \theta \cdot L$	$\delta \bar{R} = \frac{1}{n}\sqrt{\sum_{i=1}^{n}(\delta R_i)^2}$ $\delta L = \delta R_t + (\delta R_V + \delta \bar{R}) \cdot (\theta + 1)$

Notes on equations:
δX: estimate of uncertainty or variability for variable X
n: number of data values included in series
S.D.: sample standard deviation of data values 1 to n (for example, Q_{1-3}, C_{1-3}, L_{1-12}, E_{1-n}, R_{1-n})
L_i, Q_i, C_i and R_i are the successive values of load, discharge, concentration and reported load, respectively, in the indexed data set
$\delta \bar{L}$ and $\delta \bar{R}$ are the uncertainties calculated for the average pollutant load ($\bar{L}$) and average reported load ($\bar{R}$), respectively
Σ: summation of terms from i to n
i: index of summation

Fig. 3. Integrated approach for the approximation of confidence intervals for pollutant loads (L).

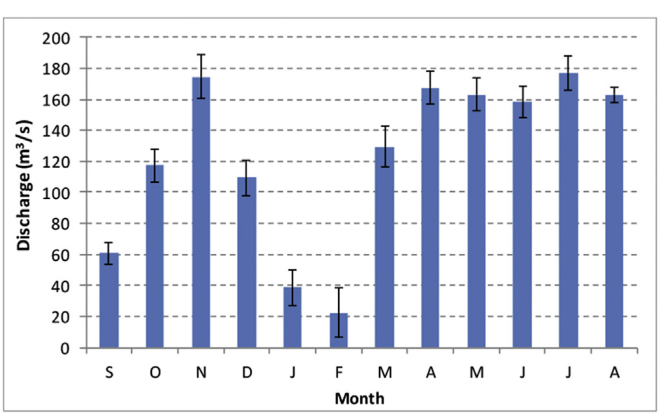

Fig. 4. Surface water discharge (m^3/s) measured monthly in the Dique Canal, 3 km upstream of its coastal outlet, between Sept. 2015 and Aug. 2016. Sample standard deviations are shown as error bars.

was characteristic of a low rainfall year resulting from an El Niño event. Thus the discharge values measured in the present study may be considered as an under-estimate of average flow conditions, particularly during the rainy season of Sept.-Dec 2015 and the dry season of Jan.-Feb. 2016.

Monthly measurements of water quality concentrations show a great seasonal variability (Fig. 5) with some parameters increasing sharply during the dry months of January and February (BOD, NO_3-N), while others are higher in October and April at the onset of the rainy season (TSS, TPP, FC). Daily loads calculated for each month also show a high amount of temporal variability with loads being 4–8 times higher in some months than others, and up to even 2 orders of magnitude higher in the cases of FC and TSS. In general, temporal variability shows a much greater influence on the confidence intervals of average annual loads than that due to the uncertainty of measurements.

