WATER RESEARCH 44 (2010) 5949–5964

Available at www.sciencedirect.com

ScienceDirect

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

Terrestrial and oceanic influence on spatial hydrochemistry and trophic status in subtropical marine near-shore waters

Sara M. Morales-Ojeda, Jorge A. Herrera-Silveira, Jorge Montero*

Laboratorio de Produccion Primaria CINVESTAV-IPN, Unidad Mérida., Carr. Antigua a Progreso km. 6, C.P. 97310 Mérida, Yucatán, México

ARTICLE INFO

Article history:
Received 14 March 2010
Received in revised form
2 July 2010
Accepted 14 July 2010
Available online 23 July 2010

Keywords:
Water quality
Trophic status
Near-shore waters
Multivariate analysis
Yucatan

ABSTRACT

Terrestrial and oceanic influences like groundwater discharges and/or oceanic upwelling define the hydrochemical and biological characteristics of near-shore regions. In karst environments, such as the Yucatan Peninsula (SE Mexico), the balance between these two influences on spatial and temporal scales is poorly understood. This study focused on near-shore waters within 200 m offshore along the Yucatan coast. The trophic status and hydrochemical zones of the study area were determined as a function of physical and nutrient data collected from 2005 to 2006. The main terrestrial influence was groundwater discharge, while the most important marine influence was related to seasonal changes in water turbulence. Spatial differences ($p < 0.05$) were observed among salinity, light extinction coefficient (k), NO_3^-, NH_4^+, and Chl-*a*. Seasonal differences were observed for all variables except for k. During the dry season, terrestrial influences are the dominant factor on near-shore hydrochemistry. The region around Dzilam exhibited the maximum influence of groundwater discharge estimated by salinity dissolution (δ). During the rainy and "nortes" seasons, there is a balance between oceanic and terrestrial influences. The trophic status measured using the TRIX index, indicated that near-shore waters were mainly oligo-mesotrophic; with a meso-eutrophic status in areas with documented anthropogenic impacts. Four hydrological zones were identified by a Canonical Variate Analysis (CVA) using salinity, NO_2^-, k and NH_4^+ as the main discriminating variables. Zones I and II showed almost pristine conditions, with well-balanced terrestrial–oceanic influences. In Zone III, terrestrial influences such as groundwater discharges and inland pollution suggesting human impacts were dominant respect to the effects of oceanic influences like upwelling and sediment resuspension caused by winds and oceanic currents. Zone IV received enhanced groundwater and associated nutrients. Anthropogenic activities have led to ecosystem degradation but the speed at which this occurs depends on local and regional characteristics. Therefore, this study has defined those characteristics so as to enact better management policies.

* *Corresponding author*. Tel.: +52 999 9429462 (direct line); fax: +52 999 9812334.
E-mail addresses: smorales@mda.cinvestav.mx (S.M. Morales-Ojeda), jherrera@mda.cinvestav.mx (J.A. Herrera-Silveira), jmontero@mda.cinvestav.mx (J. Montero).
0043-1354/$ – see front matter
doi:10.1016/j.watres.2010.07.046

Abbreviations and notations

SE	Southeast
CMW	Coastal marine waters
SGD	submarine groundwater discharges
NO_2^-	nitrite (μmol l^{-1})
NO_3^-	nitrate (μmol l^{-1})
NH_4^+	Ammonia (μmol l^{-1})
SRP	soluble reactive phosphorus (μmol l^{-1})
N:P	Redfield ratio
SRSi	soluble reactive silica (μmol l^{-1})
k	light extinction coefficient (m^{-1})
Chl-*a*	chlorophyll-*a* (mg m^{-3})
O_2	oxygen (mg l^{-1})
DOS	dissolved oxygen saturation (%)
Δ	salinity dilution (no units)
pH	inverse logarithm of the activity of the hydrogen ion Salinity (no units)
	Temperature (°C)
TRIX	Vollenweiner trophic index (no units)
DCA	detrended correspondence analysis
CVA	canonical variate analysis
PCA	principal component analysis

1. Introduction

In coastal waters, the bidirectional flux of materials and energy between land and water, as well as the aquatic life and human activities are closely related. This zone is conceived as a region where complex interactions between terrestrial variables (nutrients and sediments inputs) and oceanic factors (tides and currents) take place (Valiela et al., 1992). These interactions between forcing functions from the land and sea show spatial and temporal variation, contributing to regional or local vulnerability to human activities which threat the water hydrochemistry (White et al., 2004).

