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Nota Científica

Flushing time in Perlas Lagoon and Bluefields Bay, Nicaragua

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ABSTRACT. The flushing time of Perlas Lagoon and Bluefields Bay were studied in January, March, May, and July 2001. Calculations of the total water volume, tidal prism, mean salinity, and fresh water flows are shown. The flushing times range from 14 to 17 days for Perlas Lagoon and from 2 to 4 days for Bluefields Bay. Flushing time variability, determined largely by the fresh water contribution, is greater for Bluefields Bay, duplicating its magnitude during the dry months compared to the rainy season. In both bodies of water, the relationship between fresh water input and flushing time is inverse: for Bluefields Bay $T = 5.2 \cdot e^{-0.0008\,(FW)}$, where $r^2 = 0.835$ and for Perlas Lagoon $T = 20.2 \cdot e^{-0.0004\,(FW)}$, where $r^2 = 0.873$.

Key words: flushing time, coastal lagoons, Caribbean Sea.

Tiempo de renovación para la Laguna de Perlas y la bahía de Bluefields, Nicaragua

RESUMEN. Se estudió el tiempo de renovación de la Laguna de Perlas y bahía de Bluefields en enero, marzo, mayo y julio de 2001. Se presentan cálculos del volumen total de agua, prisma mareal, salinidad media y flujos de agua dulce. En el caso de Laguna de Perlas, los tiempos obtenidos estuvieron entre 14 y 17 días, y en la bahía de Bluefields, entre 2 y 4 días. La variación en el tiempo de renovación de ambas lagunas está dominado por el aporte de agua dulce. El tiempo de renovación de la bahía de Bluefields varió durante el período de muestreo de manera mucho más significativa, duplicando su valor durante los meses secos respecto al mes más lluvioso. En ambas lagunas existe una relación inversa entre el aporte de agua dulce y el tiempo de renovación, de manera que para la bahía de Bluefields dicha relación está expresada por la ecuación, $T = 5{,}2 \cdot e^{-0{,}0008\,(FW)}$, con un $r^2 = 0{,}835$, mientras que para la Laguna de Perlas la relación está dada por la expresión: $T = 20{,}2 \cdot e^{-0{,}0004\,(FW)}$, con un $r^2 = 0{,}873$.

Palabras clave: tiempo de renovación, lagunas costeras, mar Caribe.

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Officer (1980) defines the residence time for an estuary as the mean time a particle of a conservative substance spends in a given volume. Salt and fresh water are usually considered conservative substances in estuarine hydrodynamics. The fresh water residence time, also known as the flushing time, can be defined as the time needed to replace the fresh water volume in the estuary with a rate equal to the fluvial discharge.

There are several formulations for "flushing time", most of them strictly valid only for well-mixed reservoirs in a steady state. This was emphasized by Bolin & Rodhe (1973), who reviewed several terms such as "reposition time" and "mean transit time". In the present study, the term "residence time" was used where no further discussion was needed. This definition does not require a well-mixed reservoir. The flushing time is equivalent to the "reposition time" of Bolin & Rodhe (1973), also known as "replacement time". The definition is strictly oriented at the time needed for the volume introduced by the river flux to be equal to the fresh water volume in the lagoon, but says nothing about the processes of replacement.

The total volume of a lagoon is determined by several fluxes of continental, oceanic, and atmospheric origins: riverine discharge, coastal water incoming through passages, evaporation, and precipitation. Such fluxes have to be known or estimated to decide whether they have to be taken into account in the dynamic analysis of the ecosystem.

The salinity field is closely related to these fluxes. If the fluxes maintain a stationary state in the salinity distribution of the lagoon for a given time interval, the excess or deficit of salinity, as compared to the sea water, can be used to estimate the flushing time of the lagoon.

Assuming complete mixing within the estuary and a stationary distribution of fresh and salty water for a constant river flux, Ketchum (1950) developed simplified mixing models. Ketchum (1951) introduced variations to his original idea, dividing the estuary in segments; each segment was totally mixed. The method, called segmented tidal prism, was later improved by Dyer & Taylor (1973) who noted problems related to the principle of volume continuity and the segmentation of the estuary. Segmented tidal prism models are mainly applicable to well-mixed conditions.

