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A practical method for setting coastal water quality targets: Harmonization of land-based discharge limits with marine ecosystem thresholds

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ABSTRACT

The Caribbean Sea provides significant ecosystem services to the livelihood and well-being of countries in the region. Protection of the marine ecosystem requires policy on coastal water quality that considers ecologically-relevant thresholds and has a scientific foundation linking land-based discharges with seawater quality. This study demonstrates a practical method for setting local-scale coastal water quality targets by applying this approach to Cartagena Bay, Colombia, and setting targets for end-of-river suspended sediment loads to mitigate offshore coral reef turbidity. This approach considers reef thresholds for suspended sediments and applies a field-calibrated 3D hydrodynamic-water quality model (MOHID) to link the marine thresholds to fluvial loads. Monitoring data showed that suspended sediments were consistently above the coral reef ecosystem threshold of 10 mg/l, and the model adequately reproduced field observations. It was shown that ecosystem thresholds could be maintained within the extent of the bay by reducing suspended sediment loads in the Dique Canal from current load estimates of 6.4×10^3 t/d (rainy season) and 4.3×10^3 t/d (transitional season) to target loads of 500–700 t/d, representing reductions of ~80–90%. These substantial reductions reflect ongoing issues in the Magdalena watershed which has experienced severe erosional conditions and intense deforestation over the past four decades. The presented method is practical for countries without access to long-term datasets, and could be applied to other parameters or discharge types. The method is particularly beneficial for developing site-specific targets, which are needed considering the natural and anthropogenic variability between different coastal zones and water bodies.

1. Introduction

The Convention for the Protection and Development of the Marine Environment in the Wider Caribbean Region (WCR), also known as the "*Cartagena Convention*", is a regional legal agreement for the protection of the Caribbean Sea, adopted in 1983. Its implementation is of great importance to the region, as the ecosystem services provided by the Caribbean Sea are quite relevant to the economy and public health of the WCR's member states, many of which are small island developing states that are dependent on fishing and tourism [1]. Marine ecosystems in the region have suffered impacts such as the widespread degradation of coral reefs, which have declined from an average of 34.8% in live coral cover to just 14.3% between 1970 and 2012 [2]. This decline can be partly attributed to water quality impacts from land-based pollution, as most of the Caribbean region's wastewater is discharged to the coast without treatment [3]. In recognition of this issue, the Cartagena Convention includes a protocol concerning pollution from land-based sources and activities (LBS Protocol) which obliges countries to take measures to prevent, reduce and control coastal pollution, including the establishment of legally binding standards for sewage effluent and discharges [4]. While the country of Colombia is both a member state and depository of the Cartagena Convention, it has yet to ratify the LBS Protocol. Ironically, 35 years after the convention's adoption in the city of Cartagena, Colombia, the coastal zone of Cartagena has become one of the region's hot-spots of pollution [5,6].

To effectively manage marine pollution issues at the local, national or regional level, there is a need for water quality standards that both: i) have a scientific foundation that links land-based discharge limits with marine water quality standards; and ii) are relevant to the ecological thresholds of the receiving marine ecosystems [7–11]. In terms of land-based pollution sources, standards are needed to control point-source effluents of domestic and industrial wastewater, which are

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contemplated in the LBS Protocol, and should consider pollutant loads rather than just pollutant concentration. As the pollutant load (L) is a function of both the flowrate (Q) and concentration (C) of an effluent, the load ($L = Q \times C$) is a "universal" expression of the total quantity of the pollutant discharged into the receiving water body; To control an effluent only by its concentration would be incomplete as this would ignore the effect of changes in flowrate. There is also a need to develop targets for river outlets, such as those outlined by the European Union's Water Framework Directive (WFD, 2000/60/EC) which requires river basin management plans to link coastal and river objectives, or Australia's Reef Plan [12] which includes targets for end-of-river reductions in nutrients and sediments.

The method by which land-based discharge targets are established will determine whether or not they are relevant to the receiving ecosystem. For example, the USA's Clean Water Act entails the establishment of Total Maximum Daily Loads (TMDL) which should be designed to meet a water quality standard in an impaired receiving water body [13]. Yet effluent limits in the USA are determined by methods, such as the Best Available Technology Economically Achievable [14], which are actually focused on the economic feasibility of implementing wastewater treatment rather than on the assimilative capacity of the receiving environment. Other methods of target setting for land-based discharges have been based on pre-industrial loads [15] or the feasibility of improved agricultural practices [16]. However, if land-based discharge targets do not consider the coastal zone's hydrodynamic characteristics and marine ecological thresholds, they may not ensure the compliance of marine water quality standards [17] and thus cannot be effective in protecting marine ecosystems [9].

The coral reefs offshore of Cartagena, Colombia, adequately demonstrate the ecosystem impacts resulting from inadequate policy on water quality standards. These reefs are in the Marine Protected Area of the Rosario Islands (Fig. 1) and have an average coral cover of approximately 23% [18]. But they incur a chronic stress caused by river sediment plumes as data show that over the 2000-2013-period, the Rosario Islands were exposed to turbid waters (total suspended solids concentrations > 10 mg/l in surface waters above the reef) between 19.6 and 47.8% of the time [19]. Excessive suspended sediments concentrations in reef waters can impair coral health due to the restriction of light, the smothering of coral polyps and the associated nutrients transported with the sediments [20]. However, current policy in Colombia does not include targets for river outlets nor does it include marine ambient water quality standards for suspended sediments or nutrients [21]. Policy has recently been developed for point-source discharges in Colombia's coastal zone [22] though without established marine water quality thresholds or consideration of nearshore dispersion processes, the policy lacks the science-based foundation needed to ensure marine ecosystem relevance. Given the socioeconomic importance of Cartagena, as the country's #1 touristic destination, and the ecological relevance of the Rosario Islands, Colombia has a need for water quality standards that adequately protect its natural marine resources.

Various science-based methods have been developed to link water quality objectives for land-based discharges and marine waters. At the large scale of the Baltic Sea, Schernewski et al. [23] coupled a river basin flux model with a marine ecosystem model to set target concentrations of nitrogen, phosphorus and chlorophyll-*a* in river outlets and marine waters. This approach established a marine water reference as 150% of modelled pre-industrial conditions and then targeted the reductions in river nitrogen load needed to comply with this marine reference. Research in the Great Barrier Reef has linked end-of-river and marine water targets based on ecosystem thresholds determined by long-term ecological assessments [8]. This approach established marine thresholds of photic depth for seagrass and chlorophyll-a for coral reefs, and then used linear relationships to determine river load targets for sediments and nitrogen. While these approaches may be appropriate for large areas like the Baltic Sea or Great Barrier Reef, they may not be applicable at smaller scales where local hydrodynamics and dispersion processes could deviate from the generalized relationships of these seasonally averaged, spatially integrated approaches. Furthermore, the aforementioned studies utilized decades-worth of monthly monitoring data, which a developing country such as those of the WCR is unlikely to have.