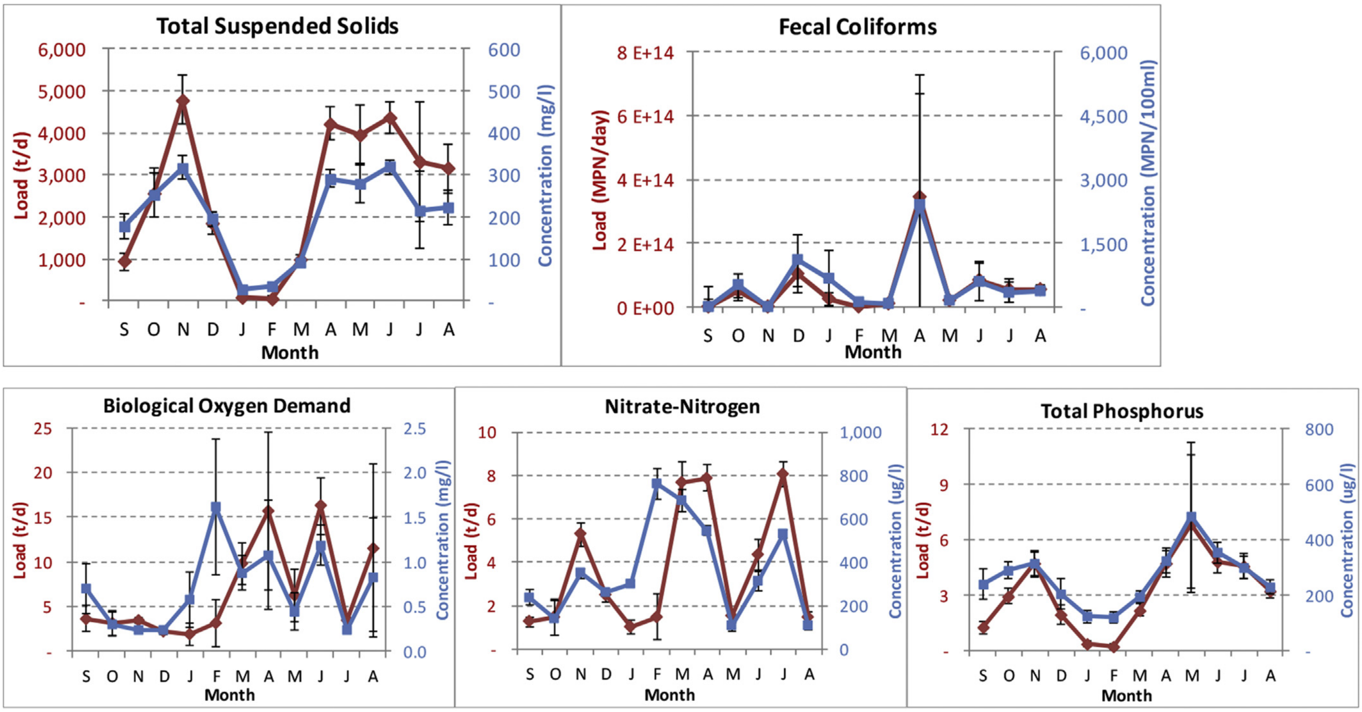

Fig. 5. Monthly concentrations of water quality parameters (blue, right axes) and average daily loads for each month (red, left axes) near the coastal outlet of the Dique Canal, between Sept. 2015 and Aug. 2016. Error bars represent the confidence intervals approximated for each value. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4.2. Coastal sources of domestic wastewater

The total population of inhabitants with no connection to the city's sewage system was calculated as 33,381 people, with a confidence interval of ±10,274 people. The non-serviced populations were distributed in various parts around the bay (Fig. 6a). These populations include various rural communities (Ararca, Bocachica, Caño del Oro, Punta Arena, Tierra Bomba, and Pasacaballos) as well as some urban neighborhoods to the south of the city.

Daily loads of nearby sources of domestic wastewater were calculated to be 1.7 ± 0.6 t/d for BOD and 1.7 ± 0.9 t/d for TSS (Table 1). Smaller daily loads were calculated for inorganic nitrogen (0.4 ± 0.1 t/d) and total phosphorus (0.03 ± 0.01 t/d), while a very large load of $6.7 \pm 3.9 \times 10^{15}$ of total coliforms was estimated. The large magnitude of confidence intervals attributed to these approximations is the result of the high levels of data uncertainty in both the export coefficients and population values.

4.3. Coastal sources of industrial wastewater

The spatial distribution of the industries identified in the coastal area of Cartagena Bay is shown in Fig. 6b. Table 2 shows the daily loads of nearby sources of industrial wastewater, calculated as the average value of the three previous publications to report this information. The loads reported by Ramírez et al. (2006) appear to be most similar to the average values calculated as well as the only reference that reported total coliform loads. The loads reported for BOD, TN and TP are relatively consistent with one another, though the large disparity between the TSS load values reported does highlight the uncertainty inherent in such data. In general, the confidence intervals for the average load values are quite high, with magnitudes that are greater than the average values themselves. This is due to the large amount of accumulated uncertainty in the average values, as large estimates had to be made to conservatively account for the uncertainty in the individual reported loads along with the potential change over time since these previous reports.