Perlas Lagoon and Bluefields Bay are estuarine-lagoon systems which have been studied for over five years. Several biological, oceanographic, and fishing issues have been addressed (Pérez, 1999; Brenes & Castillo, 1999a, 1999b) but flushing time has not been explored.

Determination of the flushing time in Bluefields Bay is of particular interest. This ecosystem supports a much larger population and economic activity than Perlas Lagoon. Residual water from the population and industrial activities, which lack a collection and disposal system, is the main source of pollution into the bay (CIMAB, 1996).

In this study, the flushing time was estimated for January, March, May, and July 2001. Flushing times obtained for Perlas Lagoon (PL) and Bluefields Bay (BB) are shown in Figure 1 as a function of the total fresh water input (Pilson, 1985).

The area of PL is 571 km^2 (Roullot, 1980). An area of 493 km^2 was used in this study, excluding the Top Lock, Sunnie, and Little Sunnie lagoons (INETER, 2000). The area of BB is 176 km^2 (CIMAB, 1996). Figure 2 shows the borders of both systems under study.

Mean bottom depths (Fig. 2) are 2.5 m for PL and 1 m for BB (Roullot, 1980; INETER, 2000). The above depths, used throughout this study, are assumed to correspond to low water conditions.

The mean tidal range, referred to the value observed in Bluefields Bay, is 0.22 m for both lagoons. The volume of the tidal prism at PL was estimated as 1.08×10^8 m^3 and the total volume was estimated at $1.34 \cdot 10^9$ m^3 (high water). The mean tidal prism volume and total volume at high water were estimated for BB as $3.8 \cdot 10^7$ m^3 and $2.15 \cdot 10^8$ m^3.

Rainfall is abundant, with a yearly mean of 4500 mm (INETER, 2000). There is no hydrological network in the study area to allow for a historical re-

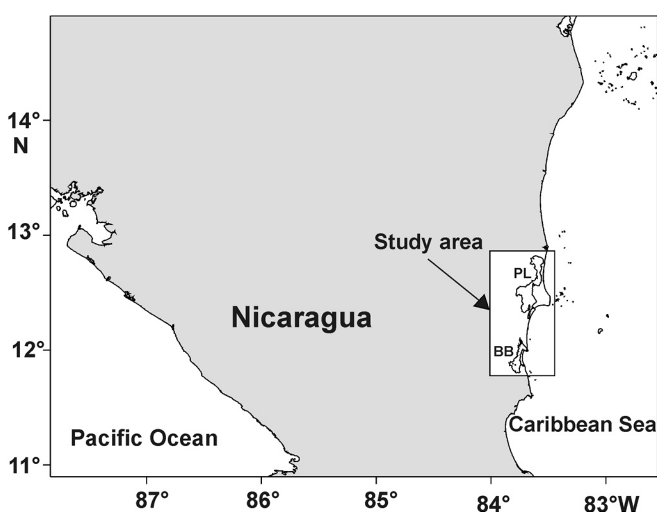

Figure 1. Study area. PL: Perlas Lagoon, BB: Bluefields Bay.

Figura 1. Area de estudio. PL: Laguna de Perlas, BB: bahía de Bluefields.