Some local-scale studies have quantified the link between land-based loads and receiving waters by applying hydrodynamic and water quality models. Deng et al. [24] and Han et al. [25] used similar methods of modelling and linear programming in Jiazhou Bay and the Yangtze River Estuary, China, respectively, to calculate the maximum river nutrient load that would maintain marine chlorophyll-*a* below the given criteria. However, this approach did not consider ecosystem-relevant seawater quality targets. Ramin et al. [26], successfully calibrated a water quality model of Hamilton Harbour in Lake Ontario, Canada, to relate land-based phosphorus loads to the harbour's water quality criteria for phosphorus and chlorophyll-*a*. However, this method was also based on seasonal averages which disregard the temporal variability that in reality could result in the frequent exceedance of the water quality criteria.

In this study, we aim to demonstrate a practical method for setting local-scale coastal water quality targets. Such methods are needed for local-scale environmental management in countries like those of the WCR that are still developing their water quality policies. We apply this method to the example of Cartagena Bay, Colombia, by setting targets for end-of-river suspended sediment loads in order to mitigate offshore reef turbidity impacts. The study's objectives are to present a method that is: i) appropriate at the local-scale, ii) science-based, iii) ecosystem-relevant, and iv) applicable to the coastal zones of developing countries where historical datasets are unlikely to be available. By considering marine ecological thresholds and applying a coupled 3D hydrodynamic-water quality model (MOHID) to link the marine thresholds to fluvial loads, the presented approach is both science-based and ecosystem-relevant. The model's fine resolution accurately captures local hydrodynamic and dispersion processes, making it appropriate at the local scale, while the two years of monthly data used in this study could feasibly be collected by a developing country devoid of historical datasets. We hypothesize that marine suspended sediment concentrations in the outer limits of Cartagena Bay can be maintained below coral reef ecosystem thresholds by reducing fluvial suspended sediment loads in the bay's principal freshwater source, the Dique Canal. Our specific research question thus asks: what fluvial suspended sediment load is needed to effectively ensure that the selected marine ecosystem target is not exceeded?

2. Materials and methods

2.1. Study area

The tropical semi-closed estuary of Cartagena Bay is situated in the southern Caribbean Sea on the north coast of Colombia (10°20′ N, 75°32′ W, Fig. 1). The bay has an average depth of 16 m, a maximum depth of 32 m and a surface area of 84 km^2, including a small internal embayment situated to the north. Water exchange with the Caribbean Sea is governed by wind-driven circulation and tidal movement through its two seaward straits [27]: "Bocachica" to the south and "Bocagrande" to the north. Movement through Bocagrande strait is limited by a defensive colonial seawall 2 m below the surface. Bocachica strait consists of a shallow section with depths of 1–3 m, including the Varadero channel, and the Bocachica navigation channel which is 100 m wide and 24 m deep [28,29]. The tides in the bay have a mixed, mainly diurnal signal with a micro-tidal range of 20–50 cm [30].

Estuarine conditions in the bay are generated by discharge from the Dique Canal which diverges from the Magdalena River at Calamar, 114 km upstream of Cartagena Bay. The Dique Canal discharges approximately 50–250 m^3/s of freshwater into the bay [6,28], the

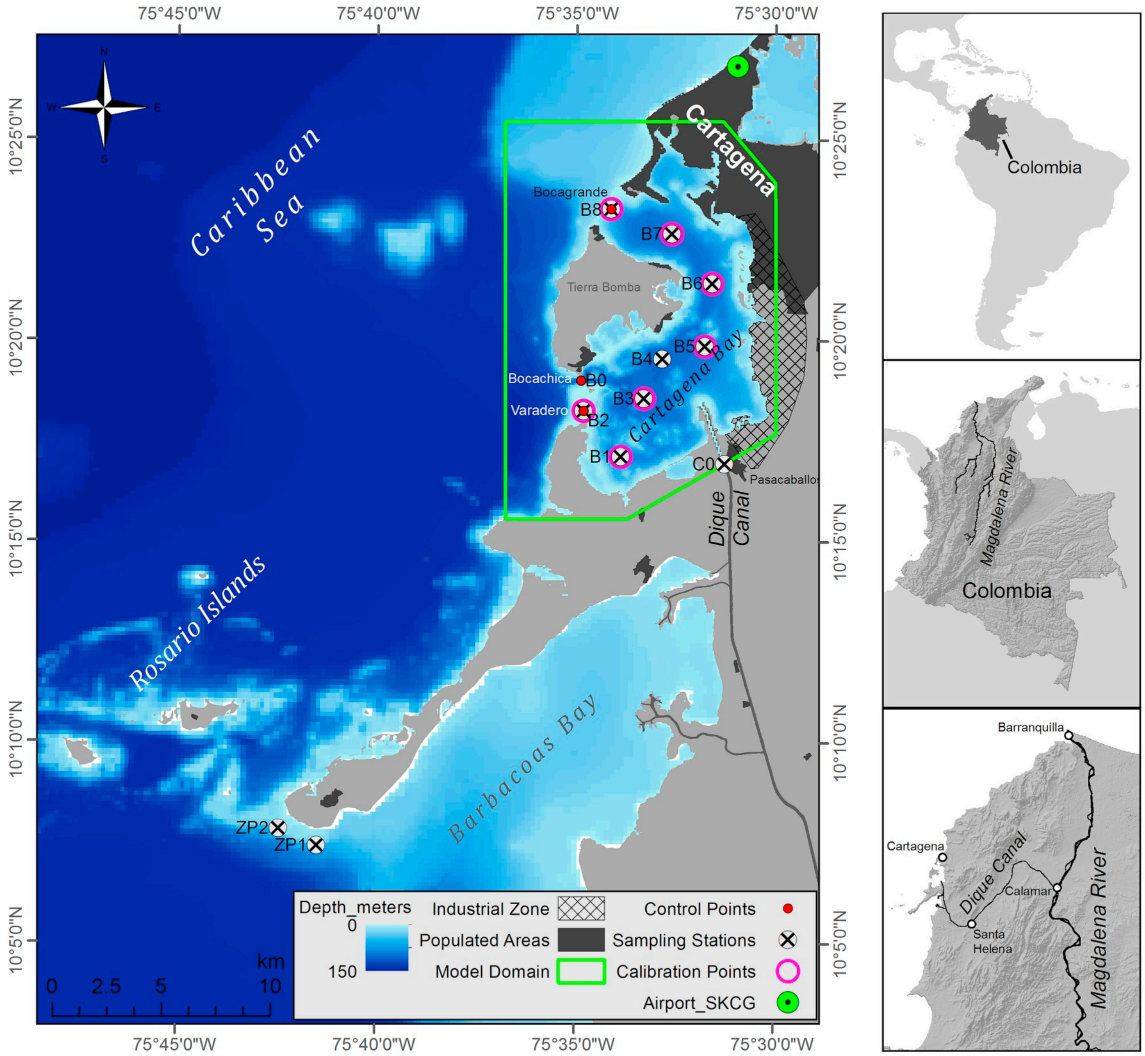

Fig. 1. Principal panel: study area showing sampling stations, model calibration points, control points, weather station (SKCG), bathymetry and model domain. Secondary panels: location of Colombia (upper panel); location of the Magdalena River (middle panel); flow of the Magdalena into the Caribbean Sea and along the Dique Canal into Cartagena Bay (lower panel).

variability of which is strongly related to seasonal runoff from the Magdalena watershed. With an area of 260,000 km^2, this basin covers approximately 25% of the country's land area and is the main contributor of fluvial fluxes to the Caribbean Sea [31]. The Dique Canal transports a total sediment flux of 1.9 Mt/y [32] which has increased over the past decade [33]. When compared with the average discharge during the 2000–2010 period, the canal's sediment load is projected to increase by as much as 317% by the year 2020 [32]. The sediments discharged into Cartagena Bay have been characterized as fine lithoclastic clays with low $CaCO_3$ content [34] and deposition rates that vary between 1.2 and 5.0 cm/y [35]. The flow of freshwater and sediments into the bay generate a highly stratified upper water column with a pronounced pycnocline in the upper 4 m of depth, above which turbid freshwater is restricted from vertical mixing and fine suspended particles tend to remain in the surface layer [28,36,37].

