LAND-OCEAN INTERACTIONS IN THE COASTAL ZONE (LOICZ)

Core Project of the
International Geosphere-Biosphere Programme: A Study of Global Change (IGBP)

MEXICAN AND CENTRAL AMERICAN COASTAL LAGOON SYSTEMS: CARBON, NITROGEN AND PHOSPHORUS FLUXES

(Regional Workshop II)

compiled and edited by S.V. Smith, J.I. Marshall Crossland and C.J. Crossland

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MEXICAN AND CENTRAL AMERICAN COASTAL LAGOON SYSTEMS: CARBON, NITROGEN AND PHOSPHORUS FLUXES
(Regional Workshop II)

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Cover: The map on the cover shows Mexico and Central America, the region in which the estuarine systems studied in this Workshop Report are located. Specific site locations can be found in Figure 1.1.

The LOICZ Reports and Studies Series is published and distributed free of charge to scientists involved in global change research in coastal areas.

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1. OVERVIEW OF WORKSHOP AND BUDGET RESULTS

Key objectives of the Land-Ocean Interactions in the Coastal Zone (LOICZ) core project of the International Biosphere-Geosphere Programme (IGBP) are to:

- gain a better understanding of the global cycles of the key nutrient elements carbon (C), nitrogen (N) and phosphorus (P);
- understand how the coastal zone affects material fluxes through biogeochemical processes; and
- characterise the relationship of these fluxes with environmental change, including human intervention (Pernetta and Milliman 1995).

To achieve these objectives, the LOICZ programme of activities has two major thrusts. The first is the development of horizontal and, to a lesser extent, vertical material flux models and their dynamics from continental basins through regional seas to continental oceanic margins, based on our understanding of biogeochemical processes and data for coastal ecosystems and habitats, and the human dimension. The second is the scaling of the material flux models to evaluate coastal changes at spatial scales to global levels and, eventually, across temporal scales.

It is recognised that there are a large amount of existing and recorded data and work in progress around the world on coastal habitats at a variety of scales. LOICZ is developing the scientific networks to integrate the expertise and information at regional levels in order to deliver science knowledge that addresses our regional and global goals.

The Mexican and Central American Coastal Lagoon Systems: Carbon, Nitrogen and Phosphorus Fluxes (Regional Workshop II) builds on an earlier workshop which focused on Mexican systems in the Gulf of California and the Pacific Coast (Smith *et al*. 1997). The Mexican coastline of some 12 000 km contains numerous, diverse and often well-studied coastal lagoons and estuaries (Contreras 1993). These systems are subject to a range of sub-tropical climatic conditions and human pressures (Smith *et al*. 1997, Bianchi *et al*. 1999). Of particular note here is the suite of coastal lagoons in the northern “head” of the Yucatan Peninsula where groundwater rather than surface flow is the dominant freshwater input to the coastal systems. These provide an invaluable set of examples by which LOICZ may gain further understanding of groundwater processes and their effects on horizontal material fluxes. The systems can also provide models for application elsewhere.

The extensive coastline of Central America contains an equally diverse array of coastal that probably represent a wider suite of models and budgets representative of increasingly tropical climatic conditions. Fewer coherent data sets are available describing these systems, and the results of this Workshop provide a first step in developing an understanding of the available information. Further efforts will be made by LOICZ to extend this set of descriptions and C-N-P budgets of the estuarine systems for the region, especially through the aegis of a recently established UNEP-GEF funded project.

The Workshop was held at the Centro de Investigacion y de Estudios Avanzados IPN Unidad Merida (CINVESTAV), Yucatan, Mexico, on 13-16 January 1999. The objectives of the Workshop (Appendix VI) and the activities (Appendices III and V) are provided in this report. Four resource persons (Prof. Steve Smith, Prof. Fred Wulff, Dr. Bob Buddemeier, Dr Chris Crossland) and two regional resource persons (Dr. Silvia Ibarra-Obando, Dr. Victor Camacho-Ibar) worked with participants from a number of coastal science agencies and universities (Appendix IV) to consider, develop and assess biogeochemical budgets for 12 coastal lagoons and estuaries in the region. In addition to the resultant budget descriptions, the Workshop provided a vital training forum that is resulting in further system budget developments and application of the principles by tertiary institutions. Beyond the success of budget production and training was the development of additional methodologies (Appendices I and II) that allow detailed assessment of biogeochemical processes associated with groundwater inputs, and the use of silicate as a tracer.

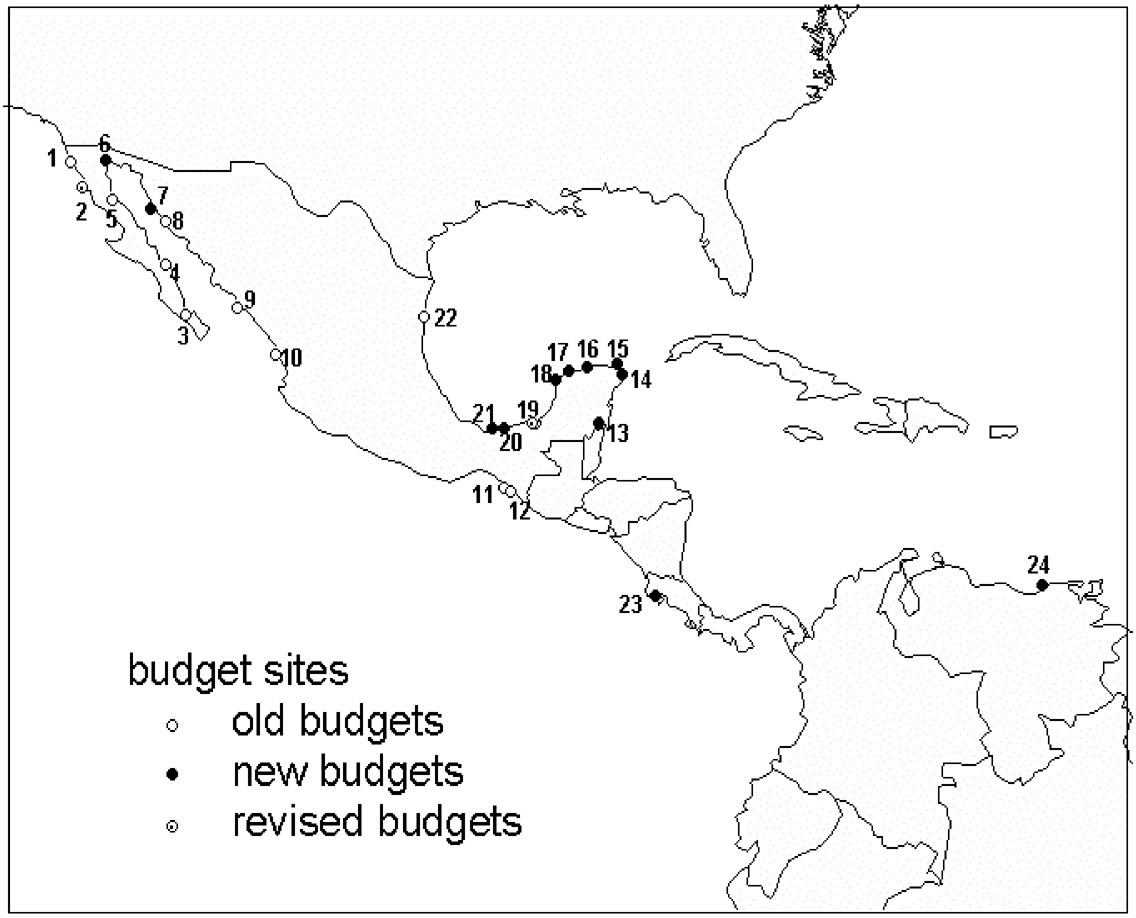

Figure 1.1. Site map for the sites budgeted as part of the Mexico Lagoons workshop (LOICZ, 1997) and the present Central American Lagoons workshop (this report). The sites are separated into old budgets, new budgets, and revised budgets. All data are summarised in this report.

The initial session of the Workshop dealt with the LOICZ approach to the global questions of horizontal fluxes of materials, and the previous and current work and contributions being made by Mexican scientists. The Bahia San Quintin estuarine system was presented as a case study, including the subsequent work of a segmented approach to the material flux budgets within the system. The LOICZ Budgets Modelling web-site was described by Prof. F. Wulff, and the pivotal role of the electronic site and its use by global scientists in making budget contributions to the LOICZ purpose was emphasised. It was noted that contributing scientists are clearly attributed as authors of their contributed budgets, and that there is provision to update and provide additional assessments of those budgets.

Participants briefly outlined the estuarine systems and the status of constructed budgets for their contributing sites. The issue of groundwater was outlined by Dr. R.W. Buddemeier (Appendix I) and its implications on freshwater inputs into the Yucatan coastal systems was highlighted and discussed. These discussions were translated into additional methodologies (Appendix II) for the LOICZ budget approach during and subsequent to the Workshop. A context and use of the scientific information derived from the constructed C-N-P budgets was provided by two plenary presentations:

“Eutrophication in Yucatan Coasts: a primary producer perspective” (Dr. Jorge Herrera Silviera) and
“Management of the coastal zone in Mexico” (Drs. Luis Capurro and Jorge Euan).

The group moved from plenary to further develop the site budgets individually and in small working groups, returning to plenary sessions to discuss the budget developments and to debate points of approach and interpretation. Twelve budgets were developed during the Workshop (Figure 1.1, Table 1.1); further advances were discussed and made for the budget assessments represented in two sites already posted on the LOICZ website (Bahia San Quintin and Laguna de Terminos). At this stage, some 24 budgets represent the region, most of them describing systems along the climatically diverse Mexican coastline.

The biogeochemical budgets reported here have been prepared usually by a group whose full authorship is duly acknowledged. The common element in the budget descriptions is the use of the LOICZ approach to budget development, which allows for global comparisons. The differences in the descriptive presentations reflect the variability in richness of site data, the complexity of the site and its processes, and the extent of detailed process understanding for the site. Support information for the various estuarine locations, with descriptions of the physical environmental conditions, related forcing functions, history and potential anthropogenic pressure, is an important part of the budget information for each site. These budgets, data and their wider availability in electronic form (CD-ROM, LOICZ web-site) will provide opportunity for further assessment and comparisons, and potential use in consideration of wider scales of patterns in system response and human pressures.

The budget information for each site is discussed individually and reported in units that are convenient for that system (either as daily or annual rates). To provide for an overview and ease of comparison, the key data are presented in an “annualised” form and non-conservative fluxes are reported per unit area (Tables 1.2 and 1.3).

Table 1.1 Budgeted Central American sites, locations, sizes, and water exchange times.

