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Tracing nitrogen pollution from wastewater on an oceanic, touristic island: Integrating local knowledge and uncertainty into a mass balance modeling approach

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ABSTRACT

Nutrient pollution from wastewater endangers coastal and marine ecosystems and contributes to health risks in many small islands in the Wider Caribbean Region. Identifying promising intervention points for management requires understanding the flows of wastewater and contained nutrients. However, on such islands data about wastewater flows is typically scarce, and knowledge is distributed among various actors and institutions. Additionally the system's complexity is high, as nutrient fate is determined by an interplay of technical, social, environmental, and ecological factors. Using multiple methods, this paper addresses these complexities, focusing on San Andrés Island, Colombia, which is subject to strong population and tourism pressure. Based on interviews with local actors, we develop a conceptual model to map the total inorganic nitrogen (TIN) fate from touristic and domestic sources to sinks in the environment. With a mass balance model that integrates diverse data sources and elicitation from local experts, we quantify TIN pathways taking into account uncertainty with parameter distributions. Based on the model, we estimate that on an average day in the dry season about 56 % of wastewater-derived TIN ends up in the ocean and 44 % in the island's land sinks. Tourists directly contribute about 13 % of TIN, though their indirect contribution is likely much higher. The main pathway of TIN to the ocean is via a centralized sewer network and to the land sink via distributed soak pits. Without additional treatment or nutrient cycling, the potential management scenarios we investigate merely shift pollution issues between environmental compartments. This research underlines the need for a systems perspective on wastewater management for small islands.

1. Introduction

Land-based wastewater pollution is a socio-ecological concern in many places of the Wider Caribbean Region that suffers from extensive eutrophication of coastal waters (UNEP/CEP, 2021). Pollution is often exacerbated by tourism, a major economic activity on small Caribbean islands.

Tourism intensifies multiple challenges to local wastewater management. It increases population pressure directly by adding the "floating" population of tourists and indirectly by attracting workers who seek employment and business opportunities. Fast growth together with a lack of sufficient wastewater infrastructure eventually leads to intentional and unintentional discharge of partially treated or untreated wastewater into the environment. In turn, this threatens common resources such as groundwater, coastal ecosystems such as coral reefs, and human health (e.g., DeGeorges et al., 2010; Wear and Thurber, 2015; Diez et al., 2019; Velásquez Calderón, 2020).

This is the case for the Colombian Island San Andrés (SAI) where the lack of comprehensive wastewater treatment infrastructure in combination with the rapid increase in tourism and population led to the

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degradation of groundwater and coastal waters around the island over the past decades (Gavio et al., 2010; Velásquez Calderón, 2020). Data from 20 years of biannual nutrient monitoring (REDCAM; INVEMAR, 2020) shows that dissolved inorganic nitrogen and orthophosphate concentrations exceed the threshold levels considered as ambient nutrient water quality standards for nearshore waters (Fig. 1). These thresholds – set to protect coral reefs from an overgrowth of macroalgae (Lapointe, 2004; as cited in DeGeorges et al., 2010) – were surpassed at all 14 monitored stations located around the island.

The most prominent point source of marine wastewater pollution on SAI is a submarine outlet pipe which discharges untreated wastewater from roughly one-third of the households into the coastal waters of SAI's north-western side (CDM Smith, 2016). For the reefs on the western side adverse consequences – such as coral diseases, the proliferation of algae and sponges, and the presence of fecal indicator bacteria *E. coli* in coral mucus – have been linked to wastewater exposure from this outlet pipe and other diffuse sources (Zea et al., 1998; Chaves Fonnegra et al., 2007; González-Gamboa et al., 2019; Navas Camacho et al., 2019; Obando Madera and Martínez Campo, 2019).

Apart from ecological concerns, wastewater pollution poses a threat to public health and economical activities such as fisheries and hospitality. Exposure to pathogenic viruses and bacteria from wastewater can cause acute infections such as gastroenteritis, dermatitis, otitis and respiratory diseases and thus also reduce the recreational quality of coastal destinations (Shuval, 2003; Fleming et al., 2006; Colford et al., 2012). Excess nutrients from wastewater on the other hand, contribute to eutrophication, which is one of the main causes of harmful algae blooms (Lapointe et al., 2015). Such blooms have been recorded in Colombian coastal waters over the past four decades and are increasing in frequency and magnitude worldwide. They contaminate coastal waters and seafood with toxic microalgae metabolites, which are a threat to human health and economic activities such as fisheries (Backer and McGillicuddy, 2006; Bauer et al., 2010; Coronado-Franco et al., 2018).

Wastewater contamination of groundwater is also a main concern around decentralized on-site wastewater systems (DEWATS) that are employed across the entire island and particularly the rural south. Of the approximately 5,900 wells existing on SAI, 69 % are considered highly contaminated by microbial contamination and/or saltwater intrusion close to shore (CORALINA, 2009). Velásquez (2020) highlighted the water crisis on SAI and social impact of underground wastewater pollution on SAI, as it exacerbates water supply problems for the local community, especially marginalized groups. This close connection between wastewater and freshwater is a common challenge on small Caribbean islands (see O'Neill, 2016).

While researchers have emphasized the importance of a comprehensive improvement of the wastewater situation of SAI (e.g., Gavio et al., 2010), this remains a challenge with many facets. In the absence of an integrated and comprehensive wastewater management solution for the entire island, heterogeneous, partly self-managed practices have developed over time across the island's geography. This is one reason why monitoring data on the wastewater system is scarce and the pathways and fate of wastewater pollutants are often poorly understood. Until now, no holistic representation and quantification of nitrogen pollution from domestic and touristic wastewaters of SAI exists. This lack of knowledge creates a fundamental gap that impedes informed decision-making in the wastewater management of SAI and the assessment of the effects of management actions.

In this study, we address this challenge from the angle of synthesizing and integrating knowledge. The starting point is the observation that despite the lack of empirical and monitoring data, local actors have extensive, yet largely unrecorded, knowledge about the specific problems and challenges faced by their wastewater management systems on SAI.

This study focuses on total inorganic nitrogen (TIN) as a key nutrient. Nitrogen occupies a central role within the biogeochemical cycles of coasts (Jiang et al., 2022). Modification of nitrogen cycles in marine environments, for instance, by large inputs from land sources, can lead to changes in structure and function of ecosystems (Galloway et al., 2004). Therefore, the monitoring of nitrogen inputs is one of the key variables for the conservation of ecosystems.

The aim of this research is an exploratory analysis of dominant TIN pollution pathways and potential intervention points. For this, we focus on the dry season, where nutrient pollution by runoff is small. The key questions we focus on are.

- What are the main pathways for TIN pollution from domestic and touristic wastewater on SAI during the dry season?
- What is the relative contribution of tourism and the local population to the island's TIN pollution during the dry season?
- How does the model approach, which combines diverse data inputs, help us understand trade-offs to different hypothetical management measures?

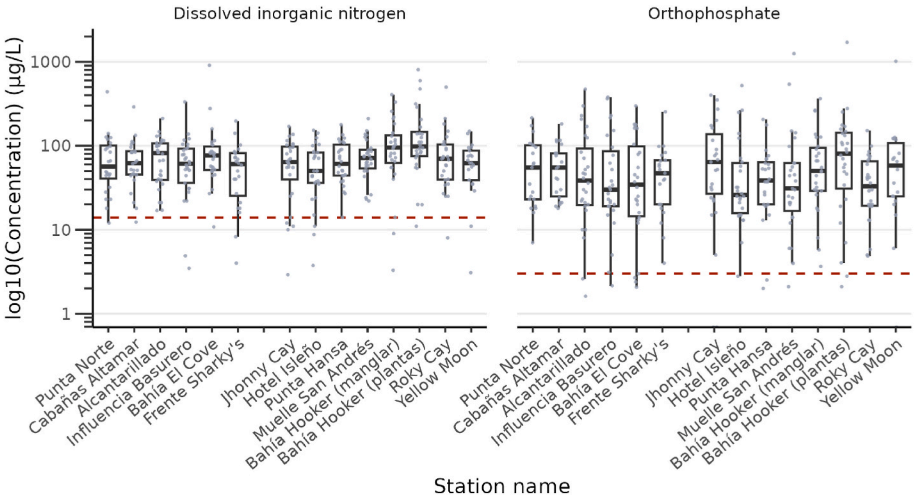

Fig. 1. Concentrations (logarithmic, y-axis) of dissolved inorganic nitrogen (left panel) and orthophosphate (right panel) for 14 sampling stations around SAI from 2005 to 2021 (REDCAM, INVEMAR 2020). The stations are ordered from north to south for the west coast (left half of the stations) and east (right half) coast (x-axis). Boxplots show the 0.25, 0.5, and 0.75 quartiles of the data; whiskers extend to the maximum and minimum points within 1.5 times the interquartile range. Dotted lines indicate water quality thresholds according to Lapointe (2004), as cited in DeGeorges et al. (2010): 14 µg/L dissolved inorganic nitrogen; 3 µg/L dissolved orthophosphate.