The hydrochemistry of a specific region may depend on the input of pollutants from land to coastal waters, water residence time, and the sources of fresh and/or marine water (e.g. riverine, groundwater, upwelling, oceanic). In temperate regions, the disturbance on the hydrodynamics and water quality characteristics of coastal waters by chemical, physical and biological stressors can cause shifts from oligo to eutrophic conditions (Xua et al., 2004).

Water quality and trophic status measurements of coastal and marine waters are often used to assess and evaluate their conditions for a better management of the coastal and marine resources (Paerl, 2006). Traditionally, coastal hydrochemistry assessments focused mainly on point sources of nutrients from land, and less attention has been given to the nutrient sources related to marine processes, or the interaction of both land and oceanic sources in areas influenced by submarine groundwater discharge (SGD) (Chen, 1996; Loubere, 2000; Cullen, 2002).

One of the distinctive features of the Yucatan Peninsula is the karstic substrate that allows rapid water infiltration and negligible surface runoff. SGD is the main pathway of freshwater from land to coastal ecosystems in the Yucatan and other places like Bosnia Herzegovina, Sierra de Libar, Spain, Haute-Normandie region and France where karst is dominant along the coast. However, little is known about the processes and variables associated with the ecosystem health and the relative importance of the terrestrial and oceanic influences coastal tropical karstic regions (Calo and Parise, 2009; Andreo et al., 2006; Valdes et al., 2007).

The highest freshwater input from SGD is usually found near the shoreline. In the Yucatan Peninsula, SGD is the main source of freshwater into the coastal ocean and it is canalized and focused in small springs (Herrera-Silveira and Morales-Ojeda, 2009). Groundwater has been estimated to contribute about 90% of the near-shore freshwater inputs to the north coast of Yucatan, while coastal lagoons contribute 5%, surface run off 4%, and harbors 1%. However, the main source of freshwater and nutrients in the Yucatan coast is groundwater, the differences in water quality are directly related to land-use, residence time of water, and weather (Aranda-Cirerol et al., 2006; Herrera-Silveira and Morales-Ojeda, 2009). Another important feature of the SGD system found in Yucatan is the “ring of cenotes” which is characterized by large discharges of freshwater into the coast, mainly in areas where the cenotes ring area meets the coastal line (i.e., localities of Celestun and Dzilam) (Pacheco Martinez and Alonzo Salomon, 2003).

The objective of this work was to determine the importance of terrestrial and oceanic influences on the spatial heterogeneity and trophic status of marine subtropical coastal waters of a karstic region as the northern Yucatan. This research would provide a better understanding of the connectivity between terrestrial and oceanic processes and characteristics of subtropical karstic environments that will further promote the establishment of ecological base lines for coastal management and monitoring programs in similar karstic coastal areas.

2. Materials and methods

2.1. *Study area*

This study was carried out along the northern Yucatan coast, in the southwest Gulf of Mexico (Fig. 1). The coast is 365 km long and represents only 3.3% of the entire Mexican coastline. There are three well-defined climate seasons in this region: dry season (March–May), rainy season (June–October) and nortes season when cold fronts dominate (November–February). The predominant winds come from the Bermuda-Azores anticyclone; in general, the wind is of low intensity (0–15 km h^{-1}) and comes from the southeast, and produces low-energy waves. The tide is mixed semidiurnal with a range from 0.4 to 0.8 m (Capurro, 2002).

The dominant terrestrial influence on marine coastal waters is via SGD, which is approximately 8.6×10^6 m^3 km^{-1} $year^{-1}$ (Hanshaw and Back, 1980). SGD is characterized by low salinity and high nitrate and silicate concentrations. The influence of