System Name	Site	Site Status	Long.	Lat.	Area	Depth	Exchange Time
			(+E)	(+N)	(km^2)	(m)	(days)
Estero Punta Banda	1	old	-116.63	31.75	12	2	11
Bahia San Quintin	2	revised	-115.97	30.45	42	2	22
Ensenada de la Paz	3	old	-110.37	24.13	45	3	33
Bahia Concepcion	4	old	-111.50	26.65	282	16	496
San Luis Gonzaga	5	old	-114.38	29.82	3	4	3
Rio Colorado delta	6	new	-114.70	31.75	450	4	31
Estero El Sargento	7	new	-112.31	29.35	11	1.5	10
Estero La Cruz	8	old	-111.53	28.75	23	1.4	33
Bahia de Altata-Ensenada del Pabellon	9	old	-107.63	24.42	460	3	29
Teacapan-Agua Brava-Marismas Nacionales	10	old	-105.53	22.13	1,600	0.8	33
Carreta-Pereyra	11	old	-93.17	15.45	35	1.5	26
Chantuto-Panzacola	12	old	-92.83	15.22	30	1.5	5
Bahia de Chetumal	13	new	-88.05	18.61	880	3	8
Nichupte Lagoonal system	14	new	-86.76	21.10	50	2	110
Ria Lagartos	15	new	-87.03	21.58	94	1	7
Dzilam Lagoon	16	new	-88.67	21.43	9	1	120
Laguna de Chelem	17	new	-89.70	21.27	15	1	40
Laguna de Celestun	18	new	-90.25	20.75	28	1.2	21
Laguna de Terminos	19	revised	-91.69	18.67	2,500	3.5	67
Mecoacan Lagoon	20	new	-93.15	18.38	50	1	33
Carmen-Machona Lagoons	21	new	-93.83	18.35	167	2.1	40
Laguna Madre	22	old	-97.50	24.00	2,000	0.7	33
Gulf of Nicoya	23	new	-85.00	10.00	525	11	40
Laguna Restinga	24	new	-64.13	10.52	26	1.5	84
number of sites					24	24	24
mean					389	3.0	56
std. dev.					684	3.0	99
median					48	2.0	33
minimum					3	1.0	3
maximum					2,500	16.0	496

Table 1.2 Budgeted Central American sites and land (including atmospheric) nutrient loads.

System Name	Site	DIP load	DIN load	Δ DIP	Δ DIN
		mmol m^{-2} yr^{-1}			
Estero Punta Banda	1	0	0	48	11
Bahia San Quintin	2	0	0	35	-80
Ensenada de la Paz	3	0	0	-16	-19
Bahia Concepcion	4	0	0	3	13
San Luis Gonzaga	5	0	0	31	-475
Rio Colorado delta	6	0	0	12	647
Estero El Sargento	7	0	0	56	-24
Estero La Cruz	8	0	0	6	15
Bahia de Altata-Ensenada del Pabellon	9	57	363	163	-257
Teacapan-Agua Brava-Marismas Nacionales	10	109	300	-106	-283
Carreta-Pereyra	11	57	86	86	86
Chantuto-Panzacola	12	100	200	0	0
Bahia de Chetumal	13				
Nichupte Lagoonal system	14	3	38	0	-8
Ria Lagartos	15	6	242	1	-195
Dzilam Lagoon	16	0	3	0	0
Laguna de Chelem	17	5	183	-4	-148
Laguna de Celestun	18	0	111	0	-60
Laguna de Terminos	19	2	162	-1	-339
Mecoacan Lagoon	20	40	60	-20	-40
Carmen-Machona Lagoons	21	48	60	54	0
Laguna Madre	22	0	0	16	31
Gulf of Nicoya	23	2	33	93	1,255
Laguna Restinga	24	0	0	-1	-7
number of sites		23	23	23	23
mean		19	80	20	5
std. dev.		33	109	51	341
median		0	33	3	-8
minimum		0	0	-106	-475
maximum		109	363	163	1,255

Table 1.3 Budgeted sites and estimated (nfix-denit) and (p-r). All stoichiometric flux calculations are based on an assumed Redfield C:N:P ratio of reacting particles.

System Name	**Site**	**(nfix-denit)** with DIN,DIP	**(p-r)**
		mmol N or C m^{-2} yr^{-1}	
Estero Punta Banda	1	-757	-5088
Bahia San Quintin	2	-640	-3710
Ensenada de la Paz	3	237	1696
Bahia Concepcion	4	-35	-318
San Luis Gonzaga	5	-971	-3286
Rio Colorado delta	6	455	-1272
Estero El Sargento	7	-920	-5936
Estero La Cruz	8	-81	-636
Bahia de Altata-Ensenada del Pabellon	9	-2865	-17278
Teacapan-Agua Brava-Marismas Nacionales	10	1413	11236
Carreta-Pereyra	11	-1290	-9116
Chantuto-Panzacola	12	0	0
Bahia de Chetumal	13		
Nichupte Lagoonal system	14	-8	0
Ria Lagartos	15	-211	-106
Dzilam Lagoon	16	0	0
Laguna de Chelem	17	-84	424
Laguna de Celestun	18	-60	0
Laguna de Terminos	19	-323	106
Mecoacan Lagoon	20	280	2120
Carmen-Machona Lagoons	21	-864	-5724
Laguna Madre	22	-225	-1696
Gulf of Nicoya	23	-233	-9858
Laguna Restinga	24	9	106
number of sites		23	23
mean		-312	-2102
std. dev.		791	5370
median		-84	-318
minimum		-2865	-17278
maximum		1413	11236

This diversity of system attributes (for example, freshwater fluxes, Figure 1.2) provides opportunity for assessment of trends in patterns of estuarine performance and response to key forcing functions, both natural and anthropogenic. Preliminary inspection of the budget and site data suggests some apparent trends:

1. All of these Central American systems also appear to experience relatively modest DIP loading, well below 100 mmol m^{-2} yr^{-1}, with the exception of one site (No. 10, Teacapan-Agua Brava-Marisma Nacionales; a major mangrove system with five river catchment inputs). Most systems appear to be slightly net DIP sources.

2. These Central American systems, similarly, appear to experience fairly modest DIN loading, generally well below 400 mmol m^{-2} yr^{-1}. Most systems appear to be slightly net DIN sinks.

3. Most of these systems are estimated to be slightly net heterotrophic, inferred from ΔDIP and based on the Redfield C:P stoichiometry assumptions for each site.

4. Most of the systems are estimated to be sites of net denitrification, inferred from ΔDIP and ΔDIN and based on Redfield N:P stoichiometry assumptions for each site.

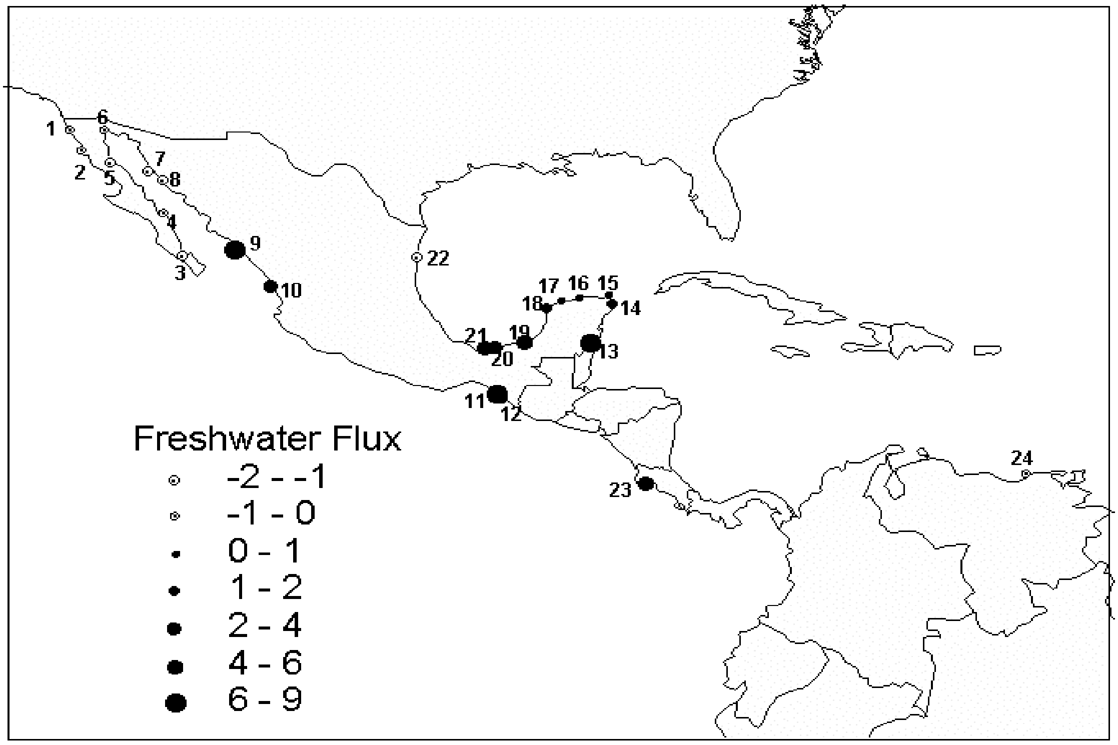

Figure 1.2. Freshwater fluxes expressed as $m.yr^{-1}$ (i.e., $V_Q + V_P + V_E$) divided by system area. The systems in Northern Mexico and the Venezuela site all are net evaporative. The systems of the northern Yucatan Peninsula tend to be in near-balance because of groundwater input. The systems of Southern Mexico, including much of the Pacific Coast south of the Baja California peninsula, and the Costa Rica site, all show large net freshwater input.

The Workshop was hosted by CINVESTAV, Merida. LOICZ is grateful for this support and the opportunity to collaborate in working to mutual goals, and is indebted to Dr Gerardo Gold Bouchet, Director, CINVESTAV and staff for their contributions to the success of the Workshop. In particular, Dr David Valdes Lozano and Dr Jorge Herrera Silveira put in much hard work as local organisers to ensure the smooth running of the Workshop. Thanks are due also to the resource people, and especially to LOICZ Scientific Steering Committee member Dr Silvia Ibarra Obanda and Dr Victor Camacho-Ibar for their contributions as regional resource people. Cynthia Pattiruhu, LOICZ IPO, has contributed greatly to the preparation of this report. LOICZ gratefully acknowledges the effort and work of the participants not only for their significant contributions to the Workshop goals, but also for their continued interaction beyond the meeting activities.

The Workshop and this report are contributions to the GEF-funded UNEP project: *The Role of the Coastal Ocean in the Disturbed and Undisturbed Nutrient and Carbon Cycles*, recently established with LOICZ and contributing to the UNEP sub-programme: Sustainable Management and Use of Natural Resources.

2. BUDGETS FOR YUCATAN ESTUARINE SYSTEMS

The Yucatan Peninsula has an interesting hydrological system with surface river flows to both the Gulf of Mexico and the Caribbean Sea to the south of the Peninsula and, to the northern ‘head’, groundwater discharge is a major coastal phenomenon (Hanshaw and Back 1980; Perry and Velazquez-Oliman 1996). Groundwater, too, probably contributes to freshwater discharges into the southern estuaries which receive riverine flows. Recognising this difference in hydrological environments, the activities of the Workshop included a particular effort to assess the magnitude and implications of groundwater discharges into the coastal zone. Further, we have described the biogeochemical budgets under two headings: Surface Flow Systems, where rivers clearly make significant contributions to the freshwater discharge volume, and Groundwater-Influenced Systems, where *cenote* and other physical evidence of groundwater discharge is apparent.