4.4. Load comparison

When comparing the loads of the three groups of land-based sources (coastal domestic wastewater, coastal industrial wastewater, and upstream continent runoff), it was found that in the case of coliforms, the principal source of pollution is clearly the nearby coastal domestic wastewater (Fig. 7). The high loads of total coliforms approximated in this study ($6.7 \pm 3.9 \times 10^{15}$ MPN/d) due to non-serviced coastal populations is several orders of magnitude higher than that of the industrial sector ($2.7 \pm 5.5 \times 10^{7}$ MPN/d) with a mean difference of $6.7 \pm 3.8 \times 10^{15}$ MPN/d between the two loads. The domestic load is also two orders of magnitude higher than the fecal coliform load from the Dique Canal ($6.2 \pm 13.1 \times 10^{13}$ MPN/d). As the range covered by the confidence interval of these mean differences does not include zero, it may be said with certainty that the domestic load is significantly greater than the industrial and runoff loads with a statistical significance of 1.7 standard deviations in both cases. While it is not normally recommended to compare results of different parameters, as is the case of analyzing total coliforms due to domestic wastewater and fecal coliforms discharged by the Dique Canal, the lack of data availability make this a necessity justified by the importance of proceeding with management actions. Furthermore, fecal coliforms are included within total coliform measurements, though the difference between the two parameters typically would not differ by more than one order of magnitude. For this reason, it is considered reasonable to accept that the principal source of coliforms is domestic wastewater.

In the case of TSS and TP (Fig. 7), the source is very clearly the Dique Canal. The approximate TSS and TP loads of the canal are $2.5 \pm 1.9 \times 10^{3}$ t/d and 3.2 ± 2.4 t/d, respectively, which outweigh

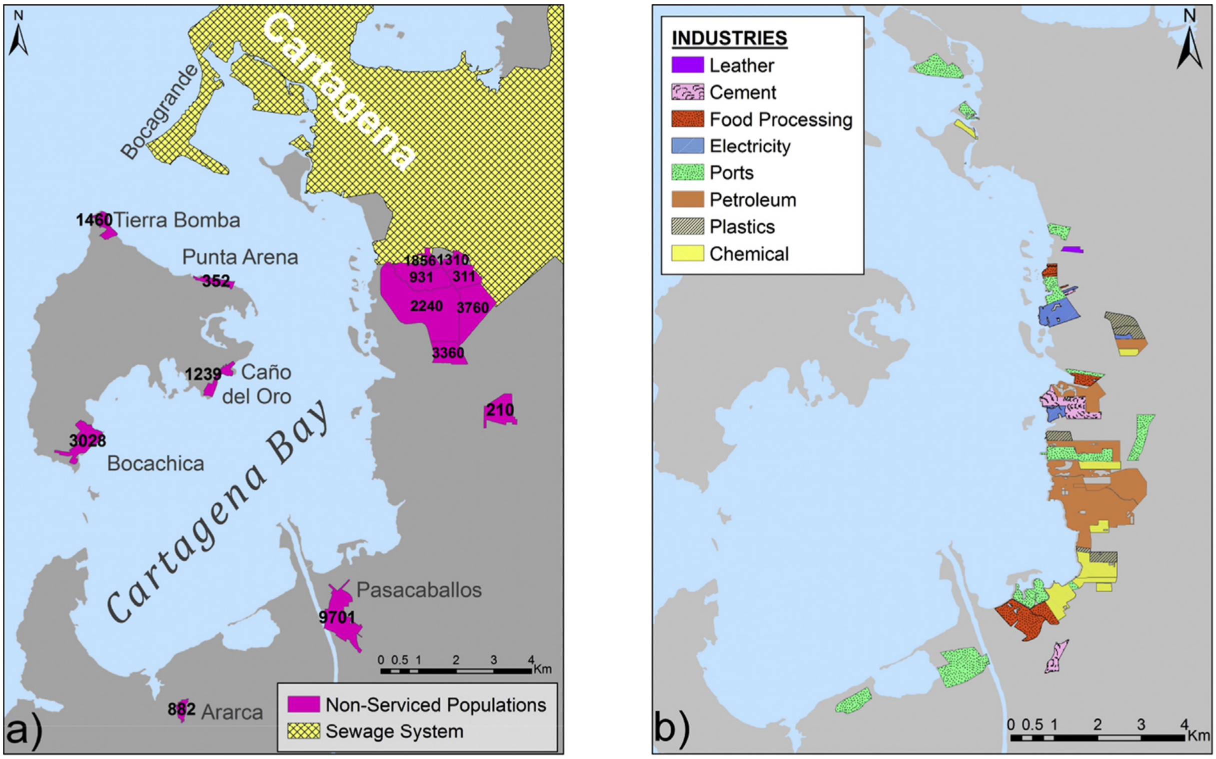

Fig. 6. a) Populations in the coastal zone of Cartagena Bay with no connection to the city's sewage system (non-serviced populations) and spatial coverage of the sewage system. Population values projected for 2016 based on the most recent census of 2005 (DANE, 2017b) are shown for each area. b) Industries in the coastal zone of Cartagena Bay, grouped by general classifications of economic activities. Spatial data was obtained from Cardique & AGD (2006).