The bay's seasonal conditions may be categorized according to the variability of winds, rainfall and freshwater discharge (Table 1). The Dique Canal's highest discharges typically occur from October to November, while its lowest levels occur from January to February. Winds are strongest and predominantly northerly from January to April due to the trade winds which coincide with the strengthening of the southern Caribbean upwelling system and the cooling of surface water temperatures [38,39]. These conditions result in seasonal variability of the bay's water quality [5] and hydrodynamics [40]. During the dry/windy season (Jan.–Apr.), vertical mixing increases and water quality improves. This is reversed during the transitional (May–Aug.) and rainy (Sept.–Dec.) seasons when vertical stratification increases and water quality worsens. The transitional season has the highest temperatures,

Table 1
Average environmental conditions measured during the rainy (19 Oct. - 17 Nov.), transition (28 June - 26 July), and dry/windy (27 Jan. - 24 Feb.) seasons in the year 2016. Parameters in the Dique Canal were measured at the canal's outlet (station C0, Fig. 1). Wind speed and direction data were obtained hourly from the Airport METAR station SKCG (Fig. 1). Rainfall data were obtained from NOAA's Global Forecast System (GFS).

	Rainy Season	Transition Season	Dry/Windy Season
Dique Canal			
Water Discharge (m^3/s)	225	167	34
TSS Concentration (mg/l)	328	297	31
TSS Load (t/day)	6373	4295	91
Meteorological Parameters			
Wind Direction (°)	309.0	10.3	16.6
Wind Speed (m/s)	3.0	3.3	5.0
Daily Rainfall (mm/day)	9.4	2.2	0.0

lowest levels of dissolved oxygen and a dominant westward surface water flow towards Bocachica strait. In contrast, the rainy season has a larger northward surface water flow towards Bocagrande and higher concentrations of suspended sediments, nutrients and pathogenic bacteria. Restrepo et al. [41] also showed that the dry season's strong northerly winds result in greater sediment deposition in the southern part of the bay, while during the rainy season there is a more homogenous distribution of sediments, the extent of which is proportional to discharge from the Dique Canal.

Marine ecosystems in this coastal zone have been degraded by poor water quality and other impacts, including the depletion of seagrass beds, coral reefs and benthic suspension feeding invertebrates [41,42]. On the seaward side of Bocachica strait lies the Varadero reef, which has a high coral cover of 45.1% despite its proximity to Cartagena Bay [43], likely due to the strong stratification of water flowing out of the bay which maintains sediments and associated contaminants in the surface layer until they are transported further offshore. Further offshore are the previously described reefs of the Marine Protected Area of the Rosario Islands (Fig. 1), which are chronically exposed to river sediment plumes [41].

2.2. Data collection

Water quality was monitored monthly in the field from Sept. 2014 to Nov. 2016 between the hours of 9:00–12:00 [44]. Measurements were taken from 11 stations (Fig. 1), including one station in the Dique Canal (C0), eight stations in Cartagena Bay (B1–B8) and two stations at the seaward end of Barú peninsula (ZP1-ZP2). At all stations, CTD casts were deployed using a YSI Castaway measuring salinity and temperature every 30 cm of depth. Grab samples were taken from surface waters while bottom waters (22 m depth) were sampled with a Niskin bottle. Surface samples were collected in triplicate at station C0. A triplicate sample was also taken at a different single station in the bay each month to estimate sample uncertainty. Samples were analyzed at the nearby CARDIQUE Laboratory for total suspended solids (TSS) by standard methods [45].

At station C0 in the Dique Canal, discharge was measured with a Sontek mini-ADP (1.5 MHz) along a cross-stream transect three times per sampling date from Sept. 2015 to Nov. 2016. Bathymetric data with 0.1 m vertical resolution were digitized from georeferenced nautical maps (#261, 263, 264) published by the Colombian Navy's Centre for Oceanographic and Hydrographic Research (CIOH-DIMAR). In the 3×2 km area of Bocachica strait, the digitized bathymetry was updated with high-precision (1 cm) bathymetric data collected in the field on 17 Nov. 2016.

Hourly METAR data of wind speed, wind direction, air temperature and relative humidity were obtained from station SKCG at Rafael Núñez International Airport (approximately 10 km north of the bay; Fig. 1). Albedo, cloud cover, and precipitation data were obtained at a location 3 km offshore of Cartagena Bay from datasets available from NOAA's Global Forecast System (GFS) with 3-h frequency. Daily profiles of temperature and salinity were obtained from the European Union's Mercator Ocean Model at a location 10 km offshore of the bay. Tidal components were obtained for numerous locations offshore of the bay from the finite element solution tide model FES2004 [46] using the MOHID Studio software. Hourly measurements of water level at a location within the bay were also obtained from the Centre for Oceanographic and Hydrographic Research (CIOH-DIMAR).

2.3. Model application

The hydrodynamics of Cartagena Bay were simulated using the MOHID Water Modelling System [47,48]. The MOHID Water model is a 3D free surface model with complete thermodynamics and is based on the finite volume approach, assuming hydrostatic balance and the Boussinesq approximation. It also implements a semi-implicit time-step integration scheme and permits combinations of Cartesian and sigma coordinates for its vertical discretization [49]. Vertical turbulence is computed by coupling MOHID with the General Ocean Turbulence Model (GOTM) [50].

Model configuration for Cartagena Bay was based on an equally-spaced Cartesian horizontal grid with a resolution of 75 m and a domain area of 196 km^2 (Fig. 1). This included an offshore area extending 2.3 km off the bay, though only the results inside the bay are considered within the limits of the monitoring stations used for calibration. A mixed vertical discretization of 22 layers was chosen to reproduce the mixing processes of the highly stratified bay by incorporating a 7-layer sigma domain for the top 5 m of depth and a variably-spaced (depth-incrementing) Cartesian domain below that depth. An optimal time step of 20 s was chosen.