2.1 YUCATAN SURFACE FLOW SYSTEMS

2.1.1 Laguna de Términos, Campeche

Laura T. David

Study area description

Laguna de Términos is the largest estuary-lagoon in México, located at the southern extreme of the Gulf of México (18.5-18.8°N; 91.3-91.9°W) (Figure 2.1). The lagoon measures 2,500 km^2 with a maximum width of 75 km shore-parallel and a maximum breadth of 35 km shore-normal. The mean lagoon depth is 3.5 m and the maximum depth is 4.7 m. The lagoon is separated from the Gulf of México by Isla del Carmen, a 38 km long and 2.5 km wide Holocene calcareous-sand barrier island (Gutiérrez-Estrada and Castro del Rio 1988). These two ocean inlets are substantially deeper than the rest of the lagoon - the western inlet, Carmen Inlet, is 3.4 km wide and has a maximum depth of 17 m and the eastern inlet, Puerto Real Inlet, is 3.2 km wide and has a maximum depth of 12 m. Mixed, mainly diurnal tides with a mean range of 0.4 m force the lagoon through the two ocean inlets at each end of Isla del Carmen. Mean lagoon circulation intermittently changes from an east-to-west flow-through to behaving as two almost independent hydrological units with an oscillatory tidal pumping through each inlet. Gomez-Reyes *et al.* (1997) developed the original LOICZ budget for Laguna de Términos in terms of a counterclockwise gyre, with ocean inflow through the eastern pass and lagoonal outflow to the west. Because of variability in lagoonal circulation, the budgets presented here revert to the more standard LOICZ model of residual outflow of ‘average lagoon water’ and mixing exchange between the ocean and lagoon.

The Laguna de Términos region is characterised by three distinct seasons: a dry season, a wet season, and *nortes,* a windy season with weather fronts. The dry season usually lasts from March to May, the rainy season from June to October. Fronts from the north-west traverse the region throughout the year but the *nortes* season is said to dominate the system when 3 or more fronts occur within a single month. In a typical year, the *nortes* season lasts from November to February. During the *nortes* season, periods between fronts in November and December behave like the wet season while calm periods in January and February behave like the dry season. Therefore, whenever data are gathered to represent the rainy and dry season only, rainy season data are multiplied by 7 months while dry season data are multiplied by 5 months and the total is divided by 12 for an annual mean.

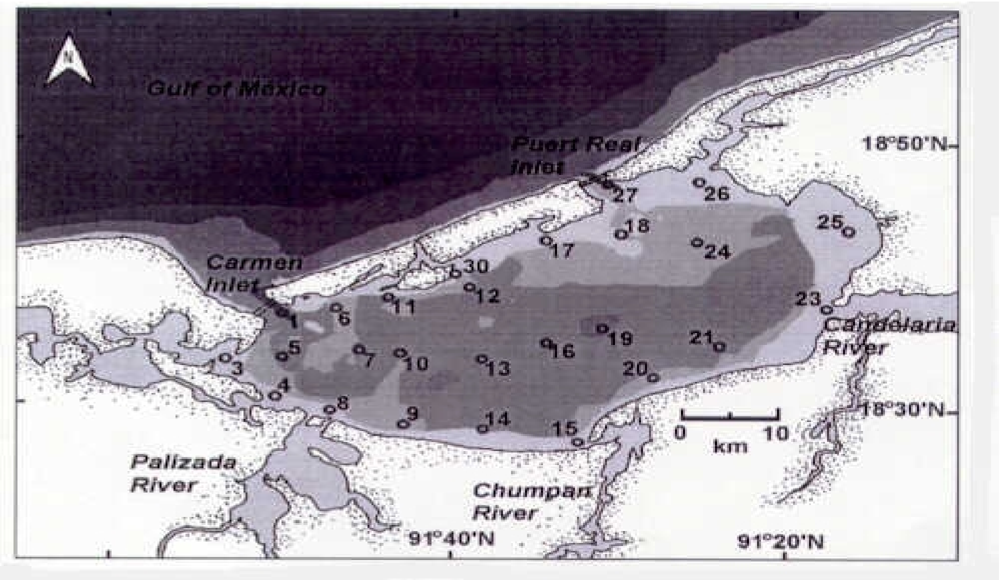

Figure 2.1. Laguna de Términos, Campeche, and the rivers that discharge into the lagoon.

Water and salt budgets

Three rivers provide most of the freshwater input to the lagoon (Yáñez-Arancibia and Sánchez-Gil 1983; EPOMEX 1993). The largest is the Palizada River, near the western extreme of the lagoon, with a mean discharge of $8.3\text{x}10^9$ m^3 yr^{-1} and a mean monthly variation from $3.6\text{x}10^9$ to $13.8\text{x}10^9$ m^3 yr^{-1} as gauged at Palizada Bridge 75 km upstream (CNDCRAA 1993). An estimate of the actual monthly discharge (q_T) from Palizada River into Laguna de Términos was calculated as the sum (q_T) of the gauged discharge at Palizada Bridge (q_M) and the computed surface runoff from the drainage basin between Palizada Bridge and the mouth of the Palizada River (q_R):

$$q_T = q_M + q_R$$

q_R is estimated based on a simple climatological model (Schreiber 1904), using the monthly rainfall (r in mm) and air temperature (T in K) measured at San Francisco Bridge (EPOMEX 1993), the area of the drainage basin between Palizada Bridge and the mouth of Palizada River (A_x in km^2), the calculated potential evapotranspiration (e_0 in mm), and the monthly runoff (Δf in mm) (Table 1):

$$q_R = A_x (\Delta f/r) (r/(8.64 D_i * 10^6))$$

$$e_0 = 1.0 * 10^9 \exp(-4.62*10^3/T)$$

$$\Delta f/r = \exp(-e^0/r)$$

where D_i is the number of days in the i^{th} month (Schreiber 1904; Sellers 1965; Holland 1978; Kjerfve 1990). On average, of the discharge from the Palizada q_R amounts to 8% of q_M. The combined results yield a mean discharge of $9.1\text{x}10^9$ m^3 yr^{-1} and a monthly discharge variation from $3.6\text{x}10^9$ to $16.1\text{x}10^9$ m^3 yr^{-1} for Palizada River, including the non-gauged area.

Discharges were similarly calculated for the Chumpán River, 30 km to the east of the mouth of the Palizada River, and the Candelaria-Mamantel rivers, located 32 km further north-east. Flow for the Chumpan River was measured 44 km upstream at Carretera Bridge, for the Candelaria River 92 km upstream at Ferroc Bridge, and for the Mamantel 32 km upstream at Mamantel Town. The calculations respectively yielded a mean discharge of 0.6×10^9, 1.5×10^9, and 0.16×10^9 m^3 yr^{-1} (Table 2.1). Thus, the combined mean freshwater runoff into Laguna de Términos is estimated to be 11.9×10^9 m^3 yr^{-1} from the three major river systems.

The average annual precipitation is measured to be 1,800 mm at Ciudad del Carmen (EPOMEX 1993), with interannual variability from 1,100 to 2,000 mm (Rojas-Galavís 1992). Therefore, direct rainfall averages 4.5×10^9 m^3 yr^{-1} for the entire lagoon. Pan evaporation measurements at Ciudad del Carmen (EPOMEX 1993) indicate an annual water loss of 1,500 mm resulting in a total loss of 3.8×10^9 m^3 yr^{-1} from the lagoon surface.

Table 2.1. Statistics for the rivers discharging into Laguna de Términos.

	Palizada	**Chumpan**	**Candelaria**	**Mamantel**
Total Drainage Basin area (km^2)	40,000*	2,000	7,160	540
% Gauged area	97	85	81	81
Adjusted Discharge:				
Mean (10^9 m^3 yr^{-1})	9.08	0.57	2.11	0.16
Minimum (10^9 m^3 yr^{-1})	3.63	0.01	0.64	0.07
Maximum (10^9 m^3 yr^{-1})	16.11	1.58	5.45	0.78
Average Drainage Basin Temp. (^{O}C)	27	25	27	27
Annual Drainage Basin Rainfall (mm)	1,844	1,602	1,457	1,517
$\Delta f/r$	0.24	0.23	0.18	0.27

* Including the entire Usumacinta drainage basin area.

Groundwater input (m^3 s^{-1}) along the coast was approximated using an equation derived from Darcy's Law (Shaw 1994):

$$Q_{approx} = -K [(h_2 - h_1)/d] L W$$

where h_1 and h_2 are the highest and lowest hydraulic head, respectively; d is the distance of a line through h_1 and h_2 perpendicular to the coastline; L is the length of the coastline; and W is the unit width of flow; all in metres. K is the hydraulic conductivity in m s^{-1} that range from 3.4×10^{-4} for silty sand to gravel to 6.5×10^{-4} for sand, gravel and silty sand. Using these two values as extreme ranges, the calculated groundwater input for Laguna de Terminos is 3×10^6 to 5×10^6 m^3 yr^{-1}. Thus the total approximated freshwater contribution from groundwater to Laguna de Terminos is only 0.03% of the total river input. The average is 4×10^6 m^3 yr^{-1}.

Ocean salinity is taken to be 36 psu. Initial calculations were made using 31 psu as the system salinity taken from salinities measured for 24 stations during all three seasons of 1994-1995 (David *et al*. in press). The author recognises, however, that representative samples for the wet season were taken during the middle of the season (the months of August and September) and not during the final months of the season when the lowest salinities were previously recorded by other researchers (Escanero-Figueroa 1983; Yanez-Arancibia *et al*. 1983). This undoubtedly has an effect on the calculation of the annual mean salinity of the system. It was therefore decided to use the concentration of 25 psu instead, taken from year-long monthly measurements made by Yanez-Arancibia *et al.* in 1980-81 and Escanero-Figueroa in 1982.

Figure 2.2 summarises the water and salt budgets. The freshwater inputs minus the evaporative output results in a net freshwater 12.6×10^9 m^3 $yr^{-1,}$used for further calculations. Residual outflow ($V_R = -V_{Q*}$) of this amount of water from the lagoon removes 384×10^9 psu m^3 yr^{-1} of salt. Mixing between the ocean and lagoon water (V_X) to balance the loss of salt due to residual flow is estimated to be 34.9×10^9 m^3 yr^{-1}. Water exchange rate ($\tau = V_{syst}/(V_X + |V_R|)$ rate is calculated to be about 2 months.