Table 1
Export coefficients and daily loads of nearby sources of domestic wastewater.

Parameter	BOD	Inorganic Nitrogen	TP	TSS	Total Coliforms
Unit	g/hab/d	g/hab/d	g/hab/d	g/hab/d	MPN/hab/d
Export Coefficient	50	12	0.8	50	2×10^{11}
Confidence Interval (±)	8	2	0.1	21	1×10^{11}
Unit	t/d	t/d	t/d	t/d	MPN/d
Daily load	1.7	0.4	0.03	1.7	7×10^{15}
Confidence Interval (±)	0.6	0.1	0.01	0.9	4×10^{15}

Table 2
Previously published results of daily loads from nearby sources of industrial wastewater. Dashes (-) indicate that data were not reported.

Previous Studies	BOD (t/d)	TSS (t/d)	TN (t/d)	TP (t/d)	Total Coliforms (MPN/d)
Ramírez et al., 2006	7.09	23.04	3.29	0.19	2.7×10^7
Tuchkovenko and Lonin, 2003	6.04	39.30	3.75	0.14	–
INVEMAR, 2009	9.47	7.96	2.28	0.13	–
Average daily load	7.54	23.43	3.11	0.15	2.7×10^7
Confidence Interval (±)	9.72	46.79	4.06	0.19	5.5×10^7

the domestic (TSS: 1.7 ± 0.9 t/d; TP: 0.03 ± 0.01 t/d) and industrial (TSS: 23.4 ± 46.8 t/d; TP: 0.15 ± 0.19 t/d) wastewater loads by 2–3 (TSS) and 1–2 (TP) orders of magnitude. When comparing the canal to industry and to domestic sources, the mean differences are $2.5 \pm 1.9 \times 10^3$ t/d for TSS and 3.1 ± 2.4 t/d for TP. The ranges of confidence on these mean differences do not include zero, and so it may be said with certainty that the TSS and TP loads from the canal are significantly greater than the respective industrial and domestic loads with a statistical significance of 1.3 standard deviations in all cases. In these cases of TSS, TP and coliforms, the upper bounds of the confidence intervals of the secondary sources are well-below the lower bounds of the principal source. The association between TSS and TP may be expected due to phosphorus' high potential for sorption to sediment particles (Schlesinger, 1997).

In the case of BOD (Fig. 7), the principal sources appear to be the Dique Canal (6.7 ± 6.5 t/d) and the industrial sector (7.5 ± 9.7 t/d), though domestic wastewater also makes a substantial contribution (1.7 ± 0.6 t/d), which lies within the lower bound of the canal's and industry's confidence intervals. The mean differences between the BOD of these sources (canal-domestic: 5.0 ± 6.6 t/d; industry-domestic: 5.9 ± 9.7 t/d) include zero within the range of confidence and so it cannot be said with certainty that $L_{canal} > L_{domestic}$ or $L_{industry} > L_{domestic}$. Furthermore, considering that the domestic wastewater load is likely an underestimate since the overflow from the city's sewage system was not included in the load calculations, the importance of the domestic BOD load should not be ignored.

In the case of nitrogen, the principal sources also appear to be the Dique Canal and the industrial sector (Fig. 7). Though this analysis is complicated by the fact that each group of sources reported a different type of nitrogen (domestic: inorganic N;