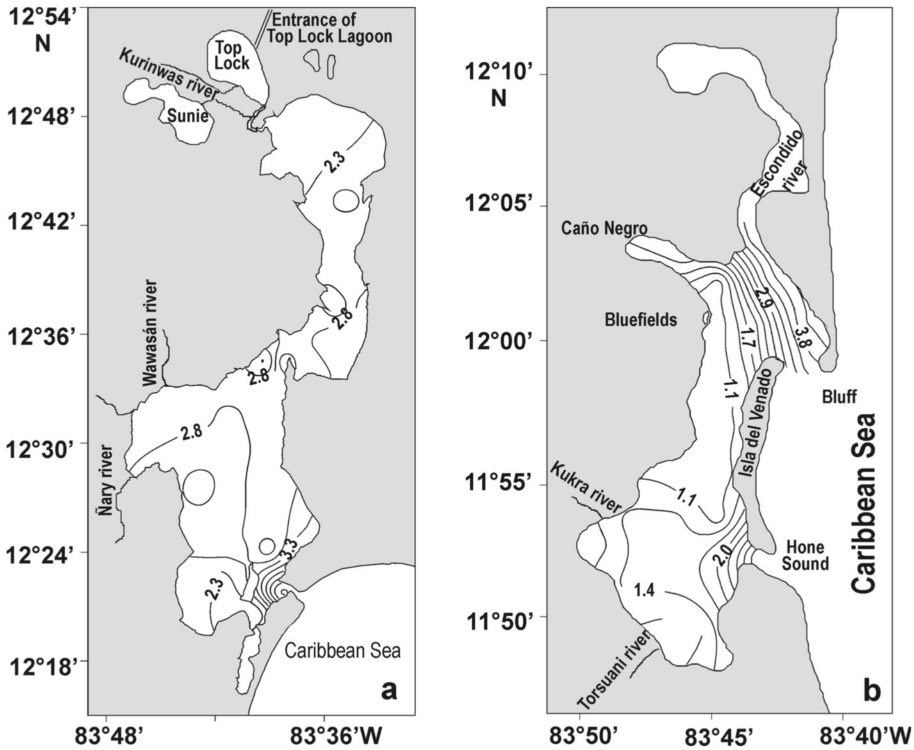

Figure 2. Bathymetry (m) of a) Perlas Lagoon, and b) Bluefields Bay.

Figura 2. Batimetría (m) de a) Laguna de Perlas, y b) bahía de Bluefields.

cord of river discharge into the lagoons. Four rivers provide the main source of fresh water inflow into PL: Grande de Matagalpa (through the Top Lock Lagoon), Wawasán, Pach, and Ñary; another four rivers flow into BB: Escondido, Caño Negro, Kukra, and Torsuani. Murray *et al*. (1982) reported mean yearly fluxes of 850 $m^3 \cdot s^{-1}$ and 950 $m^3 \cdot s^{-1}$ for the Escondido River and Río Grande de Matagalpa.

The fluxes ϕ (in $m^3 \cdot s^{-1}$, Tables 1 and 2) were estimated using surface velocities measured in January, March, May, and July 2001 as:

$$\phi = v \cdot A_T \quad (1)$$

where: v is the mean river velocity at the surface ($m \cdot s^{-1}$) and A_T the cross sectional area of the river (m^2).

Lagrangian drifters were used to determine the surface velocity. To estimate the cross sectional area A_T, the width of the river was measured along with the mean bottom depth evaluated along the transect across the river. The measurements were carried out along transects far from the river mouths, where salinity is 0.

Additional fresh water input due to precipitation on PL and BB (in $m^3 \cdot s^{-1}$) was estimated using climatological information from the Bluefields station (Table 3) as the difference between precipitation and evaporation (P-E) times in the lagoon area (Tables 4 and 5).

Mean salinity was determined from the hydrographic surveys carried out during the sampling period (Fig. 3) measuring surface and bottom salinity at high water.

It is difficult to determine the salinity of the sea water entering the lagoons, through a bar (PL) and two straits located in El Bluff in the area known as Barra Hone Sound (BB). Salinity varies with time and the mixing processes taking place in these areas are poorly understood. However, the salinity fields are consistent with a two-layer model in which a seaward, low salinity flux overlays a salty wedge entering the lagoon in the lower layer. The maximum salinity measured in the bottom layer in the external part of the lagoons was used to estimate the sea water salinity (Fig. 3, Table 6).

Table 1. Riverine fluxes into Perlas Lagoon ($m^3 \cdot s^{-1}$).
Tabla 1. Flujos de los ríos que desembocan en la Laguna de Perlas ($m^3 \cdot s^{-1}$).

River	Flux ($m^3 \cdot s^{-1}$)			
	January 2001	March 2001	May 2001	July 2001
Entrance of Top Lock Lagoon	373	367	420	942
Wawasán	126	124	48	44
Patch	20	15	6	9
Ñary	61	41	10	44
Total	580	547	484	1039

Table 2. Riverine fluxes into Bluefields Bay ($m^3 \cdot s^{-1}$).
Tabla 2. Flujos de los ríos que desembocan en la bahía de Bluefields ($m^3 \cdot s^{-1}$).

River	Flux ($m^3 \cdot s^{-1}$)			
	January 2001	March 2001	May 2001	July 2001
Escondido	349	218	132	625
Caño Negro	87	81	134	575
Kukra	19	16	75	45
Torsuani	10	12	30	30
Total	465	327	371	1275

Table 3. Monthly mean precipitation (mm) and evaporation (mm) for the Bluefields station, 1997-1999.
Tabla 3. Precipitación (mm) y evaporación media mensual (mm) para la estación de Bluefields 1997-1999.