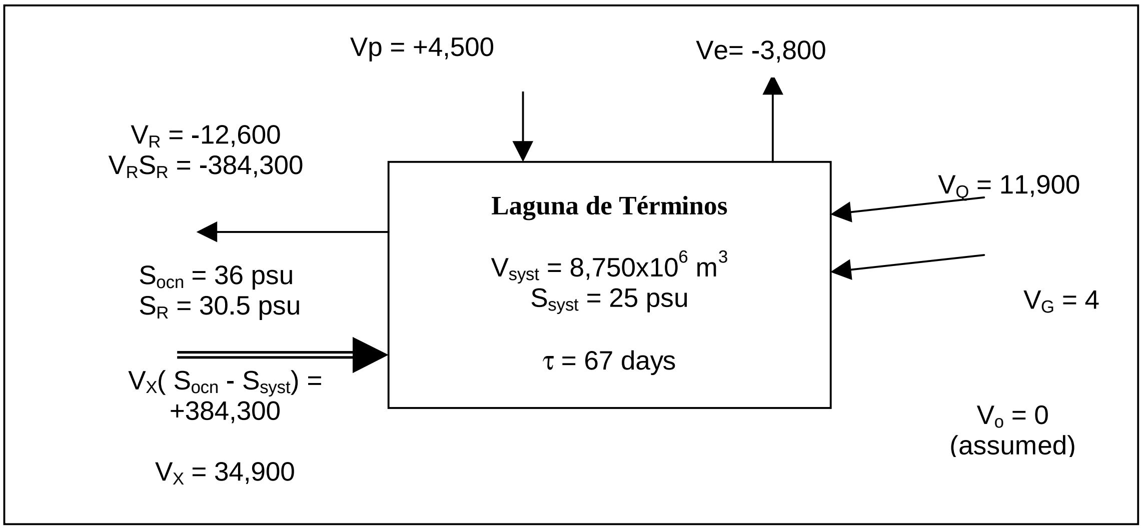

Figure 2.2. Water and salt balances in Términos Lagoon. Water fluxes in 10^6 m^3 $year^{-1}$ and salt fluxes in10^6 psu m^3 $year^{-1}$.

Budgets of nonconservative materials

The mass balance equations for the nonconservative materials explicitly identifies the different freshwater sources. Moreover, detailed mass balance equations were used whenever data were available to separate individual river contributions. Ocean concentration came from the work done by Vasquez-Guitierez *et al.* (1988). The biogeochemical flux is identified as ΔY, such that

$$\Delta Y = -V_R\, Y_{syst} - V_X\, Y_{ocn} - V_Q Y_Q - V_P Y_P - V_G Y_G$$

P balance

Phosphate concentrations for the river input (Figure 2.3) were measured in the Palizada River (Vera-Herrera and Rojas-Galaviz 1983), which accounts for about 75% of the river inflow; they are assumed to be similar for all the rivers. Groundwater concentrations were estimated to be near 0, since in general, DIP flux in groundwater flowing through carbonate terrain is known to be low. In any case, groundwater inflow is small. Calculated *ΔDIP* is $-5\text{x}10^6$ mol yr^{-1}, dramatically lower than the value of $-147\text{x}10^6$ mol yr^{-1} estimated by Gomez-Reyes *et al.* (1997). The discrepancy lies primarily in a much lower (and apparently more realistic) estimate of river DIP concentrations in the present report. There is effectively no net DIP flux between the ocean and lagoon, so the river input all appears to be trapped within the system.

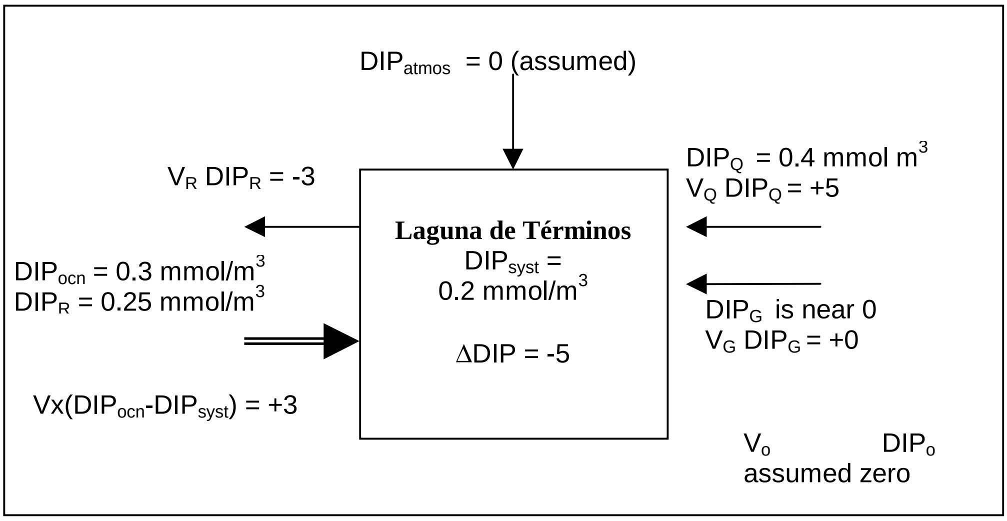

Figure 2.3. Términos Lagoon phosphate balance. Fluxes in 10^6 mol yr^{-1}.

N balance

Nitrate concentrations were individually calculated for each of the rivers (CNDCRAA 1993). The weighted average of 2 mmol m^{-3} is used for Figure 2.4. Ammonium concentration for the river input was approximately 32 mmol m^{-3} in the Palizada River (Vera-Herrera and Rojas-Galaviz 1983) and was assumed to be similar for all the rivers. Hence, total river DIN is 34 mmol m^{-3}. Groundwater concentrations were taken from a mean concentration for the Yucatan area (Herrera-Silveira *et al.* 1998). Net nonconservative DIN flux ($847\text{x}10^6$ mol yr^{-1}) which is nearly half the estimate of Gomez-Reyes *et al.* (1997) ($-1{,}426\text{x}10^6$ mol yr^{-1}). This discrepancy appears to be the result an apparent overestimation of river inflow of DIN in the earlier report. The present budget, however, estimates a substantially higher influx of oceanic DIN. This input is probably overestimated because of an unrealistically high value for oceanic DIN. However, reducing the net oceanic flux of DIN to be equal to the system DIN of 3 mmol m^{-3} would still lead to an estimate of a substantial DIN sink in the system.

Stoichiometric calculations of aspects of net system metabolism

Using the *ΔDIN* and *ΔDIP* estimates to calculate nitrogen fixation minus denitrification we have (*nfix-denit*) =*ΔDIN* –16**ΔDIP* = $-767\text{x}10^6$ mol N yr^{-1} which is equivalent to -0.3 mol N m^{-2} year^{-1} for the entire lagoon. This suggests that the system is denitrifying in excess of nitrogen fixation. This reverses the earlier conclusions of Gomez-Reyes *et al.* (1997). If ocean influx of DIN is reduced, the estimate of (*nfix-denit*) would approach 0.

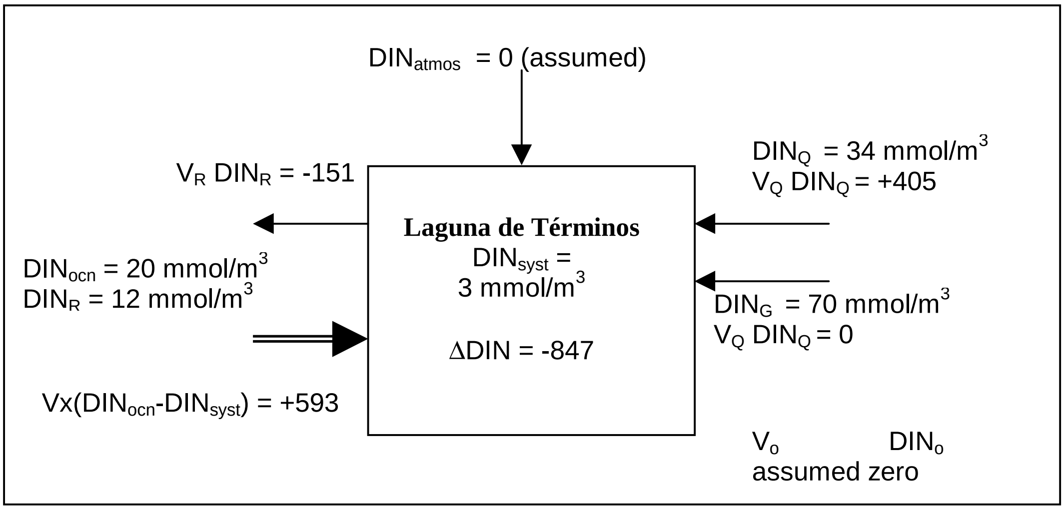

Figure 2.4. Terminos Lagoon dissolved inorganic nitrogen balance. Fluxes in 10^6 mol yr^{-1}.

The net ecosystem metabolism is calculated as $(p\text{-}r) = -106{*}\Delta DIP = +530\text{x}10^6$ mol C yr^{-1}, which is equivalent to +0.2 mol C m^{-2} yr^{-1} for the entire lagoon. This implies that the lagoon is net autotrophic by a very slight margin. The qualitative result is similar to that derived by Gomez-Reyes *et al.* (1997), but the rate is much lower than previously estimated.

Seasonality

The seasonal variability of the lagoon circulation prompted calculation of the seasonal budget. In general, the seasonal budget mirrored that of the net annual budget with no effective DIP flux between the ocean and the lagoon, and with Terminos a substantial DIN sink. The interesting difference is in the calculation of the water exchange rate. Calculating using the annual means gave an exchange rate of 67 days, whereas calculating for each season and then averaging the results gave an exchange rate of 86 days. Moreover, the seasonal calculations for the water and salt budgets suggest that the lagoon behaves similarly during the *nortes* season and the wet

Table 2.2. Seasonal salt and water budget

	Wet	**Dry**	**Nortes**
	(June-October)	(March-May)	(November-February)
V_Q (10^6 m^3 yr^{-1})	16,900	5,000	10,900
V_P (10^6 m^3 yr^{-1})	7,000	2,300	3,000
V_G (10^6 m^3 yr^{-1})	4	4	4
V_E (10^6 m^3 yr^{-1})	4,400	4,200	2,600
S_{SYS} (10^6 psu m^3 yr^{-1})	19	30	28
S_{OCN} (10^6 psu m^3 yr^{-1})	36	36	36
S_R (10^6 psu m^3 yr^{-1})	27.5	33	32
V_R (10^6 m^3 yr^{-1})	-19,500	-3,100	-11,300
V_X (10^6 m^3 yr^{-1})	31,500	17,000	45,200
τ (days)	63	159	56

season. Therefore, when seasonal data was only available for the wet and dry season, the *nortes* portion was designated to be similar to the wet season. The only exception is in the oceanic values where data were obtained during January and September (Vasquez-Guitierrez *et al*. 1988). In this instance, January data was assigned to represent both the *nortes* and the dry season. Table 2.2 summarises the water and salt budgets for the three seasons while Table 2.3 summarises the phosphate and nitrate budgets, respectively. System volume is given as 8,750x10^6 m^3.

During all three seasons the system is denitrifying in excess of nitrogen fixation. Calculation of the net ecosystem metabolism implies that the lagoon remains to be net autotrophic, with values near 0 during the *nortes* season. Table 2.4 summarises the stoichiometric calculations of aspects of net system metabolism.