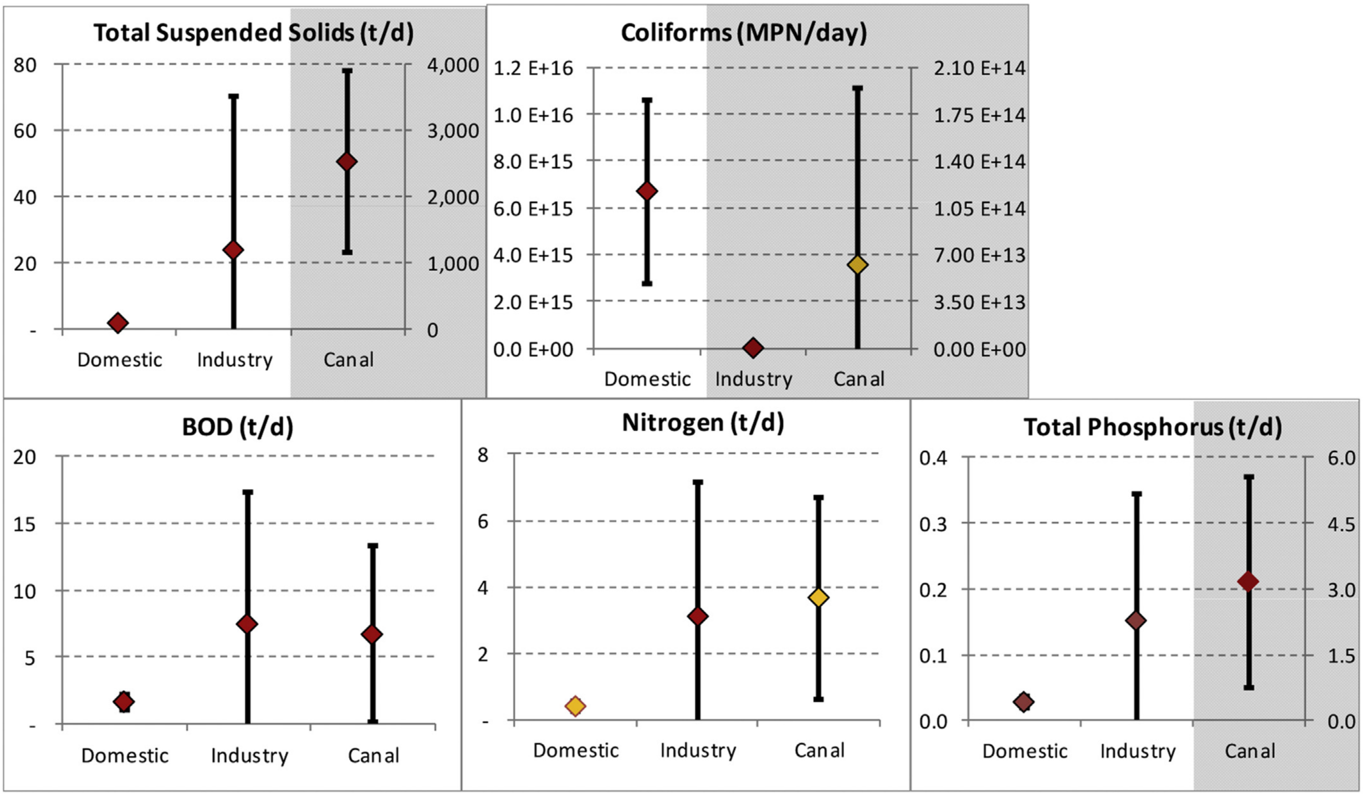

Fig. 7. Comparison of daily loads from three groups of land-based sources of pollution: coastal domestic wastewater, coastal industrial wastewater, and upstream continent runoff. Error bars represent the confidence intervals approximated for each value. Loads in grey boxes correspond to another scale on right vertical axes. Yellow symbols represent a different but inclusive form of the water quality parameter: fecal coliforms, inorganic N (domestic) and NO_3-N (canal). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

industrial: total N; canal: NO_3-N), a reasonable comparison can still be made considering that NO_3-N is a component of inorganic N, and inorganic N is a component of total N (i.e. NO_3-N < inorganic N < TN). It is therefore clear that the Dique Canal is a principal source of nitrogen as its TN concentration would be even higher than the NO_3-N load calculated in this study (3.7 ± 3.1 t/d), along with the industrial load reported as TN (3.1 ± 4.1 t/d). What is uncertain is how high the total nitrogen load of domestic wastewater sources would be, as they are reported here as inorganic N (0.4 ± 0.1 t/d) which represents just a portion of total N. Therefore, while we cannot be certain if domestic wastewater is a principal source of N, it can be stated that domestic wastewater is a significant source of N to Cartagena Bay, in consideration as well that the domestic load is an underestimate.