To address the questions, we firstly develop a conceptual systems map of nitrogen pathways (sections 3.2 and 4.1). We then construct and quantify a mass balance model incorporating multiple data sources including local knowledge to track the nitrogen flux of TIN from its origin in domestic and touristic wastewater to its final disposal sink on land and in coastal waters (sections 3.3 and 4.2). Further, we use a scenario analysis to understand trade-offs across spatial scales and between different environmental sinks (sections 3.4 and 4.3). The systems approach we present uses a mass balance model to capture local knowledge and uncertainty in data-poor environments which can be transferred to other islands dealing with similar data scarcity.

2. Case study description

The Colombian island San Andrés Island (SAI) is a karstic oceanic island in the western Caribbean Sea situated 200 km east of Nicaragua and 800 km north of mainland Colombia (Fig. 2a). It is located in the transitional zone between tropical dry and tropical humid climates and the uneven rainfall divides the climate into a dry season (January–April), characterized by stronger winds and little rainfall, and a rainy season (October–December), during which 80 % of the annual rainfall occurs (Gavio et al., 2010).

Twelve km long and 1.5–3 km wide, SAI is the largest island and the administrative center of the archipelago of San Andrés, Providencia, and

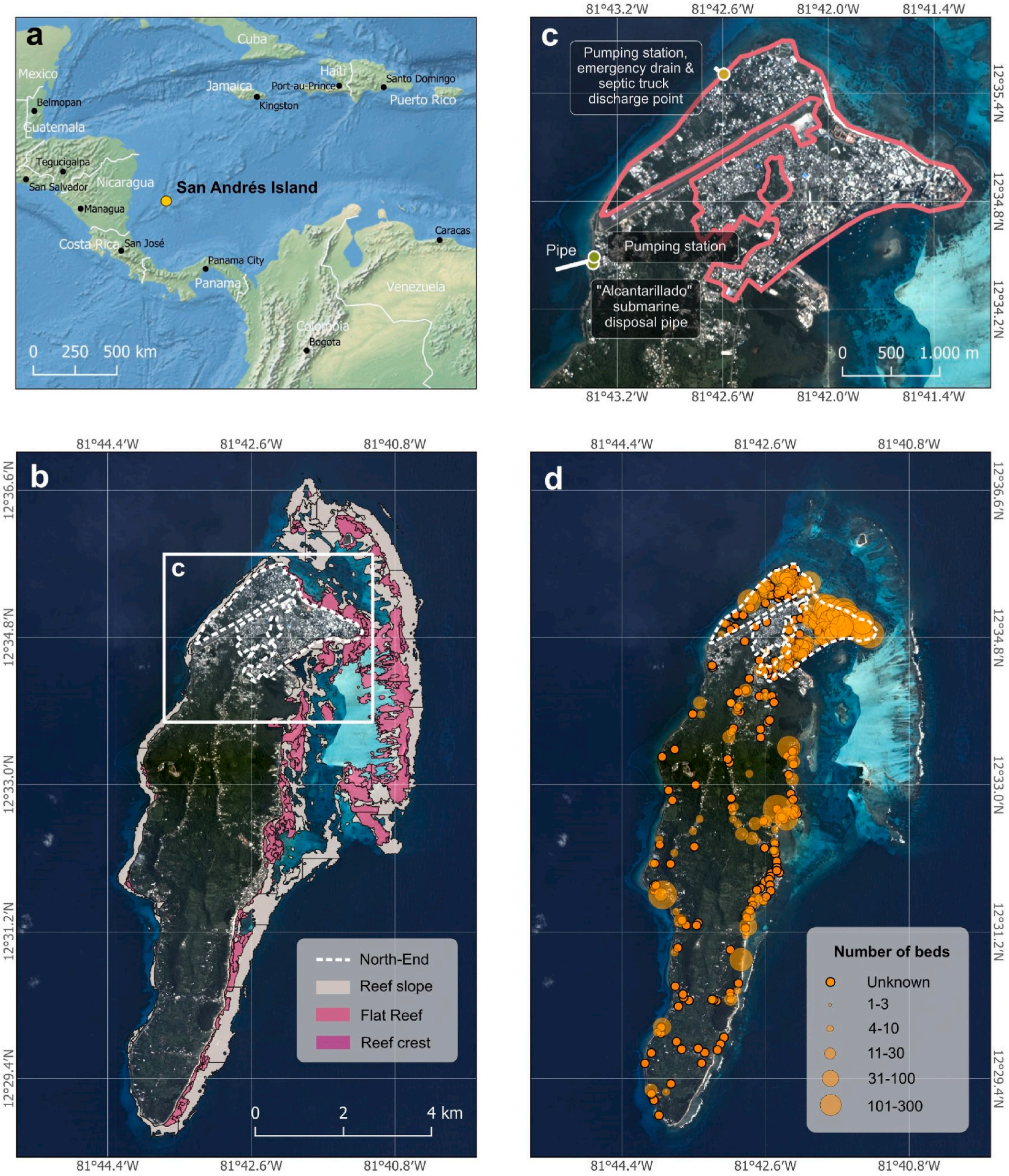

Fig. 2. **a)** An overview map of the study site location in the western Caribbean Sea; **b)** Map of coral reef locations of San Andrés (Allen Coral Atlas, 2020) and the division of SAI into the north (North-End) and south (South-End); **c)** Focus on North-End with wastewater infrastructure such as pumping station and ocean discharge point (Modified according to CDM Smith, 2016; Allen Coral Atlas, 2020). **d)** Location and size defined by the number of beds of accommodation businesses on SAI.

Santa Catalina. It was declared as a Seaflower Biosphere Reserve by UNESCO in 2000 (Taylor et al., 2013). SAI is home to biodiverse marine ecosystems such as mangroves, and seagrass meadows and is surrounded by coral reefs with a total extension of 44.7 km^2 (Fig. 2b). The reefs provide habitat for diverse marine species, substantial coastal protection, and an attraction for dive tourists from around the globe (CORALINA-INVEMAR, 2012; Gavio et al., 2010).

Until the early 1950s, only 3,700 people lived on the islet, the vast majority of them Raizales (*native islanders*), descended from English settlers, African slaves, and migrants from other islands (Taylor et al., 2013). However, the declaration as a free port in 1953 and the opening of the airport in 1955 ended the isolation of the archipelago (Geister, 1975). It experienced a rapid increase in immigration – mainly from mainland Colombia – and concurrent urbanization. Today 61,000 people are registered residents of SAI (DANE, 2018), making it the most densely populated oceanic island in the Americas (Baine et al., 2007). A local expert estimated a higher population of around 120,000 residents (Interview #8), due to unrecorded immigration. Particularly tourism is a driver of immigration (Baine et al., 2007), as it is the primary economic sector on the island, which hosted more than one million tourists in 2019 (Migración Colombia, 2021).

Today, SAI can be divided into a highly urbanized, touristic northern part “North-End” (red polygon in Fig. 2c), and less touristic rural central and southern parts “South-End” (Fig. 2d). Wastewater management strategies on SAI are also determined by this geographical divide. Details on the wastewater system are discussed in section 4.1.

3. Methods

3.1. Data and knowledge sources

To develop the conceptual and mass balance models for understanding TIN pathways, various data and knowledge sources were used. The data was collected through a mix of qualitative and quantitative research, including primary and secondary data. Semi-structured interviews (n = 6), structured expert judgment elicitation (n = 3), as well as community observation and informal conversation, were conducted during a field stay on SAI from March 15, 2022 to April 27, 2022 (see supplementary information SI–B). Sources of knowledge also included scientific and gray literature, such as government reports and statistics, as well as empirical data. An important source of system knowledge was a report by CDM Smith (2016), a synthesis of the island’s sanitation and water management, commissioned by the Financial Authority for Territorial Development (FINDETER). An overview of all collected data relevant to the models is listed in Table 1. Detailed information on data collection and processing can be found in the supplementary material (SI-A).

3.2. Conceptual system model development

The conceptual model was developed in an iterative process, as is also common for building Bayesian networks (Chen and Pollino, 2012). Based on literature review and preliminary analysis of the available reports, an initial draft of the conceptual graphical model was created. This conceptual model represents the nitrogen pollution pathways of land-based sources on SAI using a directed graph, where nodes represent entities or stocks and arcs (edges) represent relationships or flows.