Table 2.3. Seasonal budget for nonconservative materials

	Wet	**Dry**	**Nortes**
	(June-October)	(March-May)	(November-February)
DIP_Q (mmol m^{-3})	0.6	0.3	0.4
DIP_{SYS} (mmol m^{-3})	0.3	0.1	0.3
DIP_{OCN} (mmol m^{-3})	0.4	0.3	0.3
DIP_R (mmol m^{-3})	0.35	0.2	0.3
ΔDIP (10^6 mol yr^{-1})	-6	-3	-1
DIN_Q (mmol m^{-3})	23	23	55
DIN_{SYS} (mmol m^{-3})	2	5	2
DIN_{OCN} (mmol m^{-3})	12	26	26
DIN_R (mmol m^{-3})	7	16	14
ΔDIN (10^6 mol yr^{-1})	-567	-422	-1,527

Table 2.4. Calculated stoichiometry of fluxes based on seasonal data

	Wet	**Dry**	**Nortes**
	(June-October)	(March-May)	(November-February)
(nfix-denit)			
(10^6 mol N yr^{-1})	-471	-374	-1,526
(mmol m^{-2} yr^{-1})	-0.19	-0.14	-0.61
(p-r)			
(10^6 mol N yr^{-1})	+636	+318	+106
(mmol m^{-2} yr^{-1})	+0.3	+0.1	+0.0

2.1.2 Bahía de Chetumal, Quintana Roo

Teresa Alvarez Legorreta

<u>*Study area description*</u>

Chetumal Bay (Figure 2.5) is located in the extreme south-east of the state of Quintana Roo, on the Yucatan Peninsula (approximately 18.6°N, 88.1°W). It is approximately 67 km long, 20 km wide and has an area of about 1,100 km^2 (volume approximately $3.5x10^9$ m^3). The mouth that communicates with the sea is located at the south-east end of the lagoon, and the Rio Hondo, which runs along the border between Belize and Mexico from its origins in the highlands of Guatemala, discharges into the lagoon. This river has a flow of about 220 m^3 s^{-1} during the rainy season and 20 m^3 s^{-1} during the dry season.

The waters of the Rio Hondo, the inundated region that it flows into and the small freshwater and marine springs all have estuarine characteristics in that the salinity averages 14 psu (Gasca *et al.* 1994). Productivity of the system is low (Gasca and Castellanos 1993). Water movements are determined primarily by winds coming from the east and south-east, with an annual average speed of 3 m s^{-1}.

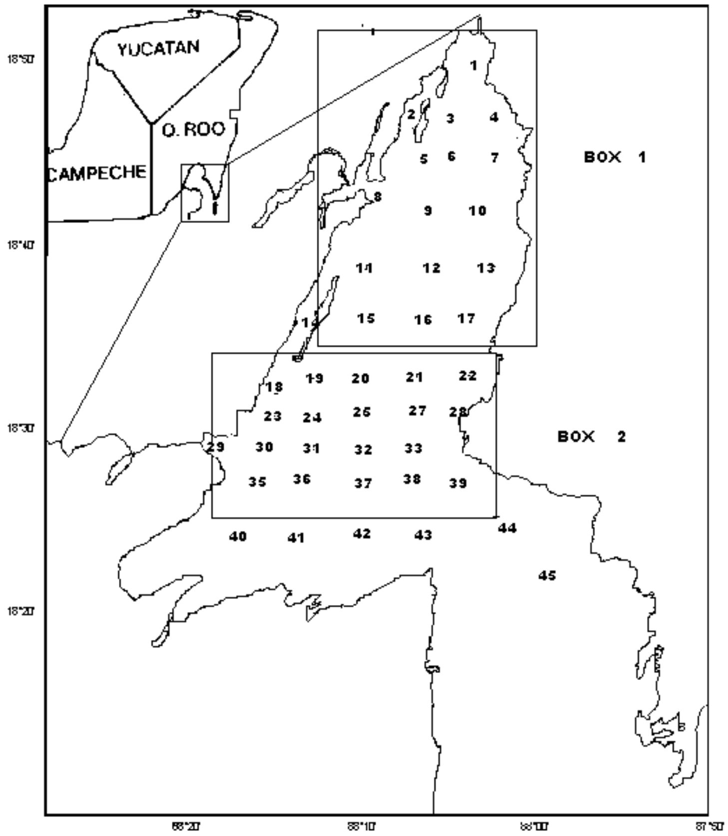

Figure 2.5. Map of Chetumal Bay, locations of sampling stations and the two boxes used in the budget analysis.

Water and salt budgets

In order to calculate the water and salt budgets for the rainy season in Chetumal Bay, salinity data from 43 stations throughout the system were used. The northern portion of the Bay was divided in two subsystems or boxes, with the area south of the southern system being treated as the 'ocean end-member'. The decision to use two boxes, rather than one, is made on the basis that there is a substantial salinity gradient between those two boxes. The northern box has an area of about 600 km^2 and a mean depth of 2.5 m; the southern box has an area of about 220 km^2 and a mean depth of 4 m. Consequently, these two boxes comprise about 75% of the bay area.

Evaporation and rainfall estimates are based on data for the months immediately prior to the sampling. During that period, the two terms were equal (6.8 mm d^{-1}), so $V_P - V_E = 0$. The main source of freshwater to the bay is the Rio Hondo ($V_Q \approx 20 \times 10^6$ m^3 d^{-1}). This inflow enters the southern box. Groundwater discharge is not quantified but is likely to be important. However, the estimate by Hanshaw and Back (1980) for the northern portion of the Yucatan Peninsula (8.6×10^6 m^3 km^{-1} yr^{-1}) is used to estimate that the daily discharge to the Bay is approximately 1×10^6 m^3 d^{-1}. It is known that the discharge around the Peninsula is not uniformly distributed. Because there are known sinkholes (*cenotes*) discharging into the northern box, all of the groundwater discharge is assigned to that box. It is obvious by inspection of these data and Figure 2.6, that groundwater discharge of this approximate magnitude in the southern box would, in any case, be minor in the water budget, while this discharge may be important in the northern box. The discharge of wastewater is small ($V_O = 0.2 \times 10^3$ m^3 d^{-1}) and is ignored in the water budget. It will eventually be important to include the wastewater discharge of nutrients in this system.

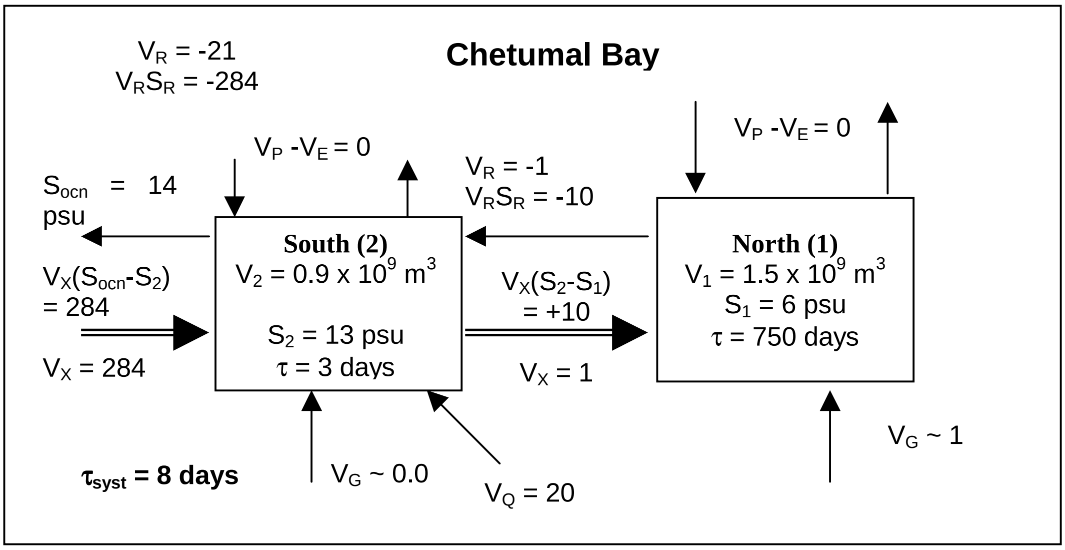

Figure 2. Water and salt budget for Chetumal Bay. Water fluxes in 10^6 m^3 d^{-1}; salt fluxes in 10^6 psu m^3 d^{-1}.

Water exchange calculated for the northern box (τ = 750 days) is unreasonably high. This may reflect reflect a substantial underestimate of groundwater inflow. Alternatively, a substantial portion of the river inflow may move along the western shore of the bay, northward into the northern box. Such a flow would not be properly represented in the water budget of the northern box. The balance for the two boxes combined is probably reasonably represented by the model and would not be greatly altered by substantially higher groundwater flow. The exchange time for the southern box (τ = 2 d) seems somewhat more reasonable. The calculated exchange time for the combined boxes is about 8 days.

Budgets of nonconservative materials

At this point, insufficient information is available to budget the fluxes of dissolved N and P in Chetumal Bay. It is hoped that, over the next year or so, such a budget will be feasible.

2.2 YUCATAN GROUNDWATER-INFLUENCED SYSTEMS

2.2.1 Laguna De Celestún, Yucatán

Jorge A. Herrera-Silveira, Luis Troccoli Ghinaglia, Javier Ramírez Ramírez and Arturo Zaldivar Jimenez

Study area description

The Celestún Lagoon is a long (21 km), narrow (0.5-2.4 km) and shallow (0.5-3 m) coastal lagoon located parallel to the coastline on the western shore of Yucatan Peninsula (20.75°N, 90.25°W) (Figure 2.7). Communication with the sea is through a mouth in the southern zone, 400 m wide. The bottom is flat; the tidal channel, a major topographic feature, is only about 20 m wide and extends from the mouth of the lagoon to 12 km beyond the mouth. The surface area is 28×10^6 m^2 and the volume is 34×10^6 m^3.

Soil in the region is karstic and highly permeable, and there are no rivers. Freshwater inputs to the lagoon occur mostly as groundwater discharges in springs, largely near the head of the lagoon. The weather in the region is hot and semiarid. Annual mean temperature is 26°C, varying from 20°C in January to 35°C in May. The mean annual rainfall is 750 mm and the evaporation rate is 1,400 mm. In this zone, two main seasons are recognised: the dry season with low rainfall (March-May, 0-50 mm), and the rainy season (June-October; >500 mm). Futhermore in this part of the Gulf of Mexico the period from November to February is known locally as the *nortes* season and is characterised by strong winds (>80 km/h), little rainfall (20-60 mm) and low temperatures (<22°C), imposed by low pressure air masses from the north. The annual rainfall-evaporation balance is negative, but is small relative to estimated groundwater flow (Herrera-Silveira 1994a).

The shores of the lagoon are covered by mangrove vegetation *(Rhizophora mangle, Avicennia germinans, Langucularia racemosa, Conocarpus erectus*). The shoreline shows a sinuous shape. Macrophyte vegetation is composed of *Chara fibrosa, Batophora oesterdi, Chaetomorpha linum, Ruppia* sp., and the shoal grass *Halodule wrightii* (Herrera-Silveira 1994b).

The spatial characterisation carried out with hydrological variables (Herrera-Silveira 1994a) indicate that the lagoon can be divided in three zones:

- Inner zone, strongly influenced by the groundwater discharges.
- Middle zone, where the mix of freshwater and seawater is evident.
- Seaward zone, where the interchange with the ocean takes place.

With this spatial and seasonal pattern, the water, salt and nutrient budgets were carried out. The data available comes from a survey carried out in 1994 with monthly samples from ten stations along the lagoon (Figure 2.7). Mean characteristics of each zone and for each season are summarised in the Table 1.