5. Discussion

5.1. Benefit of the approach

While the assessment of coastal pollution loads has been applied in the past (Garay and Giraldo, 1997; Tuchkovenko and Lonin, 2003), the approach proposed in this study allows for the comparison of loads through the quantification of confidence intervals, thus permitting a confident identification of primary pollution sources. The persistence of pollution issues in Cartagena Bay may be due in part to how difficult it has been to identify individual sources. With the pollution source identification achieved by our approach, public perception may be easier to align with reality while financially-motivated attempts to influence those perceptions can be better constrained by data. By compiling the available data and assessing these pollutant loads, the resulting load comparison permits the coastal zone manager to better inform stakeholders about which pollution sources are the dominant problem and manage them more effectively.

The inclusion of confidence intervals in the analysis provides further clarity to decision makers in that they can consider the relative uncertainty and variability of each load estimate as they compare across sources. Data availability is a common limitation to making such assessments and finding clear differences between sources. By calculating confidence intervals, even with estimates derived using different methods, it allows the analyst to better portray differences in results and identify where additional data gathering is needed. The available data will naturally be different when applying this approach in other study areas, though the methods of confidence interval approximation for the purposes of load comparison could be applied anywhere. Ultimately, the benefit of plotting these load estimates with confidence intervals allows decision-makers to base their actions on numerically supported conclusions, which may or may not support previous assumptions.

5.2. Further considerations to nearby sources of domestic wastewater

In reality, the domestic wastewater load received by the bay is even higher than the load approximated in this study because the load due to overflow of the city's sewage system was not included. The flow through this system occasionally exceeds capacity, particularly during rainy conditions as it also receives urban stormwater runoff, resulting in direct discharge into the bay through the bay's old submarine outfall and backup outlets along the coast (personal communication with the city water authority, AcuaCar). This likely explains the bay's seasonal variation of coliform concentrations which are highest during the rainy season, particularly to the north near the city, and remain high during the dry season to the south near a large non-serviced population (Tosic et al., 2017). Therefore, the solution to the issue of inadequate recreational waters would require both the mitigation of non-serviced populations as well as improved capacity to the city's sewage system.

Another potential source of pollution related to domestic wastewater could be organic matter that has accumulated over time at the bottom of the bay. The old submarine outfall in Cartagena Bay operated between the years 1960 and 2013, during which it received about 40% of the city's sewage (~48,000 m^3/day) and discharged 800 m from the coast without treatment (UNDP-UNOPS, 1999; Tuchkovenko and Lonin, 2003). Some of the lowest dissolved oxygen concentrations in the bay can be found in the area of this old outfall (Fig. 1) and so perhaps one of the causes of the bay's hypoxic conditions is the legacy organic matter accumulated in this area after so many years of untreated discharge.

5.3. Further considerations to nearby sources of industrial wastewater

Further research is needed on the discharges of the specific industries found around Cartagena Bay. While such data could not be obtained for this study, the loads reported in previous publications along with the inclusion of a rough yet conservative approximation of changes over time (±50%) into the confidence interval permitted the finding that the industrial sector contributes significant BOD and nitrogen loads to Cartagena Bay. Though the loads of specific industries are unknown, knowledge of the general characteristics of industrial discharges can be used to narrow down the potential sources. A previous study by INVEMAR-MADS (2011) showed that among the industrial activities found in Cartagena, food processing and chemical plants are the most likely to contain high levels of organic matter and nutrients in their discharge. Therefore, while further research is needed to improve the approximation of industrial loads, it may also be recommendable to focus pollution control efforts on the food processing and chemical industries towards the mitigation of the bay's hypoxia.

5.4. Further considerations to runoff

An important question is how the flow of freshwater and sediments will change in years to come. On one hand, modelling predictions based on past trends of these fluxes show that they are intensifying and sediment loads are projected to increase by as much as 317% by the year 2020 (Restrepo et al., 2016b). On the other hand, an ongoing hydraulic intervention in the Dique Canal is being implemented by the National Adaptation Fund (http://sitio.fondoadaptacion.gov.co/) which plans to construct hydraulic doors along the canal and reduce flow into the bay by ~50%. However, this plan's estimate of reduced flow does not take into account potential increases in water and sediment fluxes from the Magdalena watershed. Consequently, the resulting balance between this hydraulic intervention and the Magdalena's increasing trends remains to be seen. It should also be noted that the annual sediment load calculated by the present study (0.9 ± 0.7 Mt/year) is less than previous estimates of 1.9 Mt/year (Restrepo et al., 2016b) which may be attributed to the El Niño event that occurred during the present study.