We then solicited interviews with experts that were identified through a preliminary analysis of the stakeholders responsible for providing, constructing, overseeing, and monitoring wastewater, and the resulting environmental impacts (see semi-structured interviews in Table SI-1). The experts provided suggestions to refine the model and highlighted areas that required further exploration or clarification.

With the feedback, the model was revised, incorporating new nodes and arcs or adjusting existing ones to better represent the nitrogen pollution pathways. In some cases, this necessitated additional literature review or analysis of the reports to support the changes. The updated model was then shared again for further review and feedback. This iterative process continued until the experts were satisfied with the accuracy and completeness of the model, and no more significant changes were needed.

3.3. Mass balance model

3.3.1. Model structure development and equations

The mass balance model structure was derived from the conceptual model. It was reduced to focus on nitrogen pollution of domestic and tourism-generated wastewater, specifically TIN (Fig. 2). The endpoint TIN, instead of total nitrogen, was selected mainly because of data availability, for instance, availability of country specific estimations of nitrogen loads in TIN from Tosic et al. (2018). Due to data availability, the various on-site sanitation systems were grouped into either holding tanks or soak pits.

The final mass balance model structure (Fig. 3) included only the key processes related that can be directly addressed by wastewater management. Other sources such as agriculture, livestock and domestic animals were beyond the scope of this model. To better separate wastewater impacts from other nitrogen sources such as run-off, the study focuses on the dry season, thus minimizing the influence of these sources. We provide a detailed description of the model structure in section 4.2.

Relationships among network nodes were described using mathematical equations that ensure mass balance (see SI–C). They were developed based on physical processes, semi-structured interviews, and literature review.

Table 1
Overview of data collection, including collection type, data source, and usage.

Information	Period	Type	Source	Used for
Tourism statistics	2012-2021	quantitative	Migracíon Colombia (2021)	Exploratory analysis and fitting of the mass balance model
Location, type, and capacity of tourism accommodation on San Andrés	2020	quantitative	own data collection, see SI-A	GIS analysis on the distribution of tourism accommodation in North-End and South-End of SAI
Raster data on satellite images and benthic cover of San Andrés	2020	quantitative	Allen Coral Atlas (2020)	Creation of maps
Population numbers	2001-2018	quantitative	DANE (2018)	Exploratory analysis
Measurements of water quality parameters of the coastal waters around SAI	1997-2021	quantitative	INVEMAR (2020)	Exploratory analysis
Interviews for system understanding and model evaluation	2022	qualitative	see supplementary information SI–B	Finding and evaluation of the structure of the mass balance model
Interviews for parameterization of model variables	2022	quantitative	see supplementary information SI–B	Fitting of the mass balance model

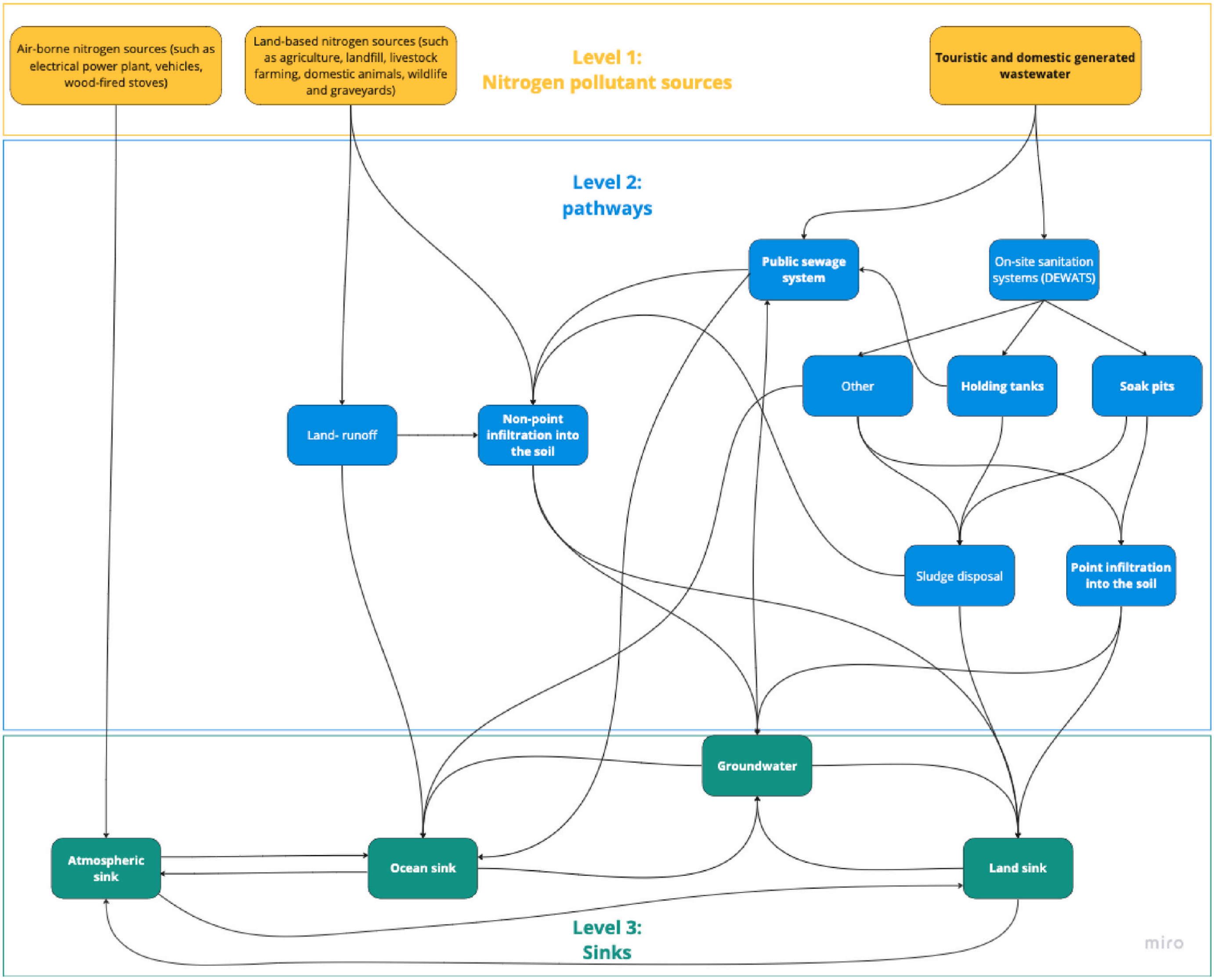

Fig. 3. Qualitative graphical structure of nitrogen pathways from land-based pollution sources on SAI. The yellow box displays the sources for nitrogen pollution, the turquoise box contains its flow through management systems and environmental systems while the green box indicates its final environmental sinks. Bold font highlights the nodes that are represented by the mass balance model developed here (section 4.2).

3.3.2. *Model parameter estimation*

Data for model parameter estimation was collected from diverse sources ranging from expert judgment, literature research, and empirical datasets to spatial analysis (Table 2 and SI-A). Expert judgment was elicited in structured interviews using the Match elicitation tool (Morris et al., 2014). Further information on the individual data sources and the estimation procedures is given in the supplementary information SI-A.

Instead of assigning a unique value, we estimated probability distributions of the states of each (input) node in the system. In this way, the inherent variability and uncertainty in the system as well as uncertainty in the expert estimates can be taken into account. By capturing a range of outcomes and their associated probabilities this provides a more robust and reliable representation of the system and its behavior than deterministic solutions.

3.3.3. *Model runs, uncertainty propagation, and analysis*

Having established the model structure, equations for the relationships, and distributions for the input nodes, we calculated the model results. R was used for all modeling and data analysis. Monte Carlo simulation was used to propagate the uncertainty of the input nodes to the results. For each input node, 100,000 samples were drawn from the specified distributions and the model ran 100,000 times using these samples. This way, we obtained a distribution for each intermediate node in the network as well as for the end nodes.

The mass balance model was further used to create a Sankey diagram to visually represent the TIN flows (e.g., Montangero and Belevi, 2007; Orner and Mihelcic, 2018). For this, we calculated mean TIN flows between all nodes by setting the inputs to their mean value and running the model once.