The collected data of water temperature, salinity, canal discharge, bathymetry, tides, winds and other meteorological data were used to configure the hydrodynamic model. The lateral forcing of the tides was determined by the harmonic components extracted from the FES2004 model at numerous locations along the boundary. Daily profiles of seawater temperature and salinity extracted from the Mercator model were imposed at the open sea boundary. Measured monthly values of discharge, velocity and TSS concentration for the inflowing Dique Canal were imposed as a time series from which the model interpolates values of water flow and momentum for each time step during the simulation period. Atmospheric variables were all prescribed as spatially-constant fields with frequencies of 1-h (METAR data: wind velocity, air temperature, relative humidity) or 3-h (GFS data: albedo, cloud cover, precipitation data). Three month-long simulation periods during the dry/windy, transition and rainy seasons were configured with start and end times coinciding with the dates of monthly field measurements. Initial conditions of water temperature and salinity were defined as vertical profiles based on CTD measurements made on the corresponding start date. Each simulation's final water temperature and salinity were extracted as profiles at each sampling station location (B1–B8; Fig. 1) and compared to the CTD measurements of the respective end date. Measurements from the CIOH tidal gauge were compared to hourly time series of water height extracted from each simulation's output at the gauge's location (Fig. 1). This process included a sensitivity analysis to identify the system's most effective calibration parameters (horizontal viscosity and bottom roughness), and subsequent calibration and validation of the model. The hydrodynamic model performed adequately in its simulation of water temperature, salinity and water height when compared to observations. For more details on the hydrodynamic model's configuration, calibration and results, see Tosic et al., [6].

MOHID Water was also utilized to model the dynamics of suspended sediments in Cartagena Bay's surface waters, as the model has previously been shown to successfully reproduce sediment dynamics in estuaries (e.g., Ref. [51]. The modelling focused on the rainy and transitional seasons, which both yield high TSS concentrations in the bay though with distinct flow characteristics. For this purpose, two periods of a lunar-month duration in the year 2016 were simulated: 28 June – 26 July (transitional season) and 19 Oct. – 17 Nov. (rainy season). Start and end times for each simulation coincided with the dates of monthly field sessions. Initial conditions of suspended sediment concentration were defined by TSS measurements made on the corresponding start date. To avert numerical instabilities, a spin-up period of one day was applied to gradually impose wind stress and open boundary forcings [51]. Outputs from the simulations were compared with field measurements of surface TSS on the respective end date at seven calibration points in the bay (Fig. 1).

The model's suspended sediment block included flocculation processes. Calibration focused on the parameterization of the settling velocity (W_s) of suspended sediments. Constant and variable settling velocity configurations were tested, with a better fit yielded by the formulation proposed by Nicholson & O'Connor [52]: $W_s = K{\cdot}C^m$, where

K is a coefficient relating to sediment mineralogy, C is the TSS concentration and the exponent m relates to particle size and shape. As suspended sediment modelling was focused only on surface waters, the effect of hindered settling in bottom waters beyond a threshold concentration ($C > C_{HS}$) was ignored. Various combinations of K and m values were tested to identify the configuration that best reproduced the TSS field observations, as quantified through model performance statistics.

Model performance statistics included the mean of observed ($\bar{O}$) and predicted ($\bar{P}$) values, and the sample standard deviation of observed (s_O) and predicted (s_P) values [53]. The average error ($AE = \Sigma(P_i - O_i)/N$), with N being the sample size, was calculated as a measure of aggregate model bias in order to identify the model's tendency to over- or under-estimate observed values, while keeping in mind that positive and negative discrepancies can cancel one another [54]. The magnitude of the model's prediction accuracy is shown by the mean absolute error ($MAE = \Sigma|P_i - O_i|/N$) and the root mean squared error ($RMSE = (\Sigma(P_i - O_i)^2/N)^{0.5}$), the latter of which is sensitive to the inaccuracies of outliers [55]. The relative error ($RE = \Sigma|P_i - O_i|/\Sigma O_i$) was calculated in order to express error as a percentage of the observed values [56], noting that this measure is dependent on the magnitude of the variable itself. The index of agreement ($IOA = 1 - [\ \Sigma(P_i - O_i)^2/\Sigma(|P_i - \bar{O}| + |O_i - \bar{O}|)^2\ ]$) was also analyzed as a standardized measure of the model's error between 0 and 1 [53].

2.4. Target setting approach

This study selected a TSS concentration of 10 mg/l as an ecosystem threshold for coral reef health. TSS threshold values for coral reef conservation can be highly controversial as factors such as local hydrodynamics, solar radiation, coral physiology and sediment characteristics can all interact to cause varied effects [7]. A wide range of TSS threshold values have been used for reefs: 2 mg/l is used for the open coastal waters of the Great Barrier Reef [57], while 5 mg/l is used in the Caribbean waters of Barbados [58] and 50 mg/l has been reported as a threshold in Western Australian reefs [59]. The value of 10 mg/l was selected because it has been reported to be a tolerance threshold for chronic stress on coral reefs in the Caribbean [60] and is a value that has also been accepted by other authors [20,61,62], including previous studies of the Rosario Islands [41].

Three control points were selected to define the spatial limit beyond which the selected ecosystem threshold of 10 mg/l should not be exceeded. The three control points were established in Bocagrande strait (B8), Varadero canal (B2) and the Bocachica navigation canal (B0; Fig. 1). By establishing the control points in the straits that separate Cartagena Bay from the marine waters outside the bay, this approach effectively defines the bay as a mixing zone in which TSS concentrations can acceptably exceed the ecosystem threshold value. This spatial delineation could be considered logical as prominent coral reefs no longer exist within the bay, while the functioning reef of Varadero inhabits the area just outside the bay. This delineation also responds to previous research which showed that TSS concentrations above 10 mg/l regularly extended outside Cartagena Bay, contributing to the chronic stress of the Rosario Islands [41].

Time series of the results generated by the model simulations were extracted at the three control points to analyze the dynamics of TSS concentration. This modelling approach optimized the available information as it permitted the analysis of data at a fine spatial (every 0.7 m depth from the surface) and temporal (hourly) resolution over the entire month-long period of the simulation, as opposed to the monthly snapshots at fixed depth of the monitoring program. The time series were analyzed to assess whether the water quality at a control point exceeded the threshold value. This step required the definition of "exceedance", an important criterion with respect to the overall time period. For example, Schernewski et al. [23] have proposed that compliance with the EU's Water Framework Directive be reached when the median concentration of a parameter over a 5-year observation period (based on annually aggregated data) remains below the threshold concentration. However, this actually implies that the parameter's concentration could be above the threshold value for up to 50% of the time, which does not support the concept of ecosystem relevance. Exposure to above-threshold concentrations for extended periods of time would constitute a chronic disturbance, which restricts ecosystem recovery [63]. On the other hand, it may be impractical to use a criterion that requires the concentration to be below the threshold for 100% of the time, as occasional pulse events can be expected to occur that result in threshold exceedance, though such an event could be considered an acute disturbance from which an ecosystem can recovery [63]. In this consideration, as a conservative estimate of the time that constitutes an acute, short-term disturbance, this study established the criterion of 10% as the maximum allowable time of threshold exceedance and thus extracted the 90th percentile value from the time series results to compare with the threshold value.