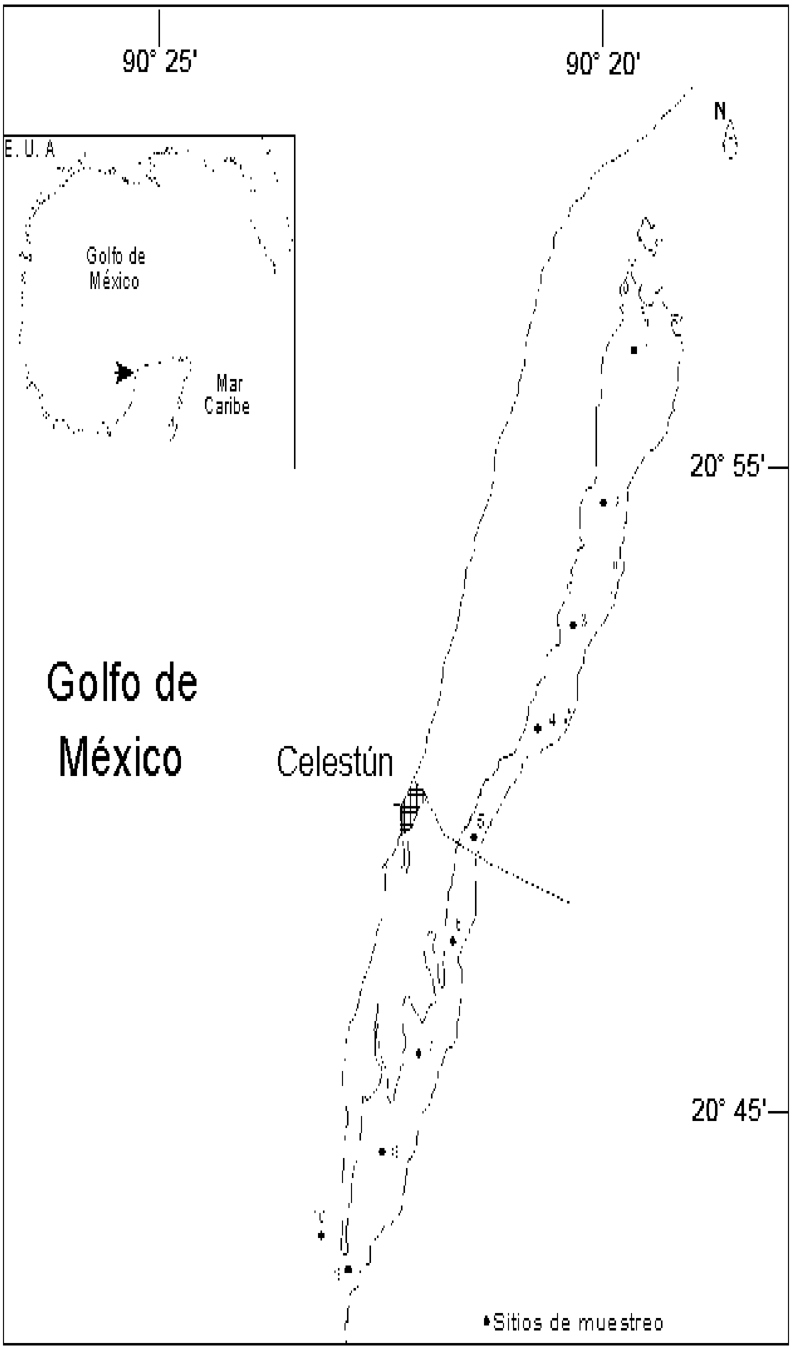

Figure 2.7. Map of Celestún Lagoon, showing sampling locations.

Table 2.5. Chemical composition of Celestún Lagoon.

	Ocean	Outer	Middle	Inner	Groundwater
Area (10^6 m^2)		9	8	11	
Volume (10^6 m^3)		10	10	13	
Dry Season					
Salinity (psu)	37.7	35.9	26.4	20.9	10
DIN (µM)	8.4	8.6	15.5	7.8	25
Phosphate (µM)	0.02	0.02	0.03	0.04	0.02
Silicate (µM)	10	35	62	106	190
Rainy Season					
Salinity (psu)	32.7	30.3	20.1	15.5	2
DIN (µM)	9.9	12.8	27.2	37.5	97
Phosphate (µM)	0.01	0.01	0.26	0.07	0.05
Silicate (µM)	8	37	88	130	320
Nortes Season					
Salinity (psu)	36.6	33.9	31.4	17.6	12
DIN (µM)	6.9	9.5	20.5	26.9	15.5
Phosphate (µM)	0.05	0.05	0.27	3.7	0.03
Silicate (µM)	10	42	47	61	190

Water and salt budgets

Figure 2.8 illustrates the water and salt budgets with seasonal trends for each zone of the system. Groundwater flow is calculated according to the equations in Appendix II. The calculations are made for flux at the mouth of the system (using measured groundwater salinity and silicate for each season). All of the groundwater flow is assigned to the inner box, because that is the only known groundwater input to the system. Calculations are not made for the individual boxes, because estimated groundwater fluxes are unstable for those boxes (see Appendix II discussion). According to the salinity-silicate calculations, both the wet and dry seasons have rather similar groundwater fluxes, while the *nortes* season appears to have substantially higher flux. While this pattern is possible, it may also reflect uncertainty in the individual groundwater calculations. Of the three sets of calculations, the *nortes* calculations are apparently the least stable. Nevertheless, we use the seasonal data as calculated. The estimated annual total groundwater flux is $72x10^6$ m^3. Expressed per length of the lagoon (21 km), this is approximately $3.4x10^6$ m^3 km^{-1} yr^{-1}. This is about 40% of the flow rate per km estimated by Hanshaw and Back (1980) for the entire northern portion of the Peninsula. Rainfall and evaporation are apparently small fluxes in comparison to groundwater flow.

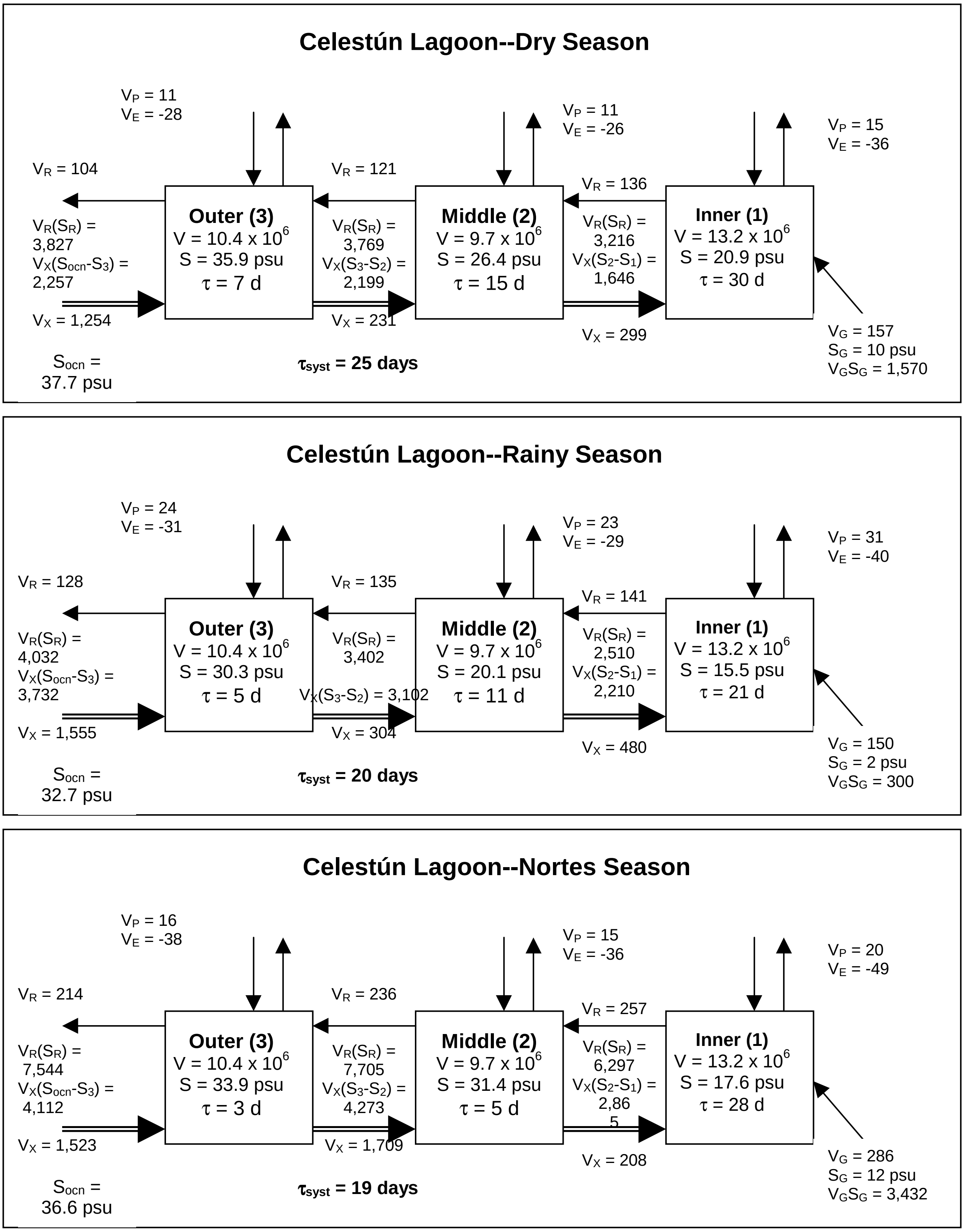

Figure 2.8. Water and salt budgets for the three subsystems of Celestún Lagoon, for the three hydrological seasons. Water fluxes in 10^3 m^3 d^{-1}; salt fluxes in 10^3 psu m^3 d^{-1}. The arrows indicate the direction of the fluxes; in the case of the mixing arrows, the directions indicated are the directions of net salt flux.

Water exchange times for the entire system are near three weeks for each season, with much shorter exchange times in the middle and outer boxes.

Budgets of nonconservative materials

Figures 2.9 and 2.10 illustrate the budgets of DIP and DIN in the system, by season and in the three regions of the lagoon. Because of rapid exchanges between the sectors, the whole system budgets (nonconservative fluxes shown in bold letter at the bottom of each diagram) are considered more reliable than the individual subsystem budgets. Nevertheless, as discussed by Webster *et al*. (1999), strongly 1-dimensional systems with longitudinal gradients are best budgeted in sectors.

P balance

Celestún lagoon shows a seasonal variability in ΔDIP. During both the dry season and the *nortes* season, ΔDIP is effectively 0, whereas during the wet season, the system appears to be a net DIP source. Weighting each of these seasonal budgets by the lengths of the seasons (dry, wet and *nortes* are 3 months, 5 months, and 4 months respectively), the annual average ΔDIP is +16 mol d^{-1}. Over the lagoon area of 28 km^2, this is equivalent to a rate of +0.2 mmol m^{-2} yr^{-1}. This is an extremely slow rate of DIP production - effectively 0.

N balance

The system is consistently a net sink for DIN, apparently with substantial seasonal variability in the proportion of groundwater DIN that is taken up. Of course the calculated ΔDIN is rather sensitive to the estimate of groundwater flux, as evident in Figure 2.10. The annual average ΔDIN is -4,700 mol d^{-1}, or -60 mmol m^{-2} yr^{-1}. While this is a relatively low rate, the consistent negative ΔDIN for each season suggests that this uptake is significant.