3.4. *Scenario development and modeling*

To better understand the potential present and future consequences of current wastewater management practices and the possible trade-offs associated with system modifications, the mass balance model was adapted to investigate seven scenarios (Table 3). The scenarios were developed drawing on personal communication of local knowledge, expert opinions and semi-structured interviews, existing studies (e.g., CDM Smith, 2016; Hämäläinen et al., 2021; Reuter et al., 2022), and relevant governmental regulations (Decreto 2667, 2012; Resolución 631, 2015; Resolución 0699, 2021; Resolución 0883, 2018). The scenarios are not concrete management alternatives or strategies that can

Table 2
Overview of input nodes, including the description of the node, the abbreviation of the node that was used in the R code, the elicitation method, the time or validity of the source, and the respective probability distribution. $\mathscr{N}_T(\mu, \sigma, min, max)$: Truncated normal distribution; $\mathrm{B}(\alpha, \beta)$: Beta distribution.

Node	Short	Source	Time validity	Distribution
Total number of population	PT	Expert elicitation	2022	$PT \sim \mathscr{N}_T(129000, 1.2 \times 10^8, 5 \times 10^4, 1.5 \times 10^5)$
Proportion of total inhabitants staying in the northern part of the island	DP	Empirical dataset, DANE, 2018	2001–2017	Sample from the empirical distribution with replacement
Total number of tourists	TT	Empirical dataset, Migracíon Colombia (2021)	2016–2021	Sample from the empirical distribution with replacement
Proportion of total tourist staying in the northern part of the island	DT	Spatial analysis in QGIS, see Fig. 1d	2020	$DwwP \sim \mathscr{N}_T(0.73, 0.05, 0.1)$
Proportion of tourists staying in an accommodation with public sewage connection in North-End	DwwT	Expert elicitation	2022	$DwwT \sim 0.2 \cdot \mathrm{B}(6.74, 1.88) + 0.8$
Proportion of inhabitants living in a household with public sewage connection in North-End	DwwP	Expert elicitation	2022	$DwwP \sim \mathscr{N}_T(0.53, 0.363, 0.4, 0.7)$
Proportion of soak pits on SAI in relation to all on-site-sanitation systems (either holding tank or soak pits)	DST	Expert elicitation	2022	$DST \sim 0.5 \cdot \mathrm{B}(10.4, 6.12) + 0.5$
Proportion of total inorganic nitrogen that passes through soil/groundwater and ends up in the ocean	DIN	Expert elicitation	2022	$DIN \sim 0.4 \cdot \mathrm{B}(3.1, 1.75) + 0.6$
Pollutant load of total inorganic nitrogen per person and day	PLN	Literature value, Tosic et al. (2018)	2017	$PLN \sim \mathscr{N}_T(0.012, 4 \times 10^{-6}, 0, 1)$
Removal of nitrogen through settling sludge in holding tanks (septic tanks)	TFN1	Estimated based on literature values from Montangero and Belevi (2007)	2007	$TFN1 \sim \mathrm{B}(9.66, 97.14)$
Settling of nitrogen through sludge in soak pits (pit latrines)	TFN2	Estimated based on literature values from Montangero and Belevi (2007)	2007	$TFN2 \sim \mathrm{B}(7.81, 37.83)$

be directly implemented. Instead, they aim to represent directions for exploring future developments on SAI. Given the socio-economic circumstances of the island, not all scenarios will be feasible nor desirable.

To evaluate the scenarios and their trade-offs, we again focused on the TIN load entering the land and ocean sinks as indicator, because it is a useful proxy indicator with its impacts on water quality and environmental consequences widely recognized (e.g., DeGeorges et al., 2010; Tosic et al., 2018). However, wastewater management will need to take into account multiple impacts and objectives across sustainability dimensions and stakeholder perspectives (Haag et al., 2019).

To model the scenarios, we modified the mass balance model by altering inputs and parameter distributions and incorporating new nodes and equations representing corresponding proposed treatment processes (Table 3 and supplementary information SI-D). To obtain the results of the scenario analysis, we followed the same procedure as in the baseline mass balance model analysis (section 3.3.3). This involved drawing samples from the (modified) distributions and propagating the values forward.

4. Results

4.1. A conceptual model of nitrogen flow pathways on SAI

Nitrogen sources can be grouped in air-borne, land-based, and wastewater sources (Fig. 3, yellow box). The main source of air-borne nitrogen is fossil fuel combustion from the island's electrical power generation plant and other combustion engines (motorcycles, cars, and buses), as well as wood-fired stoves that are used in some households (personal communication, anonymous source). They are emitted into the atmosphere and may precipitate back on the land or the ocean. On SAI land-based nitrogen sources are mainly agriculture, a landfill, livestock farming, domestic animals, wildlife, and graveyards. However, agricultural production tends to be subsistence, with little tendency for expansion, given the low interest of local commerce in these products and their low profitability. Likewise, livestock farming is very limited and confined to the south and San Luis area (CDM Smith, 2016). Land-based nitrogen is emitted through the leaching of nutrients into the soil or direct surface runoff. Lastly, nitrogen originates from domestic and touristic wastewater released either intentionally or unintentionally into the environment and ocean.

The dominant wastewater management strategy in the urban North-End is a centrally managed public sewage system with 46 % connectivity, including all registered hotels (Interview #1; Fig. 3, blue box). Here, wastewater is collected in an underground pipe system with pumping stations, channeling the wastewater to a submarine disposal pipe at a station called "Alcantarillado" (Spanish for *sewerage/sewage system*; Fig. 2c) in the north-east of SAI. Through this pipe, wastewater is discharged (180–200 L/s Interview #1) without treatment ca. 400 m out and 20 m below the surface into the open ocean. This pipe is the main point-source of ocean pollution (CDM Smith, 2016).

Due to the generally high groundwater table on SAI, the sewer system is located close to the phreatic surface. Especially during the rainy season, some sections are therefore prone to groundwater infiltration into the pipe system (Interview #1). During the dry season, wastewater leaking from the pipes can reach the groundwater and ultimately reach the sea through submarine groundwater discharge.

In total, San Andrés has a sanitary sewer system coverage of about 26 %. The remaining 74 % of properties in SAI, including the entire South End, rely on individual decentralized on-site wastewater systems (DEWATS; CDM Smith, 2016). The design and sophistication of these DEWATS vary greatly. A hand-full of hotels and public facilities use on-site treatment plants with activated sludge or advanced anaerobic digestion, with or without absorption fields. On the other hand, although illegal, direct discharge of wastewater into the ocean through pipes or connections to the pluvial system still persists in very few places. Together with open-terrain-disposal (e.g., in backyards and vacant lots), particularly in vulnerable and low-income neighborhoods (CDM Smith, 2016, Interview #1), these practices are summarized as "other" in Fig. 3. The most common DEWATS may be described as either soak pits or cesspools (also called *pozas sépticas*) or single-chamber holding tanks (*tanques sépticos*), although the actual implementation varies widely.

Following the definition by Reuter et al. (2022), this study considers a holding tank a watertight storage with a lid on top from which it must be emptied regularly. The holding tanks on SAI are large, fully sealed chambers made of concrete or fiber which must be evacuated by septic tank trucks (*carrotanque sépticos*) (Decreto 0324, 2016; interview #6). In intervals of weeks to years, these trucks, which are run by commercial businesses, pump out the liquid phase of the holding tanks and introduce it to the public sewage pipe system at pumping station number three in the north-west of SAI (see Fig. 2c–section 2). Thus, nutrients in the liquid phase of these tanks are centrally discharged into the ocean through the

Table 3
Overview of the developed scenarios including a description and the adaptation steps in the model. For some larger changes to the system, more information on the systems and assumptions are provided in the supplementary information SI-D.