Multiple scenarios of reduced sediment load were simulated with the model in order to evaluate the effect of load reductions on TSS concentrations at the control points. In order to not disturb the prevailing hydrodynamics, reduced sediment load scenarios were configured by reducing TSS concentrations in the Dique Canal, while the canal's freshwater discharge was left constant. The simulated scenarios of reduced TSS in the canal included concentrations of 225, 150, 100, 50 and 25 mg/l. The time series results of TSS concentration at control points in the bay under reduced TSS load scenarios were analyzed for both the rainy and transition seasons. Plots of the 90th percentile value versus mean TSS load in each scenario permitted the identification of the end-of-river target load. The corresponding reductions in TSS load required to meet the end-of-river target were then calculated as a percentage of the current load.

3. Results

3.1. Monitoring results

Monthly mean TSS concentrations in the Dique Canal ranged from 30 to 400 mg/l with a pronounced seasonal variation and higher concentrations occurring from April to June and Oct.–Nov. (Fig. 2). While low concentrations were generally observed in the months of Jan., Feb., July and Aug., distinctly lower concentrations were found in the canal during the months of July–August 2015 and Jan.–March 2016, likely related to the El Niño phenomenon occurring during this period. This period of decreased flow yielded lower discharge values of 30–60 m^3/s in Sept. 2015 and Jan.–Feb. 2016 (Fig. 2). Peak discharge values of 215–230 m^3/s were found in Oct.–Nov. 2016, while discharge during the rest of the study period ranged between 110 and 175 m^3/s. These measurements yielded a wide range of TSS load estimates, from 89 t/day in Jan.–Feb. 2016 to 6.4×10^3 t/day in Oct.–Nov. 2016 and a mean load (± standard deviation) of $3.2 \pm 2.2 \times 10^3$ t/day over the one-year period from Dec. 2015 to Nov. 2016.

TSS concentrations in the bay ranged from below detection limits (D.L. < 4.2 mg/l) to 76.0 mg/l (Fig. 2) with a mean of 20.1 mg/l, a median value of 15.0 mg/l and a standard deviation of 14.1 mg/l. Greater TSS concentrations were generally found in bottom waters than in surface waters. Station B5 directly north of the canal outlet yielded higher concentrations than other stations, particularly during the rainy season, while similar concentrations were found at station B3 (west of the canal) during the transitional season. High TSS concentrations were also observed during the dry/windy season in the southwest part of the bay (stations B1, B2). Mean TSS concentrations in the straits of Bocachica (B2) and Bocagrande (B8) were 16.3 ± 13.0 mg/l and 17.0 ± 11.6 mg/l, with ranges of < 4.2–60.0 mg/l and 5.3–51.6, respectively. High TSS concentrations were also found outside the bay at the offshore stations ZP1 and ZP2, with means of 22.1 ± 18.7 mg/l and 22.4 ± 20.1 mg/l, respectively, demonstrating the influence of

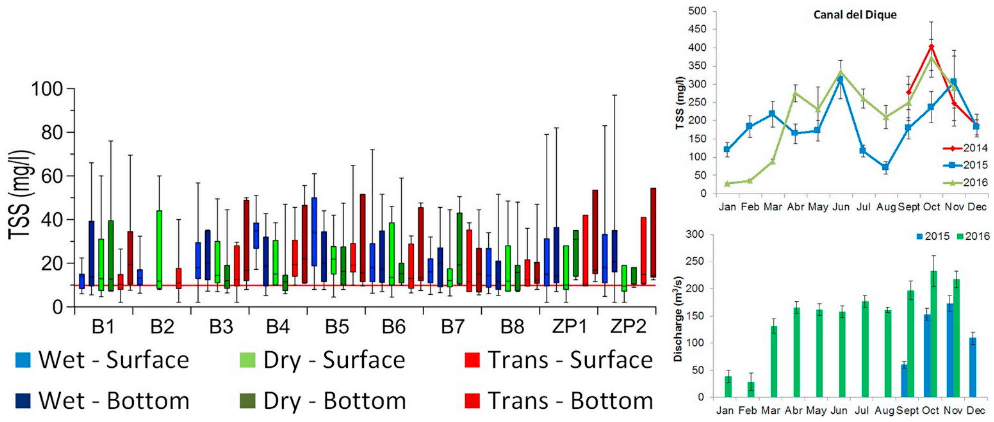

Fig. 2. Left: Box plot of total suspended solid concentration (mg/l) measured monthly from Sept. 2014 to Nov. 2016. Colours differentiate the rainy (Sept.–Dec.), dry/windy (Jan.–Apr.) and transitional (May–Aug.) seasons as well as surface and bottom waters (see legend). The red line drawn across the plot represents the threshold value of 10 mg/l. Station locations are shown in Fig. 1. Right: Mean TSS concentration (above) and mean discharge (below) measured in the Dique Canal. Error bars show standard deviations. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

sediment plumes in the Rosario Islands.

3.2. Modelling results

The calibrated model adequately reproduced field observations of surface water TSS concentrations during the 2016 rainy (Oct.–Nov.) and transition (June–July) seasons, as shown by the different performance statistics analyzed (Table 2; Fig. 3). Mean TSS values observed during the two simulation months were in close agreement with mean values produced by the model, yielding differences of just 0.1–0.2 mg/l. Greater standard deviations were found among values predicted by the model than those of observed data, showing that the model augmented the spatio-temporal variability of TSS in comparison to observations. However, the additional variability generated by the model was equally distributed above and below the means, as shown by the very small values of average error (AE: −0.2, 0.1 mg/l) which suggest that the model showed almost no bias in over- or under-estimating TSS concentrations. MAE and RMSE values of 2.8–3.5 mg/l and 3.9–4.1 mg/l, respectively, suggest adequate model performance as these error values are within the range of the laboratory detection limit (4.2 mg/l) and the natural variability shown by triplicate sampling (standard deviations between 0.2 and 9.6 mg/l). However, the values of RE are rather high (21–32%), though this may be expected given the magnitude of uncertainty due to natural variability and laboratory limits. It must also be taken into consideration that observations are made at single points in time while model values are obtained at hourly intervals for comparison, which could also contribute to the large RE and greater variability of predicted values. The Index of Agreement (IOA) value of 0.9 (out of a maximum index value of 1.0) also supports the assessment that the model performs adequately.

Time series analyses of model results at the designated control points (B0, B2, B8) in the bay's straits showed that TSS concentrations were frequently above the threshold value of 10 mg/l (Fig. 4). At station B2 in Varadero canal, TSS was consistently above the threshold value in both the rainy and transition season simulations with maximum values greater than 20 mg/l. At station B0 in Bocachica canal, TSS was also consistently above the 10 mg/l threshold during the rainy season, particularly in the top 3 m of surface water. During the transitional season, TSS values at B0 oscillated around the threshold value, with a mean concentration of 9.9 mg/l. At station B8 in Bocagrande strait, concentrations were consistently below the threshold during the transition season, while rainy season values were consistently above 10 mg/l in the top 3 m of surface water.

TSS concentrations were observed to oscillate inversely with the water level, as flood tides coincided with lower TSS and ebb tides coincided with higher concentrations. The concentrations of TSS thus have a mixed, mainly diurnal signal opposite to the tides, which have

Table 3
Total suspended sediment (TSS) loading of the Dique Canal into Cartagena Bay under present conditions and the reduced target load scenario. Present discharge and concentration values are based on monthly measurements in the Dique Canal in the year 2016.