5.5. Community perception

To have an idea of what the public perception is of pollution issues in Cartagena, we asked 110 local artisanal fishermen the simple open-ended question: “what do you think is the source of pollution in Cartagena Bay?” Responses were grouped in general categories, including the Dique Canal and industries which accounted for 39% and 45% of the responses, respectively. However, the fishermen did not identify domestic wastewater as a pollution sources, but rather tourism (16%). These fishermen are the people that are most affected by the bay's pollution issues, as the resulting impacts on fish populations have a direct effect on their livelihood. Their perception of the canal's impact may be expected, as it is evident from the year-round prevalence of sediment plumes flowing from the canal into the bay. While industry might have a less visible effect on water quality, perhaps their perception of industrial impacts reflects an association between the bay's increased industrial activities and the simultaneous degradation of their fish stock. The depletion of fish populations and the growth of tourism have resulted in an economic shift towards tourism for these people (Garzón, 2016; Castillo, 2016). However, the fish stock's depletion is complex as there are many likely causes in addition to hypoxia, such as past chemical and oil spills, over-fishing and changes in the bay's sewage outfall.

6. Conclusions

The benefits of applying an integrated approach for the assessment of land-based pollutant loads have been shown by this study for the case of the coastal zone of Cartagena Bay, Colombia. Despite the lack of available data, the approach permitted an approximation of pollutant loads by combining multiple computation methods with a focus on estimating confidence intervals for the data and calculations utilized. By implementing a monthly monitoring program at the outlet of a large coastal watershed, the consideration of seasonal variability in the assessment was made possible. While the available data will naturally be different for other study areas, the methods for estimating loads and confidence intervals shown here could easily be adapted to make this approach applicable to other coastal areas with similar problems commonly found across the Wider Caribbean Region.

When comparing the loads of three groups of land-based sources (coastal domestic wastewater, coastal industrial wastewater, and upstream continent runoff) in Cartagena Bay, it was found that the principal source of coliforms is nearby coastal domestic wastewater. The high loads of total coliforms approximated in this study ($6.7 \pm 3.9 \times 10^{15}$ MPN/d) due to non-serviced coastal populations is several orders of magnitude higher than that of the industrial sector ($2.7 \pm 5.5 \times 10^{7}$ MPN/d) and two orders of magnitude higher then the fecal coliform load from the Dique Canal ($6.2 \pm 13.1 \times 10^{13}$ MPN/d). This problem is further compounded by domestic wastewater that occasionally overflows from the city's sewage system, which is the likely explanation for the increase in coliform concentration in the bay's surface waters during the rainy season.

The principal source of TSS and TP in the bay is clearly the Dique Canal which discharges approximate loads of $2.5 \pm 1.9 \times 10^{3}$ t/d and 3.2 ± 2.4 t/d, respectively, which outweigh the domestic and industrial wastewater loads by 2–3 (TSS) and 1–2 (TP) orders of magnitude. While turbidity issues in Cartagena Bay can clearly be related to the canal, the issues of hypoxia may be associated with all three of the sources evaluated. The greatest BOD and nitrogen loads appear to come from the canal and the industrial sector, though a significant contribution of these parameters was also found for domestic wastewater sources as well.

Acknowledgements

This work was carried out with the aid of a grant from the International Development Research Centre, Ottawa, Canada (grant number 107756-001). Financial support was also provided by EAFIT University, Corporación Autónoma Regional del Canal del Dique (CARDIQUE; agreement number 15601), as well as a scholarship granted to the lead author by the Erasmus Mundus Doctoral Programme in Marine and Coastal Management (MACOMA). Special thanks are made to Laura Castillo Ardila of Los Andes University for carrying out the fishermen surveys, to Aguas de Cartagena (AcuaCar) for providing information on the city's sewage system, and to CARDIQUE for providing data and reports on the city's industrial sector. The authors also thank the following persons and organizations for their support in data collection: John Bairon Ospina, Mariana Jaramillo, Jesús Pérez, Carlos Gutiérrez, Jhonnatan Ballestas, Benjamin di Filippo, Fundación Hernán Echavarría Olózoga and Escuela Naval de Cadetes "Almirante Padilla". We also thank the journal editor and two anonymous reviewers who made helpful comments on the manuscript that resulted in its improvement.

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