Scenario	Scenario description	Model adaptations and assumptions
1. Population and tourism growth	Tourism numbers and, as a consequence, the local population continue to increase at a similar pace in the past until the year 2050. The current state of wastewater management practices is not adapted.	The new input for tourism numbers was determined by fitting a linear regression model to historic tourist data and predicting tourism numbers and their uncertainty for 2050. The new input for population numbers was determined by calculating the ratio of tourists per local for historical data and multiplying this ratio with the predictions for tourist numbers.
2. Increase sewer connectivity in North-End	Increase of public sewage system coverage in North-End: Reaching 100 % connectivity of households and hotels to the public sewer system.	We set the proportion of public sewage coverage for the population in the north (DwwP) to 1. We set the proportion of sewage coverage for tourists in the north (DwwT) to 1.
3. Centralized WW treatment for North-End	Set-up of an advanced wastewater treatment plant (WWTP) at the end of the sewage system, before the marine outlet. Introduction of primary, secondary, tertiary wastewater treatment with denitrification.	Additional treatment step for wastewater in the pipe system. Assuming that we can design and operate WWTP with 80 % +-10 % nitrogen removal efficiency (via denitrification). Assumption that there are no overflows in the system and all water in the sewer system is treated.
4. Convert all soak pits to holding tanks	Island-wide transformation of all soak pits and other structures that infiltrate wastewater into the ground into sealed holding tanks.	Set the proportion of septic pits (DST) to 0, so this wastewater goes to holding tanks. In our model, the liquid portion of wastewater in a holding tank is pumped and discharged into the sewer network. The sludge portion is disposed of in a landfill.
5. Convert all holding tanks to soak pits	The opposite of scenario 4. Replacing all sealed holding tanks with soak pits that infiltrate wastewater locally. The piped network is not affected.	Set the proportion of holding tanks to 0 (DST = 1). The liquid portion of wastewater is infiltrated locally, sludge remains in the pits and tanks.
6. Upgrade decentralized treatment	Convert all septic tanks and pits on the island to more advanced decentralized treatment, such as anaerobic baffled reactors.	Set the proportion of soak pits (DST) to 0, so this wastewater goes to holding tanks. These tanks are converted to decentralized treatment reactors. Assumption that reactors can be designed to achieve 20 % +-5 % nitrogen removal (via denitrification) and 10 % higher retention of nitrogen in sludge. Effluent is infiltrated locally. Sludge is disposed of at landfill.
7. Biogas plant and hydrochar production	Introduction of biogas production by processing of septic sludge from the WWTP and from holding tanks. The digested sludge is then converted to hydrochar.	Additional treatment step for wastewater in the pipe system with partial nitrogen removal (similar to scenario 3). Sludge from the WWTP and the holding tanks is moved to a biogas plant. A fraction of the nitrogen becomes part of the biogas. Sludge after digestion is used for hydrochar production, where another fraction of the nitrogen will be bound. Remaining nitrogen is disposed of via the marine outlet.

submarine disposal pipe. Septic tanks with an outlet and local infiltration are less common on SAI.

The settled sewage sludge is not pumped out by the septic trucks as it would exceed their pumping capacity and is suspected to cause blockages in the disposal site's pipe system. It is collected by a second service which dries and deposits the sludge on in-land landfills (Interview #4). Therefore, in the mass balance model (next section) the inorganic nutrients contained in the sludge are attributed to the lank sink. Exceptions to this system exist, particularly in areas inaccessible to sewage trucks due to unplanned urbanization, as well as in economically disadvantaged areas. There, homeowners empty the tanks independently and deposit the sludge and liquid elsewhere, for instance, on vacant lots or in private landfills (CDM Smith, 2016).

Soak pits, as the second common DEWATS, we define as lined chambers with permeable floors that allow infiltration into the surrounding soil. Soak pits on SAI commonly consist of a concrete chamber with an open bottom and a concrete lid and ventilating snorkel (Interview #6). Some of these pits, however, are not covered and may rather be classified as pit latrines.

The soak pits infiltrate wastewater into the soil and are only pumped out to resolve clogging (Interview #6). Depending on the location of the soak pit, the infiltrated nutrients may remain in the land sink, i.e., be stored and transformed in the soil, or are further transported to the groundwater and finally may end in the ocean sink via ocean groundwater exchange (Fig. 3). The latter process is more likely with decreasing distance to the ocean, decreasing distance from the soak pit to the groundwater table, increasing permeability of the underlying soil, and increasing slope and density of septic systems (Knee et al., 2010; Mallin, 2013; Norat-Ramírez et al., 2019; Reay, 2004).

4.2. *Mass balance modeling of nitrogen flows*

The purpose of the mass balance modeling was threefold: i) to quantitatively represent the wastewater-derived TIN flow on SAI from source to sink; ii) to estimate daily amounts of domestic and touristic wastewater-generated TIN discharge to land and ocean sinks, and iii) to generate a system understanding of existing and potential management practices and their influence on the land and ocean TIN pollution.

For a targeted analysis of the TIN pollution, we reduced the qualitative systems structure to elements that can be addressed by wastewater management (Fig. 4). In the model, the wastewater-derived nutrients stem from either residents or tourists (first level, yellow box, in Fig. 4). To provide a spatial representation of the main differences in wastewater management strategies across the island, we partitioned the island into north and south. The wastewater streams from tourism and population in the two sectors are divided based on data on tourism numbers and hotel numbers.

The variety of on-site treatment and storage options are simplified by reducing them to holding tanks and soak pits, neglecting illegal deposition and simplifying the more advanced solutions. Using treatment factors, or transfer coefficients, we indicate the amount of TIN settled in

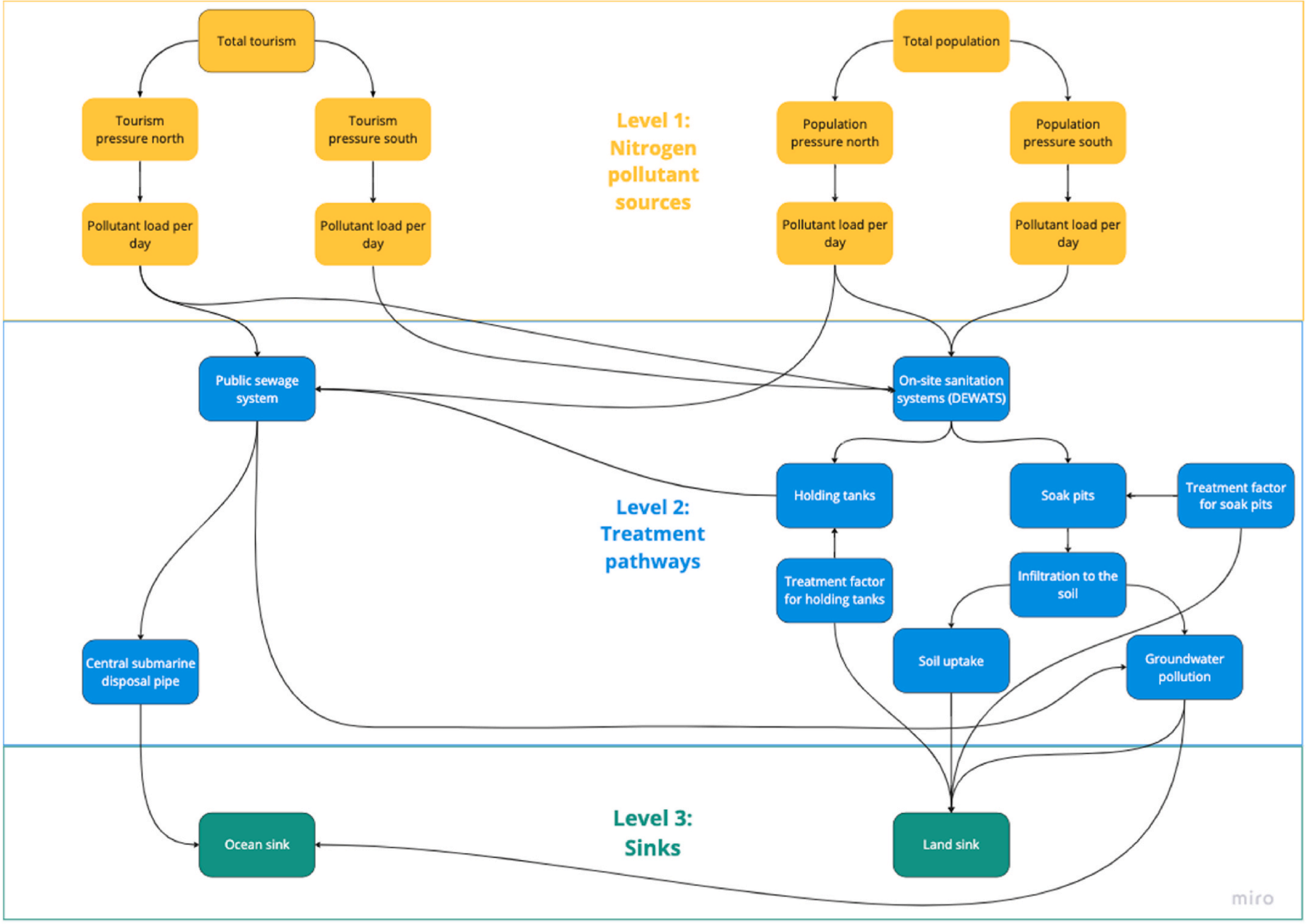

Fig. 4. Conceptual structure of the mass balance model of the TIN flows originating in touristic and domestic wastewater. The yellow box displays the TIN pollution sources from either domestic or touristic wastewater, the turquoise box contains its flow through the different wastewater treatment systems while the green box indicates its final environmental sinks. The mass balance model structure was developed using miro online whiteboard.