Month	Precipitation (mm)	Evaporation (mm)	P-E (mm)
January	250.3	127.7	122.6
March	46.6	165.4	-118.8
May	206.1	171.4	34.7
July	568.5	158.0	410.5

Source: INETER, 2000.

Table 4. Estimated total fresh water input (FW) into Perlas Lagoon ($m^3 \cdot s^{-1}$).
Tabla 4. Estimación del aporte total de agua dulce (FW) en la Laguna de Perlas ($m^3 \cdot s^{-1}$).

Source	Flux ($m^3 \cdot s^{-1}$)			
	January 2001	March 2001	May 2001	July 2001
Rivers	580	547	484	1039
Precipitation - Evaporation	22.5	-21.8	6.4	75.5
Total fresh water (FW)	602.5	525.2	490.4	1114.5

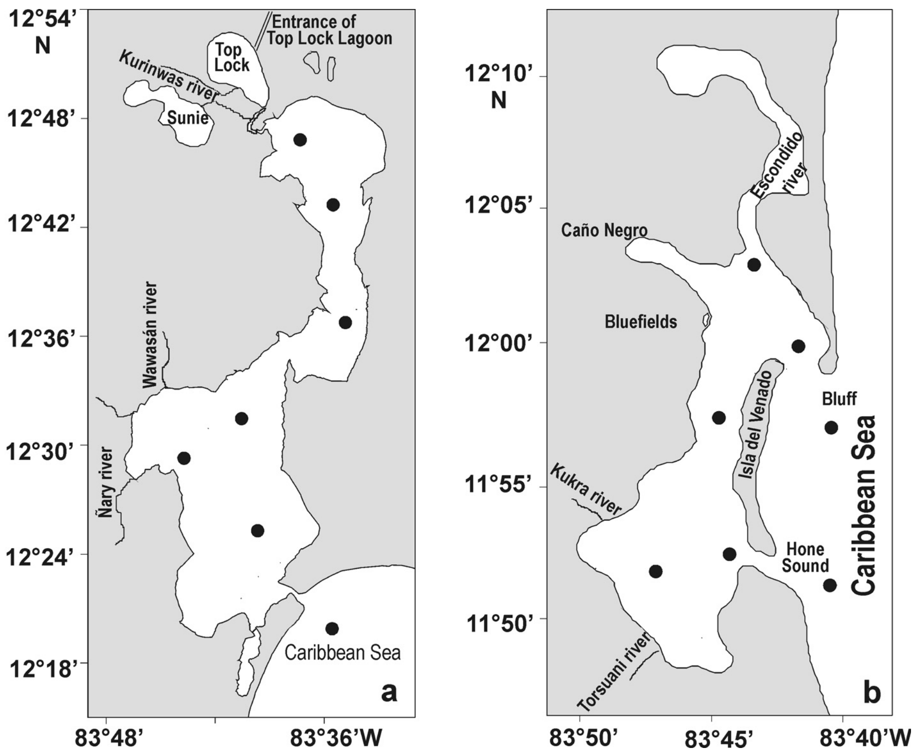

Figure. 3. Location of the hydrographic stations in a) Perlas Lagoon, and b) Bluefields Bay.

Figura 3. Localización de las estaciones hidrográficas en a) Laguna de Perlas, y b) bahía de Bluefields.

The total fresh water volume V_D within the lagoons was estimated as in Ketchum (1950):

$$V_D = \left(1 - \frac{S_M}{S_O}\right) \cdot V_L \qquad (2)$$

where: S_M is the mean salinity of the lagoon, S_o the sea water salinity entering the lagoon, and V_L the lagoon volume at high water.

According to the previous discussion, the lagoons were estimated to have volumes of $1{,}340.9 \cdot 10^6$ m^3 (PL) and $2.15 \cdot 10^8$ m^3 (BB).

The time needed for the fresh water entering the lagoon to equal the total lagoon volume was calculated as:

$$T = \frac{V_D}{FW\,(86{,}400)} \qquad (3)$$

where: T is the flushing time in days (1 day = 86,400 s), FW the monthly fresh water entering the lagoon in m$^3 \cdot$s^{-1} (Tables 4 and 5), and V_D the total fresh water volume (Table 7). Table 8 shows the values obtained for the flushing time as a function of the input of fresh water.