Canal Parameters	Rainy Season		Transition Season	
	Present	Reduction	Present	Reduction
TSS Load (t/day)	6373	486	4295	723
Discharge (m^3/s)	225	225	167	167
TSS Concentration (mg/l)	328	25	297	50
Percent Reduction		92%		83%

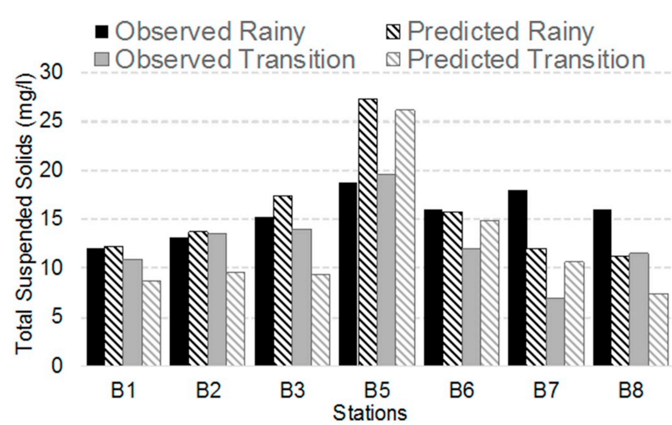

Fig. 3. Predicted model results compared to measured observations of total suspended solid concentration in surface waters at the end of two simulations (rainy and transition seasons) at calibration stations in Cartagena Bay (see Fig. 1).

Table 2
Statistics of model performance in predicting suspended sediment concentration: mean and standard deviation of observed ($\bar{O}$, s_O) and predicted ($\bar{P}$, s_P) values, average error (AE), mean absolute error (MAE), root mean squared error (RMSE), relative error (RE), and index of agreement (IOA).

Parameter	Season	$\bar{O}$	$\bar{P}$	s_O	s_P	AE	MAE	RMSE	RE	IOA
TSS (mg/l)	**Transition**	12.6	12.4	3.8	6.5	−0.2	3.5	3.9	32%	0.90
	Rainy	15.6	15.7	2.4	5.6	0.1	2.8	4.1	21%	0.90

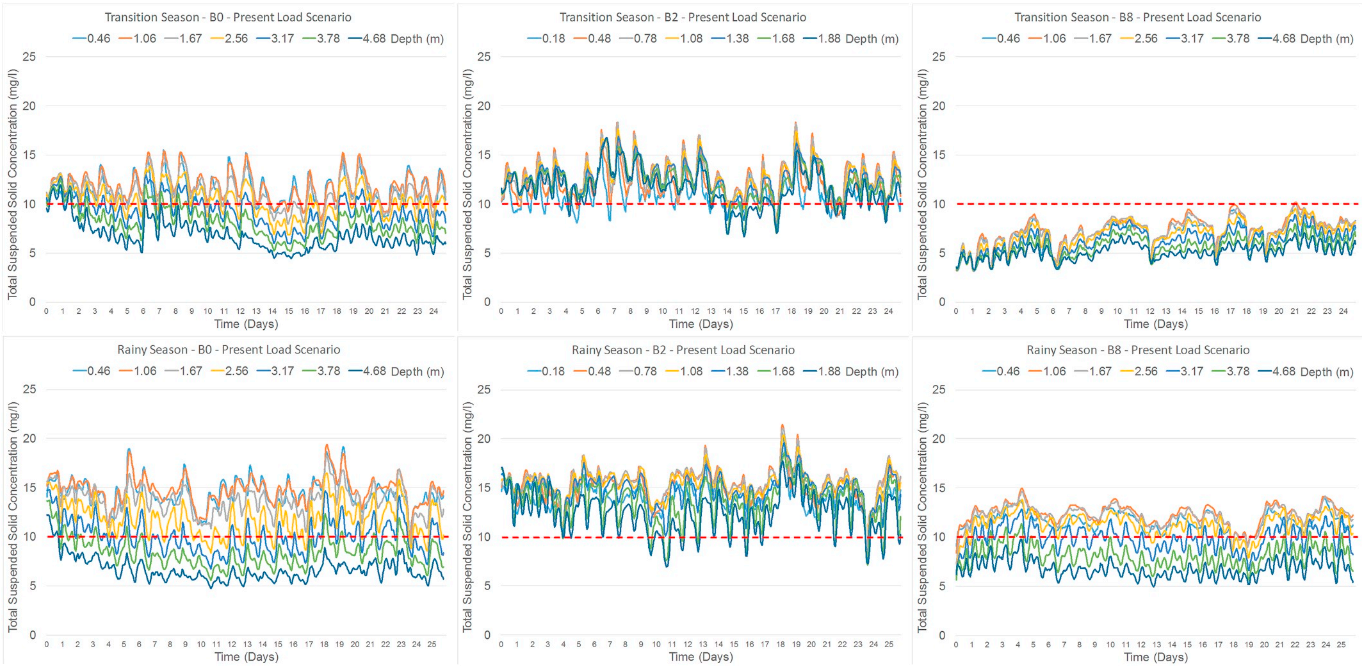

Fig. 4. Time series of total suspended solid concentration (mg/l) during simulations of present load conditions of the transition (above) and rainy (below) seasons at control points B0 (left), B2 (centre) and B8 (right). Coloured lines represent results at different depths from the surface (see legend). The red dashed line highlights the threshold value of 10 mg/l. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

principal tidal constituents K_1 and M_2 with amplitudes of 9 and 7 cm, respectively [30]. The magnitude of the oscillation in TSS concentrations varied between approximately 1-5 mg/l, showing the importance of tidal phase on water sampling times. A gradual increase in TSS concentrations over the month of the transitional season was also observed at station B8 (Fig. 4), possibly related to the TSS loads that gradually increased over the simulation period, though this trend was not observed at the other stations or during the rainy season.

3.3. Target setting

The 90th percentile values of TSS concentration at the three control points during simulations of the 2016 rainy and transition season were all above the 10 mg/l threshold value, with the exception of station B8 during the transition season (Fig. 5). Mean TSS loads during these months were approximately 6373 t/d (rainy) and 4295 t/d (transition). Simulated scenarios under conditions of decreased sediment load showed that load reductions gradually lowered the 90th percentile values of TSS at the control points, with a more pronounced effect at loads below 2000 t/d (Fig. 5).

Under the transition season scenarios, compliance of the 90th percentile value with the threshold value at all three control points was eventually reached at a TSS load of 723 t/d. Under the rainy season scenarios, even further reductions to a TSS load of 486 t/d were required to achieve compliance of the 90th percentile value with the threshold, likely due to the greater discharges during the rainy season generating faster surface currents and a broader dispersion of sediment plumes. Fig. 6 demonstrates the effectiveness of these reduced loads as TSS concentrations are shown to be consistently below the 10 mg/l threshold value at all three control points throughout the duration of both the rainy and transition season simulations.

The identified end-of-river target loads reveal the need for significant reductions in the upstream watershed. Under rainy season conditions, decreasing the load from 6373 t/d to 486 t/d represents a reduction of 92% (Table 3). Transition season conditions would require a reduction of 83% to decrease loads from 4295 t/d to 723 t/d. If the present flow conditions in the watershed were to be maintained, to achieve these load reductions with the discharge levels observed in 2016 would require a considerable decrease in canal TSS concentrations, down to 25 and 50 mg/l in the rainy and transition season, respectively.