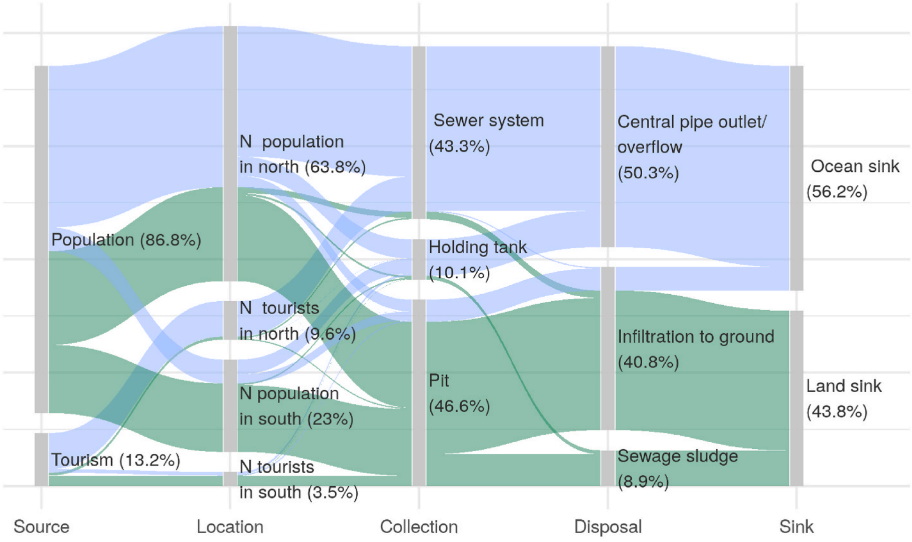

Fig. 5. Sankey diagram visualizing the average flows of total inorganic nitrogen from sources, population, and tourism, to sinks in the ocean (blue) and the land (green). The percentages refer to the stocks relative to the total input, i.e., the percentage of TIN that enters a system compartment, such as the sewer system, not the individual flows between compartments.

sludge, neglecting denitrification and atmospheric release of nitrogen from the sanitation systems (see Montangero and Belevi, 2007). Further, for holding tanks it was assumed that all sludge is disposed fully in landfills not leaching into the groundwater system. For soak pits with permeable walls and floors, it was assumed TIN infiltrates into the surrounding ground where it is partially absorbed by the soil or groundwater. Due to the narrow geographical width of San Andrés – and thus short distances to ocean – its predominantly nearshore urbanization, and highly permeable karstic geology, the distance of soak pits from the shore was not taken into account. Instead, it was assumed that the same transfer coefficient of TIN to soil, transfer into the groundwater, and from there into the ocean sink respectively.

The model's final level (green box in Fig. 4) are the daily TIN amounts ending in ocean or land sink. The ocean and land sinks here are not concrete geographical places, but abstract compartments that receive TIN pollution from different sources (Fig. 4).

The Sankey diagram (Fig. 5) visualizes the averaged flow of TIN from source to sink. In total, about 56 % of the generated TIN of the island discharges into the ocean while about 44 % are estimated to end in the island's land sinks. One question of this research was to understand the relative contribution of tourism and the local population to the TIN flux into the environmental sinks of SAI. Based on this model, almost 87 % of the wastewater-derived TIN on SAI is generated by the local population, while the remaining 13 % of TIN comes from tourism.

With the main tourism hospitality located in the North-End, most of the tourism-generated TIN discharges in the ocean sink via the central submarine pipe. Looking at the population, about half of the daily population-generated nutrients enter the ocean sink via the pipe.

The liquid portions from holding tanks across the island are collected by septic tank trucks and discharged into the sea via the central outlet pipe on the western site of the island. This shifts nutrients across the island's geography. However, holding tanks only contribute to about 10 % of the TIN released to the island's environment.

The main pathway to the land sink is the discharge of wastewater into soak pits. They transfer 41 % of the total produced TIN on SAI to the land sink either via infiltration of the liquid or deposition as sludge on the landfill. Through submarine groundwater exchange, they also contribute 10 % of the TIN entering the ocean-sink.

The Sankey diagram provides an averaged view of the situation, yet, large uncertainties exist around the model inputs and parameters. We propagated these uncertainties through the model and derived uncertainty distributions of the daily TIN load entering the ocean and land sinks (Fig. 6). The ocean is the dominant sink for TIN on SAI. In half of our simulations, 850–1120 kg of TIN entered the ocean sink and 660–890 kg entered the land sink on a daily basis in the dry season. This would add up to an annual load of 310–408 tons and 240–325 tons of TIN respectively.

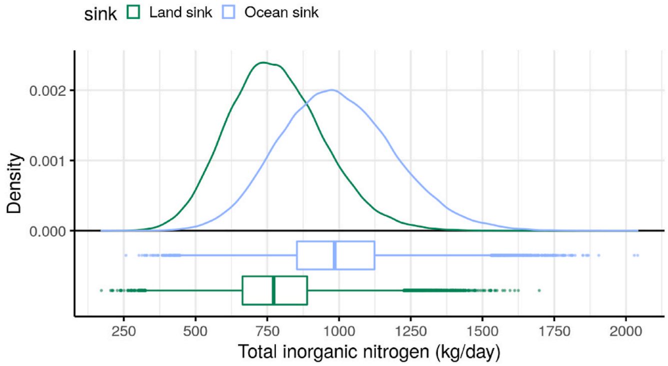

Fig. 6. Distributions of daily dry-season total inorganic nitrogen loads (x-axis) entering different sinks (colors) as estimated by the mass balance model. The upper curves show the densities of the probability distributions and the lower boxplots show the 0.25, 0.5, and 0.75 quartiles of these distributions. Whiskers extend to the maximum and minimum points within 1.5 times the interquartile range.

4.3. *Scenario analysis*

Seven scenarios (Table 3) and their effects on the amount of TIN entering the ocean sink or the land sink of the island were investigated (Fig. 7). If business as usual would be continued with increased population and tourism numbers for 2050 (scenario 1), this would lead to a nearly two-fold increase in TIN loads ending up in the ocean and land sink compared to the current baseline (Fig. 7).

In three scenarios, it was tested how shifting the proportion of inhabitants' connectivity to the different, currently employed, sanitation systems would play out. Connecting all inhabitants and tourists to the sewer system in the north sector (scenario 2) would decrease the TIN load in the land sink nearly by half, but would, in turn, add this TIN to the ocean sink. Sealing all forms of soak pits to prevent local infiltration into the soil (scenario 4) would eliminate most pressure on the land sink, including groundwater, but would shift all nutrients to the ocean sink through pumping of holding tanks and release at Alcantarillado. Increasing local infiltration of currently sealed tanks (scenario 5), results in only a moderate decrease in ocean pollution and an equivalent increase in land-sink pollution. As there is no additional treatment or nutrient cycling, in these three scenarios, we only see a shift in the pollution burden between different sinks, in the spatial distribution of pollution, and diffuse vs. point-source pollution.

Subsequently, the effects of introducing further treatment to the wastewater management of SAI were investigated. Improving nitrogen removal in decentralized treatment by using improved septic tanks or reactors instead of simple unsealed soak pits (scenario 6), would decrease nitrogen going to the ocean sink. A state-of-the-art wastewater treatment plant (WWTP) with tertiary treatment and denitrification before the pipe outlet in the ocean (scenario 3), could lower the TINentering the ocean sink drastically. However, without additional measures such as septic tank conversion or an increase of connectivity, it would not change any nutrient emission to the land-sink or emission through groundwater discharge.

Last, we explored the effects of a WWTP with secondary treatment, but advanced sludge treatment that includes producing biogas and hydrochar (scenario 7). This would slightly lower land-sink pollution, as septic sludge can be utilized, and considerably lower ocean pollution, though less than a WWTP with tertiary treatment. Thus, additional treatment would be effective in lowering TIN loads entering the sinks, but also would require considerable investments and changes in infrastructure, operations, and management.