Pilson (1985) analysed the propagation of errors using the present method to calculate the flushing time in the Bay of Narragansett. According to that study, the flushing time obtained with the technique is proportional to the volume used for the lagoon. If the mean bottom depth of the lagoon used was 1 m larger, the estimated flushing time would increase by 12%. Choosing the volume corresponding to low water or high water would result in a variation of 7% with respect to the value corresponding to the mean tide volume.

The calculation of the uncertainty in the fresh water input is a difficult task. Having measured fluxes near the mouths of the systems, we can assume that such uncertainty is small. The major problem here is how to adjust the salinity measurements in time, taking into account the response of salinity to the mean fluxes of the rivers and precipitation. Available hydrological data are insufficient to accomplish such a task. Given the nature of the

Table 5. Estimated total fresh water input (FW) into Bluefields Bay ($m^3 \cdot s^{-1}$).
Tabla 5. Estimación del aporte total de agua dulce (FW) en la bahía de Bluefields ($m^3 \cdot s^{-1}$).

Source	Flux ($m^3 \cdot s^{-1}$)			
	January 2001	March 2001	May 2001	July 2001
Rivers	465	327	371	1275
Precipitation - Evaporation	8.0	-7.8	2.3	27.0
Total fresh water (FW)	473	319.2	373.3	1302

Table 6. Average lagoon salinity and selected values of sea water salinity entering the lagoons.
Tabla 6. Salinidad promedio de las lagunas y valores seleccionados de la salinidad oceánica que entra a las lagunas.

Month	Mean salinity			
	Perlas Lagoon		Bluefields Bay	
	Lagoon	Sea water	Lagoon	Sea water
January	12.0	35.0	8.3	35.0
March	16.0	36.0	16.0	37.0
May	18.0	37.0	17.5	37.0
July	1.0	36.0	0.2	36.0

communities living around the lagoons, it is difficult to estimate the input of waste water. However, the uncertainty in this quantity is relatively constant and should not exceed 2% (Pilson, 1985).

The results obtained in the present study are a first approach to the exchange rates between the estuarine system and the sea. Previous studies (Brenes & Castillo, 1999a) show that the dynamics of Perlas Lagoon are strongly determined by fresh water input and wind forcing. The contrast in salinity between the inner and seaward sections of the lagoons found in the present study is consistent with previous results. In PL, the amount of fresh water input is important during the rainy season. In the lower layers of the coastal zone, the differences in salinity with time were not significant, but in the inner part, these differences exceeded 15.

Flushing times shown in Table 8 suggest that the exchange rate between the lagoons and the ocean is controlled by the balance between the fresh water input and the flux of salty water coming from the adjacent coastal zone. The flushing time is smallest in July, when the input of fresh water is largest. For the other months, the variation in this parameter is relatively small and lower than 10% between January and May. The flushing time in PL appears to remain nearly constant, between 16 and 17 days, virtually the whole year round. Only during extremely heavy precipitation conditions (*e.g.*, July, P = 800 mm) does the flushing time show a clear diminution (Table 8).

There is an inverse relationship between fresh water input (FW) and flushing time (T) given by the expression

$$T = 5.2 \cdot e^{-0.0008(FW)},\ r^2 = 0.835$$

for BB, whereas for PL the relationship is

$$T = 20.2 \cdot e^{-0.0004(FW)},\ r^2 = 0.873$$

No extrapolations for very large fresh water inputs can be made using the above expressions.

There are several estuaries where the fresh water input strongly controls exchange processes and the flushing time decreases with increasing fresh water input: Boston Harbor (Ketchum,1952), Bay of Newark (McCormick *et al*., 1983), Bay of Narragansett (Pilson, 1985), and the lagoon system of Nichupté, Cancún (Merino *et al*., 1990), among others.

In this study, the flushing time in BB never exceeds five days. The small size of the bay and the large volume of water carried by the rivers discharging into it result in a very short flushing time. The

Table 7. Total fresh water volume V_D (m^3) obtained using equation (2).
Tabla 7. Volumen total de agua dulce V_D (m^3), obtenido a partir de la ecuación (2).