Stoichiometric calculations of aspects of net system metabolism

Stoichiometric estimates can be based on the molar C:N:P ratio of material likely to be reacting in the system. We assume that this material is plankton, with a Redfield C:N:P molar ratio of 106:16:1.

An estimate of nitrogen fixation minus denitrification (*nfix-denit*) is established as the difference between observed and expected ΔDIN, where the expected ΔDIN is ΔDIP multiplied by the Redfield N:P ratio of 16. ΔDIN_{exp} = 16 x (+0.2 mmol m^{-2} yr^{-1}) = +3 mmol m^{-2} yr^{-1}. The observed ΔDIN is -60 mmol m^{-2} yr^{-1}, so (*nfix-denit*) is -63 mmol m^{-2} yr^{-1}. This is a relatively modest rate of net denitrification.

Net ecosystem metabolism (*p-r*) is estimated as -106 x ΔDIP. This rate is -20 mmol m^{-2} yr^{-1} - effectively 0.

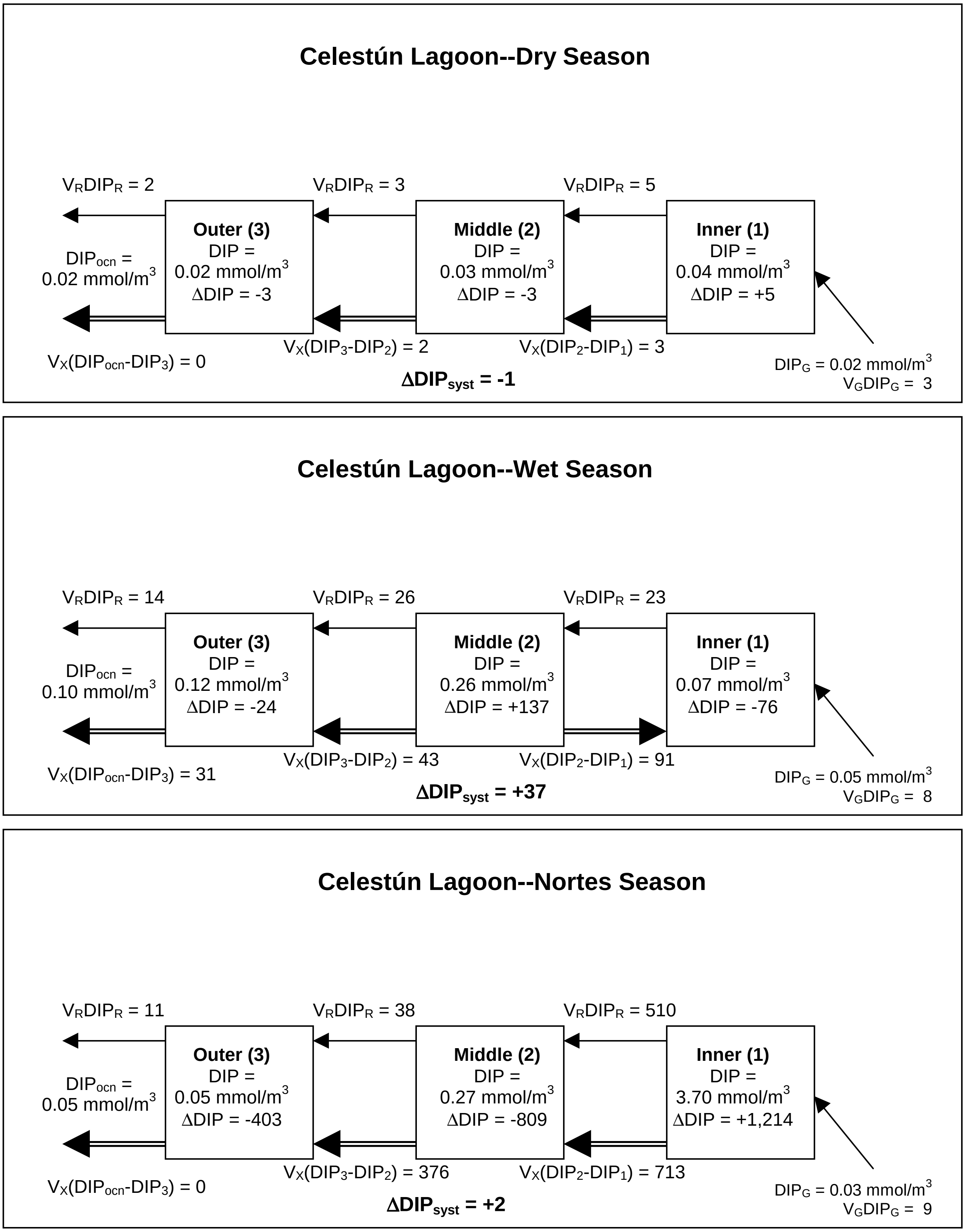

Figure 2.9. DIP budgets for the three subsystems of Celestún Lagoon, for the three hydrological seasons. Fluxes in mol d^{-1}. The arrows indicate the direction of the fluxes.

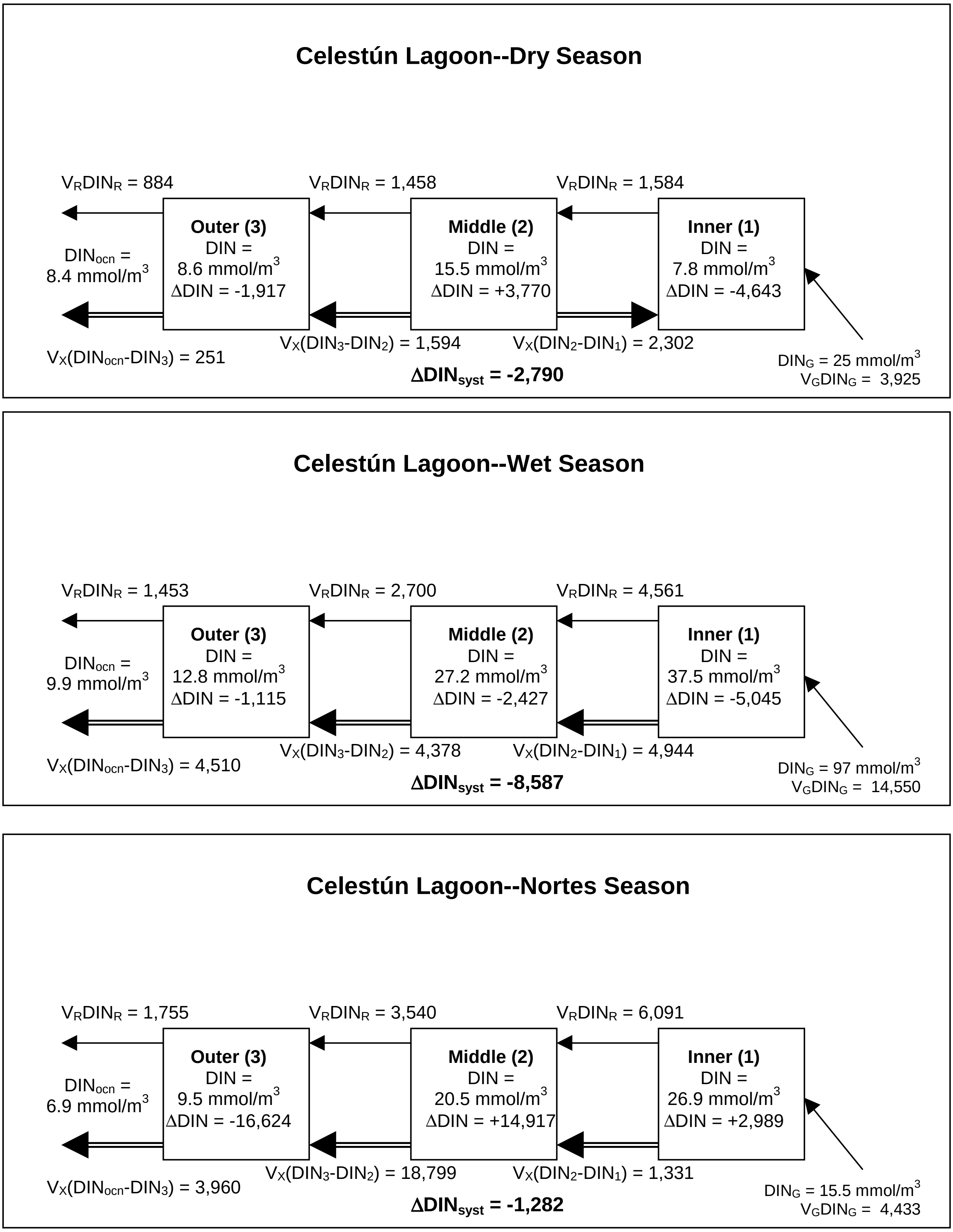

Figure 2.10. DIN budgets for the three subsystems of Celestún Lagoon, for the three hydrological seasons. Fluxes in mol d^{-1}. The arrows indicate the direction of the fluxes.

2.2.2 Chelem Lagoon, Yucatán, Mexico

David Valdes

Study area description

Chelem lagoon, located on the Gulf of Mexico coast of Yucatan Peninsula (21.27°N; 89.7°W), is a typical tropical barrier island lagoon Class of III-A in Lankford's classification (Lankford 1977) (Figure 2.11). The average annual air temperature is between 24 and 26°C, precipitation 400 mm yr^{-1}, evaporation between 1,400 and 2,300 mm yr^{-1}, with the maximum occurring between April and June (Secretaria de Programacion y Presupuesto, Estados Unidos Mexicanos 1981). The hydrology of lagoon (Valdes 1995, Valdes and Real 1998) is result of the low precipitation, high evaporation and low fresh groundwater discharges that is related to the Cretaceous geological history of the region (Marin *et al.* 1990, Perry *et al*. 1995, Hildebrand *et al*. 1995). It was a hypersaline body of water with intermittent communication with the open sea through two natural mouths until 1969, when an artificial channel was opened for the construction of Yukalpeten Harbor. This considerably increased lagoonal interaction with open waters. The tide is diurnal, with a range of 0.6 m, surface area of 15 km^2 and depths between 0.5-1.0 m except in the port, where dredging deepened it to 3.0 m. In the central and eastern zones there are patches of sea-grass *Halodule wrightii*, the western part with red algae *Eucheuma* sp., while the sides not altered by human activities are covered by mangrove patches dominated by *Avicennia germinans* with *Rhizophora mangle* also present. Urban and industrial developments around and through the lagoon have seriously affected circulation and water quality (Morales 1987). Bottom sediments showed the existence of nutrient recycling sites for the water column (Valdes and Real 1994). The whole region is of karstic nature. The above processes generate considerable temporal and spatial variations in salinity, nutrients and suspended solids in water.

Chelem Lagoon can be divided into three systems separated by the roads that cross this coastal water body. System 1 (the eastern zone) is from the Merida-Progresso road to the east, and has an area of 0.4 km^2, depth 1 m, volume 0.4×10^6 m^3. System 2 (the central zone, with communication with the ocean) is between the Merida-Chelem road and the Merida-Progresso road: area 4.8 km^2, depth1 m, volume 4.8×10^6 m^3. System 3 (the western zone) is from the Merida-Chelem road to the west: area 10.0 km^2, depth 1 m, volume 10.0×10^6 m^3. The systems communicate, as the roads have bridges that permit water exchange.