5. Discussion

5.1. *Evaluation of the mass balance modeling approach to integrate knowledge and data*

Extensive local expertise about wastewater management and nutrient pollution exists on the island of SAI. However, this is only partially reflected in quantitative datasets and monitoring statistics used for operational planning, which do not easily translate to system understanding and decision-making. In a system mapping approach (Barbrook-Johnson and Penn, 2022), this study captured different sources of knowledge in a conceptual model of wastewater management elements, thus engaging stakeholders in the modeling process (cf. Chen and Pollino, 2012). While the type of "box-and-arrow" mass balance model used disregards detail, it is a powerful tool to combine different types of data. Expert judgment is a common approach for environments where data is scarce, but where local knowledge is available (Montangero and Belevi, 2007). Collecting and structuring expert knowledge in a model is a difficult task (e.g., Uusitalo, 2007). This modeling approach structured this process by breaking it down into steps: first the development of the

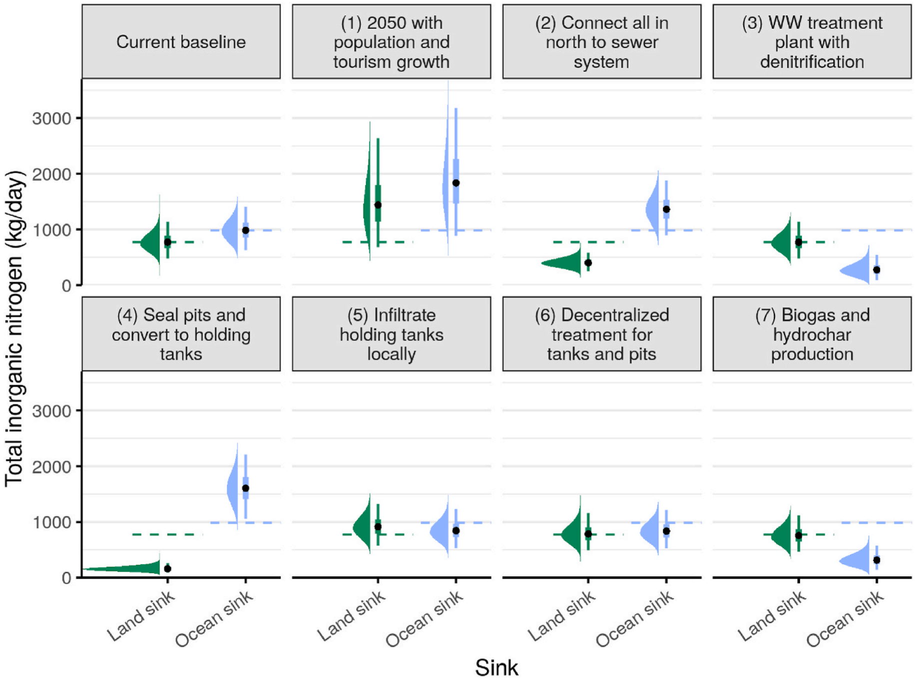

Fig. 7. Scenario analysis. Predicted total daily TIN load (y-axis) ending up in the land or ocean sink (x-axis and colors) under different changes in the system (scenarios; panels). The scenarios are described in Table 3. The densities show the estimated distribution of TIN, and the boxplots to the right of the densities indicate the median (dot), 50 % (box), and 95 % interval (whiskers) of this data. The dotted lines indicate the median of the baseline scenario.

model structure, then the definition of quantitative relationships.

The elicitation of parameter distributions from experts used established protocols (Morris et al., 2014, SI-A). In our experience, the task was understandable and feasible for the experts. The elicited probability distributions are supposed to represent the inherent uncertainties due to variations in time and space and the uncertainty of the experts themselves due to their limited knowledge. Still, as highlighted by Ban et al. (2015), expert knowledge may be highly variable and thus can introduce additional uncertainties. The elicited distributions, therefore, may be subject to various cognitive or also motivational biases (O'Hagan et al., 2006).

A weakness of this study however, is the simplification of spatiality and temporality. Temporally, the system was regarded as static, assuming a continuous emission of TIN into the environmental sinks. However, in reality, the time of pollution generation and transport to the sink is variable and it can arrive in pulses. For the TIN flowing through the central pipe, this time shift is likely small. However, for the holding tanks, the time of nutrient emission and the time of nutrients entering the marine ecosystem after pumping the tank may vary considerably. While they receive less wastewater in the low tourism season, the tanks fill up quickly in the high season and need more pumping and deposition.

To separate wastewater impacts from other TIN sources such as terrestrial run-off, we focused on the dry season. However, the introduction of nutrients from wastewater is likely higher in the wet season as holding tanks, soak pits, and the public sewage system may overflow due to the high volume of rainwater infiltrating the systems (Arnade, 1999; interview #3). Therefore, the results presented here can be considered as a lower bound estimate of land-based and groundwater flows of TIN to the ocean sink.

Spatially, all nitrogen flows were summarized into an abstract "ocean sink" and a "land sink". However, the spatial distribution of pollution is important as discharge concentration as well as ecosystem vulnerability matter for the ultimate impacts. While nitrogen discharged into the ocean sink via the submarine pipe arrives at the west coast through a point source, discharge through groundwater is spread across the island's coastline, but mainly enters the ocean at the coast of the urbanized north and San Luis in the east.

The lack of spatial differentiation also affects the variability of processes we represent. This concerns for example the soil uptake of nitrogen during infiltration into the ground. The uptake is highly determined by the type of soil, and other environmental factors (Barton et al., 2005; Lee et al., 2009; interview #5). This suggests that a higher level of spatial differentiation is required to draw conclusions for specific places of the island.

5.2. Nitrogen pathways and wastewater sources

A question of this study was to understand the relative contributions of tourists and the local population to TIN pollution. The model results indicate that tourists only contribute 13% of the TIN directly. However, this does not equal the contribution of *tourism*, as tourism development on the island has driven population growth (Baine et al., 2007) and therefore caused an increased overall emission of nutrients. This causal relationship is not represented in our temporally static model.

In addition, we assumed that the pollutant load per person is the same for tourists and residents. The pollutant load per person depends on various regional, socio-economic factors (e.g., Rout et al., 2021). It is possible that tourists, who may have a higher financial background and standard of living, may have different pollutant loads per person compared to the local population of SAI.

Looking at the endpoints of the model, most of the tourism-generated TIN discharges in the ocean sink via the central submarine pipe. On the population side, more than half of the resident's pollution is also ending up in the ocean sink; however, compared to tourists, a considerably higher amount is ending in land sinks. This could lead to the false conclusion that tourism does not contribute to soil and groundwater pollution, which is incorrect because leaks from the public sewage network infiltrate the groundwater. Moreover, an unknown number of tourists are staying in private homes (*posadas nativas*) or may use toilets outside the sewered sector during their stay.

Contrary to the assumption of the public sewage system being the major system on the island, the soak pits, which are officially already prohibited by law, are the main sanitation system on the island in terms of TIN pollution. These infiltration based on-site sanitation systems contribute to groundwater contamination due to aforementioned factors such as i. a. Low lying terrain and high groundwater tables.

With our model, we estimated that in 50 % of our simulations between 850 and 1120 kg of TIN enters the ocean sink and 660–890 kg enters the land sink on a daily basis during the dry season. While we had no direct empirical data to evaluate these results, data from INVEMAR in 2002 (cited by Gavio et al., 2010) show estimates of 700 kg of nutrients (nitrogen and phosphorus) per day are discharged to coastal waters around SAI. While this might suggest that our model overestimates the daily amounts of nitrogen entering the ocean, it is more likely that it underestimates TIN pollution, given the higher number of residents and tourists nowadays. Especially since there are a considerable number of other sources contributing to nutrient pollution (see section 4.1).

5.3. Wastewater management trade-offs and scenarios

The wastewater and sanitation system of an island can be a key aspect for nutrient management (Firmansyah et al., 2017). In the following, we discuss four aspects around wastewater management on SAI that emerged from the scenario analysis and the interviews with local experts: (1) pollution shifting, (2) freshwater quality and quantity, (3) additional treatment, (4) issues of implementation and operations.

Scenarios that use the existing infrastructure elements, but adapted their capacities and coverage (scenarios 1, 2, 4, 5) showed that these are insufficient approaches for TINmanagement on SAI. In these scenarios, overall TINpollution was not reduced, but only shifted across island geographic scales or between environmental sinks. All of them fail at the aim of nutrient pollution reduction, which is an explicit aim of the Regional Nutrient Pollution Reduction Strategy and Action Plan (RNPRSAP) for the entire WCR (UNEP/CEP, 2021).

Increasing connections of households and hotels to the sewer system (scenario 2), would be a straightforward approach that does not require shifts in the wastewater regime or organizational structures. The report by CDM Smith (2016) also suggested that the low coverage of the public sewage network in the rural areas of the island is the main reason for wastewater pollution. However, this approach would increase point pollution as more TIN is disposed of via the submarine ocean pipe. Increasing the connectivity without additional treatment and updates would therefore not be sufficient, but even increase the pressure on the fringing coral reefs exposed to effluents of the submarine pipe. These coral reefs shape the island substantially (Geister, 1975; Zea et al., 1998) and provide important ecosystem services to the people and communities (Woodhead et al., 2019), making reef degradation a serious concern.