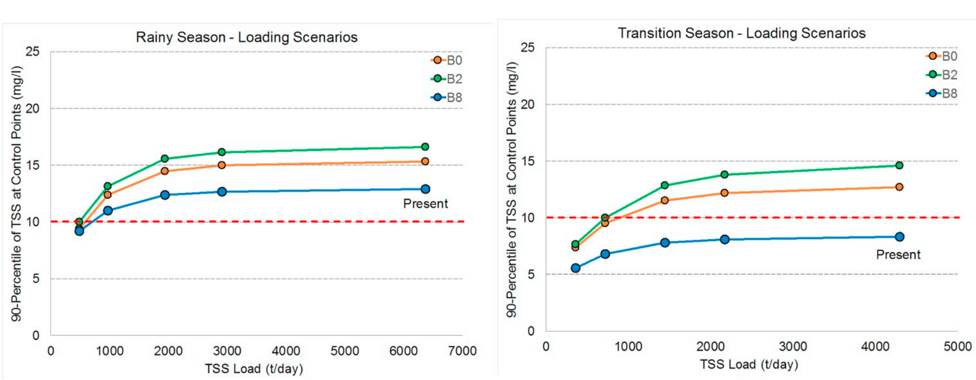

Fig. 5. TSS loading scenarios of the Dique Canal into Cartagena Bay in the modelled rainy (left) and transition (right) seasons. The present and reduced TSS load scenarios (t/day) in the Dique Canal are shown along the x-axis. The 90th percentile values of TSS concentration (mg/l) at three control points (B0, B2, B8; see Fig. 1) during the simulated 1-month time series (see Figs. 4 & 5) are shown along the y-axis. The red dashed line highlights the threshold value of 10 mg/l. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Fig. 6. Time series of total suspended solid concentration (mg/l) during simulations of reduced load conditions of the transition (above) and rainy (below) seasons at control points B0 (left), B2 (centre) and B8 (right). Coloured lines represent results at different depths from the surface (see legend). The red dashed line highlights the threshold value of 10 mg/l. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

4. Discussion

4.1. Feasibility of load reductions

Of course, reducing TSS concentrations in the canal without reducing its freshwater discharge (Table 3) is an abstract concept, as naturally the discharge and TSS concentration are related. The reduced sediment load scenarios of this study were configured by only reducing TSS concentrations in the canal while leaving its discharge constant in order to not disturb the bay's prevailing hydrodynamics. Despite this simplification, the recommendation is to focus mitigation on the reduction of TSS loads in general.

The task of reducing suspended sediment loads by 80–90% would seem daunting to any environmental manager or decision-maker, especially considering the enormous 260,000 km^2 area of the Magdalena Watershed. However, the drastic reductions needed to ensure adequate marine water quality are simply a reflection of ongoing issues of watershed management. Between the years 2000 and 2011, the Magdalena streamflow and sediment load experienced increases of 24% and 33%, respectively, compared to the 1972–1999 year period [32]. These trends reflect poor land management practices, as 79% of the catchment is classified to be under severe erosional conditions, and an intense rate of deforestation, as more than 70% of natural forests were cleared between 1980 and 2010 [33].

One of the solutions proposed to decrease these flows of freshwater and pollution into Cartagena Bay is a hydraulic intervention that plans to construct hydraulic doors along the Dique Canal [64]. However [6], have shown that the bay's water renewal time scales are principally dependent on the Dique Canal's discharge level, and so reducing this freshwater discharge would result in slower water renewal time scales in the bay. This result could actually worsen the bay's water quality issues as local wastewater pollution sources would then persist with less seawater renewal. Regardless, the closing of the Dique Canal would still result in the Magdalena River's full flow volume discharging to the coast of Barranquilla to the north (see Fig. 1), from where sediment plumes can still impact the reefs of the Rosario Islands [42]. It is therefore imperative that efforts to reduce fluvial sediment loads be focused in the watershed itself.

The implementation of Best Management Practices (BMP) to the wide range of activities in the Magdalena Watershed would be a recommendable initiative to improve erosion rates. For example, BMP implementation on farming practices in the US State of Ohio, such as conservation tillage or no tillage, decreased river TSS annual loadings by 50% over about 5 years [13]. A large proportion of load reductions can also be achieved quite economically, as Roebeling et al. [65] show that BMPs can reduce TSS loads by 35% and dissolved inorganic nitrogen (DIN) loads by 50% at no additional cost (and potential benefit) to farmers.

Strategies to reduce sediment fluxes to the coast could also include watershed restoration, flood risk mitigation and improved water resource management. The restoration and preservation of lands that act as natural buffer zones to waterways can effectively reduce terrestrial sediment loss via runoff. Examples of this strategy have been demonstrated through the Everglades Restoration Initiatives in South Florida [66] which have also included the treatment of stormwater by routing it through man-made wetlands. The protection of buffer habitats can also be combined with hydraulic engineering of river channels and flood plains to mitigate flooding events, which cause extensive erosion, as shown by the Dutch Room for the River Programme [67]. Initiatives for land management would also need to be supported by improved implementation of regulations for wastewater discharges throughout the Magdalena watershed [68].

Considerable load reductions, such as the 80–90% target of the present study, have also been proposed in other watersheds. Recommended reductions for the watersheds adjacent to the Great Barrier Reef (GBR) include targets of 50–63% for TSS [7,8] and 80–90% in DIN loads [11]. The most substantial of these reductions is needed for the Burdekin River watershed, which has an area of 130,000 km^2, is the largest single exporter of suspended sediment ($\sim 4 \times 10^6$ t/year) to the GBR and contributes 25% of the total average annual load exported from the GBR catchment area [69]. While the Magdalena watershed is just twice the size of the Burdekin watershed, the Magdalena's average annual sediment load of 188.2×10^6 t/year [33] is nearly 50 times greater than that of the Burdekin, underlining the immense amount of work needed to improve watershed management in Colombia.

Without improved management in the Magdalena watershed, future sediment loads are expected to increase. Projections of the catchment's hydrological trends show that water discharge and sediment flux from the Canal del Dique will increase by ~164% and ~260%, respectively, by the year 2020 when compared with the average discharge of the 2000–2010 period [32]. These trends correspond closely with land-cover changes in recent decades [33] while future precipitation increases due to climate change and the intensification of the El Niño-Southern Oscillation could also be expected to further heighten freshwater flows [32,70,71]. Extrapolation of the relationships observed in Fig. 5 suggests that such increases will worsen seawater TSS concentrations and thus exacerbate impacts on the coral reef system.

4.2. Feasibility of achieving ecosystem improvement

This study showed that TSS load reductions of 80–90% are needed to ensure that sediment plumes do not extend outside of Cartagena Bay in concentrations exceeding the ecosystem threshold value of 10 mg/l. While this management strategy focuses on sediment plumes dispersing from Cartagena Bay, it should be noted that there are also other sediment sources affecting the Rosario Islands, including plumes from Barbacoas Bay to the south and the Magdalena River's principal outlet to the north at Barranquilla [41,42]. Nevertheless, all three of these sources originate in the Magdalena watershed (see Fig. 1) and so improved land use management would effectively reduce the loads of all three sources.