Month	V_D = Total fresh water volume (m^3) · 10^9	
	Perlas Lagoon	Bluefields Bay
January	0.89	0.16
March	0.75	0.12
May	0.70	0.11
July	1.30	0.21

Table 8. Estimated fresh water volume (FW) entering the lagoons and flushing time for the studied months.
Tabla 8. Volumen estimado de agua dulce (FW) que entra a las lagunas y tiempo de lavado para los meses de muestreo.

Month	Perlas Lagoon		Bluefields Bay	
	FW ($m^3 \cdot s^{-1}$)	Flushing time (days)	FW ($m^3 \cdot s^{-1}$)	Flushing time (days)
January	602	17	473	4
March	525	16	319	4
May	490	16	373	4
July	1114	14	1302	2

results obtained for the flushing time in BB (Table 8) suggest that the exchange rate between the bay and the ocean is also controlled by the fresh water input.

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REFERENCES

Brenes, C.L. & E. Castillo. 1999a. Caracterización hidrográfica de la Laguna de Perlas, Nicaragua. Proyecto DIPAL II, Bluefields, Nicaragua, 46 pp.

Brenes, C.L. & E. Castillo. 1999b. Hidrografía de la bahía de Bluefields. Proyecto DIPAL II, Bluefields, Nicaragua, 22 pp.

Bolin, B. & H. Rodhe. 1973. A note on the concepts of age distribution and transit time in natural reservoirs. Tellus, 25: 58-62.

Centro de Ingeniería y Manejo Ambiental de Bahías y Zonas Costeras (CIMAB). 1996. Centro de Ingeniería y Manejo Ambiental de Bahías y Zonas Costeras. Estudio de Caso: La Laguna de Blufields Nicaragua, bases para la formulación de un Plan de Manejo Ambiental. Proyecto Regional PNUMA CAR/P/CR/5101-90-05(2494), La Habana, 86 pp.

Dyer, K. & P.A. Taylor. 1973. A simple segmented prism model of tidal mixing in well-mixed estuaries. Estuar. Coast. Mar. Sci., 1: 411-418.

Instituto Nicaragüense de Estudios Territoriales (INETER). 2000. Instituto Nicaragüense de Estudios Territoriales. Dirección de Meteorología. Informe escrito, 25 pp.

Ketchum, B.H. 1950. Hydrographic factors involved in the dispersion of pollutants introduced into tidal waters, J. Bos. Soc. Civil Eng., 37: 296-314.

Ketchum, B.H. 1951. The exchanges of fresh and salt waters in tidal estuaries. J. Mar. Res., 10: 18-37.

Ketchum, B.H. 1952. Circulation in estuaries. Proceedings Third Conference on Coastal Engineering, pp. 65-76.

McCormick, J.M., R.I. Hires, G.W. Luther & S.L. Cheng. 1983. Partial recovery of Newark Bay, NJ, following pollution abatement. Mar. Poll. Bull., 14: 188-197.

Merino, M., S. Czitrom, E. Jordán, E. Martin, P. Thomé & O. Moreno. 1990. Hydrology and rain flushing on the Nichupté Lagoon system, Cancún, México. Estuar. Coast. Mar. Sci., 30: 223-237.

Murray, S.P., S.A. Hsu, H.R. Roberts, E.H. Owens & R.L. Grout. 1982. Physical processes and sedimentation on a broad, shallow bank. Estuar. Coast. Mar. Sci., 14: 135-157.

Officer, C.B. 1980. Box models revisited. In: P. Hamilton & R.B. Macdonald (eds.). Estuarine and wetland processes. Mar. Sci. Ser., Plenun Press, New York, 11: 65-114.

Pérez, M. 1999. Biología pesquera y aspectos ecológicos de la ictiofauna más importante de la cuenca de Laguna de Perlas en la región autónoma del Atlántico sur (RAAS) de Nicaragua. Proyecto DIPAL II, Bluefields, Nicaragua, 142 pp.

Pilson, M.E.Q. 1985. On the residence time of water in Narragansett Bay. Estuaries, 8: 2-14.

Roullot, J. 1980. Informe de la misión en la Laguna de Perlas, Nicaragua. Programa Interregional de Ordenación y Desarrollo Pesquero. Informe WECAF, 34: 62 pp.

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