Changes to the DEWATS can have similar effects of pollution shifting. One scenario modeled (scenario 4) is to seal all soak pits and convert them to holding tanks, similar to the cesspit conversion strategy implemented in the US state of Hawai'i in 2015, where soak pits were converted to sewer connected systems, septic tanks, or aerobic treatment units (Barnes et al., 2019; Mezzacapo et al., 2020). If the wastewater in tanks is disposed of via the central sewage system, this would concentrate the island's TIN emission further at the submarine outlet point source.

In contrast, scenario 5, the conversion of holding tanks to soak pits with local infiltration, reduces the ocean pollution and pressure on the coral reefs near the submarine outlet pipe. However, the disadvantages include an equivalent increase of the nutrients and pathogens in the island's soil and groundwater system. As the soak pits are not always set up properly, this has strong impacts on groundwater which is the main drinking water supply for the island. Therefore, this scenario is only sensible in combination with improved decentralized treatment. Additionally, the removal of holding tanks in the South-East would be to the detriment of the San Luis reef in southern SAI. To the disadvantage of the fringing reefs of western SAI, the San Luis reef benefits from nitrogen being removed from San Luis by the transport of holding tank content and its discharge elsewhere.

Looking at groundwater and drinking water quality, our model shows that converting the open soak pits (scenario 4) would lead to a decrease in groundwater contamination and likely also has positive effects on groundwater quality in regards to parameters relevant to human health, such as bacterial contamination. In contrast, scenario 5 would further diminish the water quality of the groundwater. As the current sewage system is in exchange with the groundwater due to breakages and overflows (CDM Smith, 2016), higher connectivity (scenario 2) is not a direct solution to groundwater contamination. It must be complemented with the improvement of the public sewer system to prevent infiltration.

Infiltration of wastewater does have the positive effect that it increases the recharge of freshwater to the soil and closes the cycle of groundwater use. An unintended consequence of removing infiltration and discharging wastewater via the central sewer system is the removal of freshwater from the island. This would increase the strain on already scarce freshwater resources (Velásquez Calderón, 2020). It puts further pressure on the island's groundwater lens, which suffers from saltwater intrusion (CORALINA, 2009), and also deprives land ecosystems that depend on groundwater.

To protect ecosystems from the current poor water quality on SAI coastal waters (Fig. 1), reducing nutrient emissions through updates to decentralized systems or central solutions is unavoidable. Therefore, three additional scenarios were explored to test the effects of the implementation of secondary and tertiary treatment, thus removal of TIN, in centralized or decentralized approaches.

A centralized wastewater treatment plant could effectively decrease nutrient concentrations in the wastewater stream before ocean discharge and thus lead to a considerable decrease in marine pollution, also by TIN (scenario 3). On the other hand, a wide variety of decentralized sanitation options exist, also adapted to the Caribbean context (Reuter et al., 2022). To address the nutrient management challenges, proper decentral collection of the wastewater and additional treatment would be necessary. Nitrogen removal in on-site sanitation systems is often not easy to achieve. In scenario 6 we estimated that decentralized treatment is unlikely to have a large contribution to overall nitrogen removal, as large pollutant loads are handled in the centralized system. However, it can make a large difference locally. Practically, centralized and decentralized treatment would both need to be tackled for SAI, as a full transition to either regime is not likely.

The wastewater and nutrient challenges of San Andrés are connected to challenges with energy production and freshwater availability. If we take a more holistic view, which is a strength of systems models, we can think of scenarios that address several challenges at once from the perspective of wastewater management (Hoffmann et al., 2020; Ormerod, 2016) and nutrient cycling (Lin et al., 2014).

One example is the introduction of a biogas plant with hydrochar production as part of a centralized wastewater treatment plant (scenario 7) (Hämäläinen et al., 2021). This would bring additional biogas production and energy recovery from fecal sludge and possibly other organic sources, such as marine macroalgae ("Sargassum"). As it would be connected to a wastewater treatment plant, a reduction of marine point pollution can be expected. Concerning the freshwater scarcity, further alternatives with freshwater regeneration or the reuse of treated wastewater should be considered (Ormerod, 2016).

Wastewater and nutrient management on SAI is not a monolithic regime with one centrally organized system. Instead, it exhibits properties of a splintered regime (van Welie et al., 2018) with several technical systems as well as organizational and institutional structures existing in parallel and with different degrees of functionality. Some of the sanitation systems are aligned, such as service trucks pumping wastewater from holding tanks to the centralized system. However, other systems are not even functioning sustainably internally, such as unmanaged soak pits that leach contaminants into groundwater. This poses great challenges for the operation of the current system and for the transition towards other configurations outlined above.

Challenges of decentralized solutions on SAI include the acceptance and proper use of the solutions provided by the population (CDM Smith 2016). Operations and maintenance can be further major hurdles for decentralized solutions (Hoffmann et al., 2020). Since regulation prohibiting soak pits is already in place on SAI, it remains to be seen how a transition from these systems to improved on-site systems can be implemented and enforced across the board.

Increasing centralization of wastewater management – with or without further treatment – also faces challenges. They range from technical problems as the already exceeded hydraulic capacity of the current system, economic barriers of extending the network, to social challenges such as rejection to connect to the sewer system (Ministerio de Vivienda, Ciudad, y Territorio, 2019). A problem more specific to SAI is the susceptibility of sewer networks to storm damage (Chisolm and Matthews, 2012). Improper use of the sewage system by users for the disposal of other forms of waste, such as fats and oils, is also decreasing the system's function (CDM Smith, 2016). In addition, the cost of connecting large parts of SAI to a centralized sewage system and maintaining that network will be prohibitive. Centralization may be easier to implement and oversee by the government, however decentralized treatment will remain an important component of solving the island's wastewater challenges.

This heterogeneity on a technical, but also organizational and institutional level complicates nutrient management on SAI. With our modeling and the investigated scenarios, the focus was on technical solutions. These solutions are necessary but not sufficient, as management requires more than building additional infrastructure. A more comprehensive assessment of other effects and impacts (e.g., environmental, economic, social, and health aspects; see Haag et al., 2019) as performed, for instance, by Wada et al. (2021) for Kona Hawai'i should be an aim of further studies on SAI.

6. Conclusions and outlook

This research identified pathways of TIN from touristic and domestic wastewater into land and ocean sinks for the small Caribbean island of San Andrés in the dry season. One main pathway is via the existing sewer system and a submarine pipe to the ocean. The other main pathway is via different forms of soak pits into the land sink and groundwater. In the rainy season these pathways may shift. The direct influence of tourists is lower than of residents and workers, as their numbers are lower. However, tourism is a major driver for population growth and development on the island.

Our study emphasizes the need for holistic and effective wastewater management on small islands in the Wider Caribbean Region to mitigate risks to marine ecosystems and public health. By taking such a view, which is a key strength of systems models, we could better understand the impacts and trade-offs of potential management scenarios. Switching the entire wastewater system to any of the current main solutions found on the island, onlys redistributes pollutants between the sinks. This highlights that removal of TIN from the system needs to be targeted instead.

The combination of systems mapping and mass balance modeling effectively combined different types of data, including expert opinion, to understand how TIN moves from its source to sinks. The use of probability distributions for model parameters enabled to address some of the existing uncertainties. This makes the approach practical for studying environments with limited information. The versatility of the method helped to adapt it to the specific local situation and to bring together different sources of knowledge.

Our research highlights the need for a systems perspective on wastewater management for small islands and the integration of stakeholder knowledge in data-sparse environments or systems. Conceptual models such as the one developed here can be a powerful tool to show the interconnectedness of the system, especially in the process of knowledge sharing and decision making. The developed approach can be transferred to other islands that are facing similar issues as a first step in understanding difficult trade-offs for management decision making.

CRediT authorship contribution statement

Annika Jaax: Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Resources, Software, Visualization, Writing – original draft, Writing – review & editing. **Sarah Zwicker:** Conceptualization, Investigation, Methodology, Resources, Supervision, Visualization, Writing – original draft, Writing – review & editing. **Marie Fujitani:** Conceptualization, Funding acquisition, Project administration, Writing – review & editing. **Alice Pohle:** Data curation, Resources, Writing – review & editing. **Shelly Palmer Cantillo:** Resources, Validation. **José Ernesto Mancera Pineda:** Writing – review & editing, Validation. **Fridolin Haag:** Conceptualization, Investigation, Methodology, Software, Supervision, Visualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

Co-author serves as a guest editor for this special issue in Ocean & Coastal Management - MF.

Data availability

Public data available from the respective authorities (e.g., https://www.dane.gov.co). Code for model available at https://doi.org/10.5281/zenodo.11104975. Other data available from the authors upon request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ocecoaman.2024.107135.

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