Of more concern to the feasibility of achieving ecosystem improvement is that the reefs of the Rosario Islands may be impacted by a variety of stressors other than just sediment plumes [5,42]. Additional stressors such as excessive nutrients, rising sea temperatures or irresponsible tourist activities could likewise impair the marine ecosystem regardless of reductions in sediment plumes [20,72]. Cumulative impacts of multiple stressors make the ecosystem particularly vulnerable [11,60,61,63], which further supports the importance of mitigating sediment loads as one of the principal stressors.

4.3. Benefit of the approach

The demonstrated approach of setting targets for coastal water quality may be considered practical as its implementation does not require a long-term database. While the collection of two years of monitoring data and calibration of a coupled hydrodynamic-water quality model are labour-intensive activities to undertake, the method could still be carried out in a relatively short amount of time when compared to the time scales of policy development. The modelling approach also optimizes the amount of available data as the time series analysis provides more information than the snapshots of monitoring data. In this sense, the practicality of this method makes it accessible to countries like those of the WCR that are still developing their water quality policies.

Also important are the facts that this approach is science-based and ecosystem-relevant. Without considering nearshore hydrodynamics or ecosystem thresholds, the process of developing coastal effluent limitations can be relegated to an *ad-hoc* process of determining limits without the scientific knowledge needed to predict the consequences on coastal water quality and marine ecosystems. Of course, decision-makers may still prefer to utilize economically-based methods (e.g. Best Available Technology Economically Achievable), but the presented approach can at least inform decision-makers with science-based knowledge on the ecological relevance of a proposed target.

Furthermore, the presented method is appropriate for setting coastal water quality targets at the local-scale. Characteristics such as hydrodynamics, morphology and pollution sources vary greatly between different coastal zones, which makes each stretch of coastline, bay, lagoon or estuary unique. This variability is recognized by instruments such as the WCR's Cartagena Convention, which entails the distinction between Class 1 and Class 2 waters, or the GBR's Water Quality Guidelines [57], which classify trigger values by water type (enclosed coastal, open coastal, midshelf, offshore). Eventually, site-specific targets should be developed for individual coastal water bodies [23] and by capturing local hydrodynamic and dispersion processes with a calibrated model, the presented approach can accomplish this.

The presented method could also be applied to other parameters or discharge targets. For example, control points could be established outside the swimming areas of Cartagena's beaches and microbiological parameters (e.g. *E. coli*, Enterococcus) could be modelled to set targets relevant to the recreational use of beach waters. Similarly, targets for industrial effluents could also be set by this method using discharge and water quality data from a coastal industry. Of course, when multiple pollution sources are present in a single coastal water body, a method of load allocation would need to be applied to set targets for the multiple pollution sources and satisfy the total load target [24,25]. In the present study of TSS loads in Cartagena, however, load allocation was not necessary as it has been established that the Dique Canal is the principal source (99%) of sediments in the bay [6].

4.4. Limits of the approach

As the approach does not incorporate long-term hydrological data, it does not provide knowledge on the relevance of the simulated discharge conditions in comparison to maximum flood plume conditions. The maximum discharge value used in this study (233 m^3/s) is similar to the high range value of 250 m^3/s reported by Tuchkovenko & Lonin [28]; but unfortunately, the present study's discharge data comprise the only monthly dataset in the Dique Canal outlet published to date. The relevance of the simulated rainy season conditions with respect to maximum flood conditions could be better verified with a long-term data set of daily discharge from upstream. As such, the potential for higher flood conditions could result in more threshold exceedance than predicted by this study's simulations of the year 2016, making the target loads and reductions a conservative estimate. However, considering the substantial TSS load reductions of 80–90% needed based on the modelled conditions, it is unlikely that refined information based on maximum flood conditions would be relevant in endorsing the need for improved watershed management.

A potential criticism of this method could also be in its selection of an ecosystem threshold value, rather than establishing the value by conducting an ecological study. While it is true that biological assessments provide better information than physical-chemical indicators [13], it could also be argued that the urgent need to establish water quality standards justifies the use of the information available. The range of identified threshold values for a given parameter in a given ecosystem or water use may be refined in time as further research establishes a better understanding of the parameter's impact on the ecosystem or water use. Though conversely, it is also possible that the range of identified threshold values becomes broader in time, as further research could find a greater variability in ecosystem response to the combined effects of water quality and other stressors. Deliberation over the specific causes of coral reef degradation or the threshold value at which degradation occurs can require a lengthy process to come to a consensus. Such deliberation can deter action, and may be one of the reasons that action was not taken prior to the wide-scale decline of the world's coral reefs [73]. What is important is not to delay water policy until ecosystem thresholds are defined with undisputed certainty, as this day may never come. Improved policy on controlling land-based discharges is urgently needed now, as current policy is inadequate, and the process of improved watershed management can be very long. If ecosystem thresholds become more refined in the future, the policy on land-based discharge limits can be updated accordingly.

5. Conclusions

In demonstrating the presented method to the example of Cartagena Bay, it was shown that TSS concentrations could be maintained below ecosystem thresholds within the extent of the bay by reducing TSS loads in the Dique Canal. To effectively ensure that the coral reef ecosystem threshold of 10 mg/l is not exceeded outside the bay, current load estimates of 6.4×10^3 t/d (rainy season) and 4.3×10^3 t/d (transition season) would need to be reduced to target loads of approximately 500–700 t/d, representing load reductions of approximately 80–90%. This considerable reduction needed in TSS loading reflects ongoing issues in the Magdalena watershed which has experienced severe erosional conditions and intense deforestation over the past four decades. The implementation of Best Management Practices in the Magdalena Watershed is recommended as this could contribute to substantial load reductions at no additional cost (and potential benefit) to farmers.

Policy and management actions to mitigate the impacts of sediment plumes and other types of pollution on coral reef ecosystems are urgently needed as these systems are particularly vulnerable to multiple stressors. The influence of sediment plumes in the Rosario Islands is evident as field observations show that TSS concentrations there were consistently above the threshold value, as were concentrations in the straits of Cartagena Bay. Without improved management, sediment impacts on the coral reef system will likely worsen due to future increases in TSS load caused by ongoing land-cover change and climate change. Current policy on coastal water quality in Colombia is inadequate to mitigate this issue as it does not include marine ambient water quality standards nor end-of-river targets, while discharge limits for coastal wastewater effluents were determined without established marine ecosystem thresholds or consideration of nearshore dispersion processes.

Coastal water quality policy in Colombia and other Caribbean countries could be improved with science-based, ecosystem-relevant methods such as that presented in this study. By optimizing monitoring data with a calibrated model that adequately reproduces TSS field observations, this method can be applied to effectively set targets for coastal land-based discharges without the need of a long-term database. This approach is thus accessible to countries like those of the Caribbean that are still developing their water quality policies. The presented method could also be applied to other parameters or discharge types. Such methods are beneficial to environmental management for the development of site-specific targets, which are needed in consideration of the natural and anthropogenic variability between different coastal zones and water bodies.

Declarations of interest

None.

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