Sixteen stations along the Chelem Lagoon were sampled from January 1988 to October 1992, every month except the following: Dec.'88, Dec.'89, March '90, April '90, July '90, Oct.'90, March '91, Oct.'91, Jan.'92 and Aug.'92; a total of 48 sets of data. Table 2.6 summarises means for various properties in the three subsystems, as well as at the mouth and in the coastal ocean.

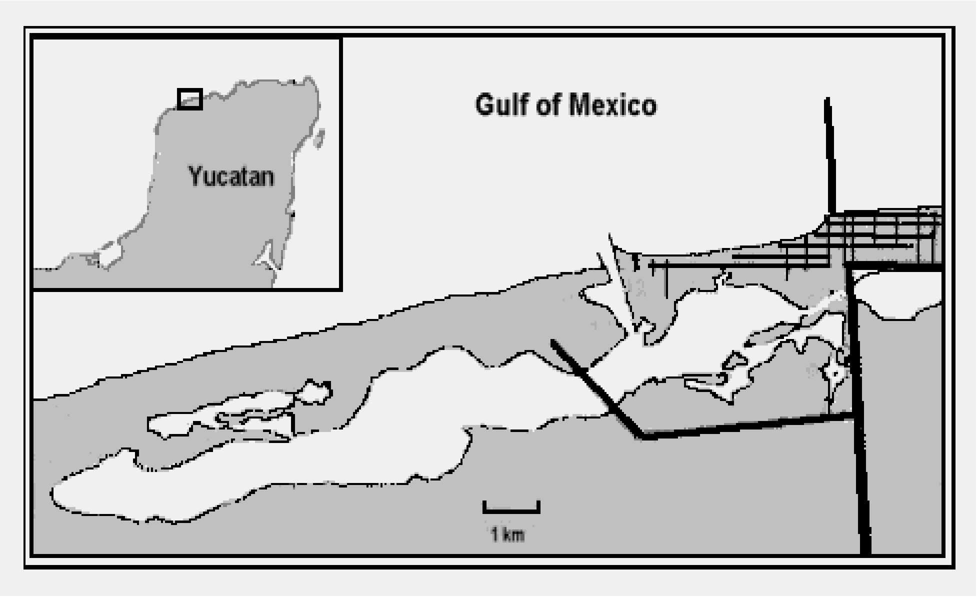

Figure 2.11. Chelem Lagoon. The heavy dark lines represent roads and bridges, while the grid in the northeast corner of the map is the city of Progresso.

Table 2.6. Mean concentrations of properties in the three subsystems of Chelem Lagoon, as well as in the coastal ocean and at the lagoon mouth over 1988-1992 period.

Property	**Ocean**	**System 1**	**System 2**	**System 3**
Salinity (psu)	37.32	43.26	36.60	37.04
Ammonium (µM)	4.4	10.4	7.2	9.9
Nitrate (µM)	1.7	3.9	2.6	3.4
Phosphate (µM)	0.44	1.05	0.56	0.60
Silicate (µM)	4.6	81.3	45.8	56.7
Total alkalinity (meq/l)	3.0	5.2	3.57	3.79
Calcium (mM)	10.7	10.6	10.51	10.51
POM (mg/l)	2.0	27.4	6.7	4.4
PON (µg/l)	30	432	65	44

Salt and water budgets

The lagoon is in a karstic region; surface rivers do not exist in this particular region and groundwater flow is very localised. Direct precipitation is about 400 mm yr^{-1} (40 years mean at Progresso City, beside the lagoon), while evaporation is estimated to be 2,000 mm yr^{-1}.

Equation (5) of Appendix II can be used to estimate groundwater flow from the combined salinity and silicate data. The equation has been solved using groundwater salinity to be 2 psu and silicate concentration to be 200 µM, although sensitivity analyses demonstrated that the estimated groundwater flow changed little over a range of 0-5 psu salinity and 100-250 µM silicate. The calculation therefore seems fairly robust in this system. The equation was solved for sub-systems 1 and 3, using sub-system 2 as the 'ocean end member', and then solved for the whole lagoon, by evaluating exchange between the ocean and sub-system 2. Groundwater flux into sub-system 2 was then obtained by difference between the whole-lagoon estimate and the other two sub-systems. Resultant groundwater flow, shown on Figure 2.12, is 0.3, 13.9 and $13.5\text{x}10^6$ m^3 yr^{-1} into subsystems 1-3 respectively, for a total of approximately $28\text{x}10^6$ m^3 yr^{-1}. If we take the lagoon length to be approximately 20 km, then the groundwater flow to the coast in this region is estimated to be about $0.9\text{x}10^6$ m^3 km^{-1} yr^{-1}. This number is interesting. It is only about 15% of the flow of $8.6\text{x}10^6$ m^3 km^{-1} yr^{-1} estimated by Hanshaw and Back (1980) for the northern part of the Yucatan Peninsula, confirming the view that groundwater flow in this region is relatively low. Nevertheless, groundwater flow into this system actually exceeds the difference between rainfall and evaporation (~$24\text{x}10^6$ m^3 yr^{-1}).

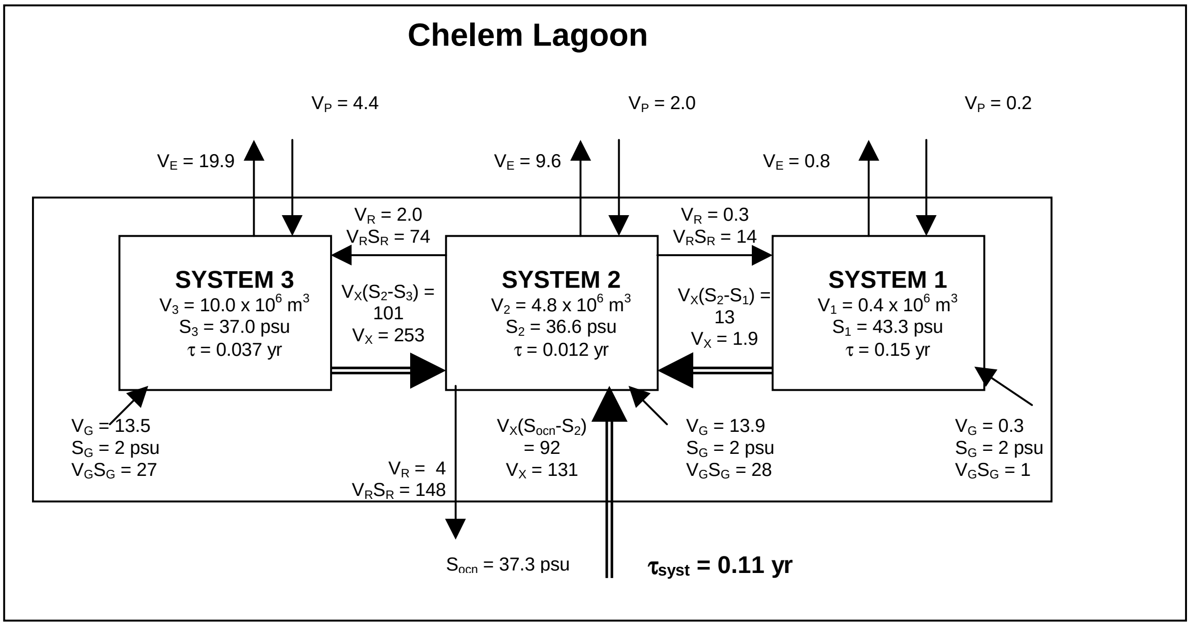

Figure 2.12. Water and salt budgets for the three subsystems of Chelem Lagoon. Water fluxes in 10^6 m^3 yr^{-1}; salt fluxes in 10^6 psu m^3 yr^{-1}. The arrows indicate the direction of the fluxes; in the case of the mixing arrows, the directions indicated are the directions of net salt flux.

Budgets of nonconservative materials

The budgets of nonconservative fluxes for DIP and DIN are shown in Figure 3. Estimates of nutrient concentrations in the groundwater are taken from a summary paper about various water bodies on the northern portion of the Yucatan Peninsula by Herrera-Silveira *et al.* (1998). It is further assumed that about 10% of the 40,000 people living in the city of Progresso may discharge domestic wastes into this lagoon. Based on tabulated estimates of per capita DIP and DIN loading, we approximate these discharges of other materials (V_ODIP_O, V_ODIN_O) as approximately 30 000 mol DIP yr^{-1} and 800 000 mol DIN yr^{-1}. Further, it is assumed that this material enters the eastern box, near the city of Progresso.

P balance
ΔDIP for Chelem Lagoon is -56×10^3 mol yr^{-1}, equivalent to about -4 mmol m^{-2} yr^{-1}. Most of the uptake appears to occur in the eastern subsystem, which receives some waste input from Progresso. The estimate of that input is uncertain, but it appears that little of the waste DIP is likely to escape this subsystem. Note also that the nominal concentration used for groundwater is the average value from Herrera-Silveira *et al.* (1998). That estimate could also be low, and of course the waste discharge might actually reach the system via groundwater.

N balance
Figure 2.13 demonstrates that Δ*DIN* for this system is about -2,222x10^3 mol yr^{-1}, equivalent to about -146 mmol m^{-2} yr^{-1}. As with Δ*DIP*, these numbers are somewhat uncertain due to the uncertain sewage load as well as the composition of groundwater, which appears to be a significant DIN source to the system. It appears likely that well over half of the terrigenous DIN addition to this system is taken up.

Stoichiometric calculations of aspects of net system metabolism
The rates of nonconservative DIP and DIN flux can be used to estimate the apparent rates of nitrogen fixation minus denitrification (*nfix-denit*) and primary production minus respiration (*p-r*) in this system.

The rate (*nfix-denit*) is calculated as the difference between observed and expected Δ*DIN*, where ΔDIN_{exp} is Δ*DIP* multiplied by the N:P ratio of organic matter which might be reacting in the system. If this material has a composition near that of plankton (16:1), then ΔDIN_{exp} is 16 x (-56x10^3) mol yr^{-1}, or -896x10^3 mol yr^{-1}. Observed Δ*DIN* is -2,222x10^3 mol yr^{-1}, so (*nfix-denit)* is estimated to be -1,326x10^3 mol yr^{-1}. This is equivalent to a net denitrification rate of about 87 mmol m^{-2} yr^{-1}. By comparison, laboratory incubations have yielded an estimated denitrification rate of 43 mmol m^{-2} yr^{-1} (Valdes 1995, Valdes and Real 1994) in this system. This is a relatively modest rate of net denitrification, and the agreement between the laboratory data and budgetary calculations is encouraging.

Net organic metabolism, or (*p-r*), is calculated on the assumption that Δ*DIP* is dominated by decomposition of organic matter. Δ*DIP* multiplied by the C:P ratio of the reacting organic matter becomes an estimate of (*p-r*). If the reacting organic matter has a composition near that of plankton, then (*p-r*) = -106 x (-56x10^3) mol yr^{-1} = +5.9x10^6 mol yr^{-1} = +0.0.39 mol m^{-2} yr^{-1}. The system appears to be slightly net autotrophic.

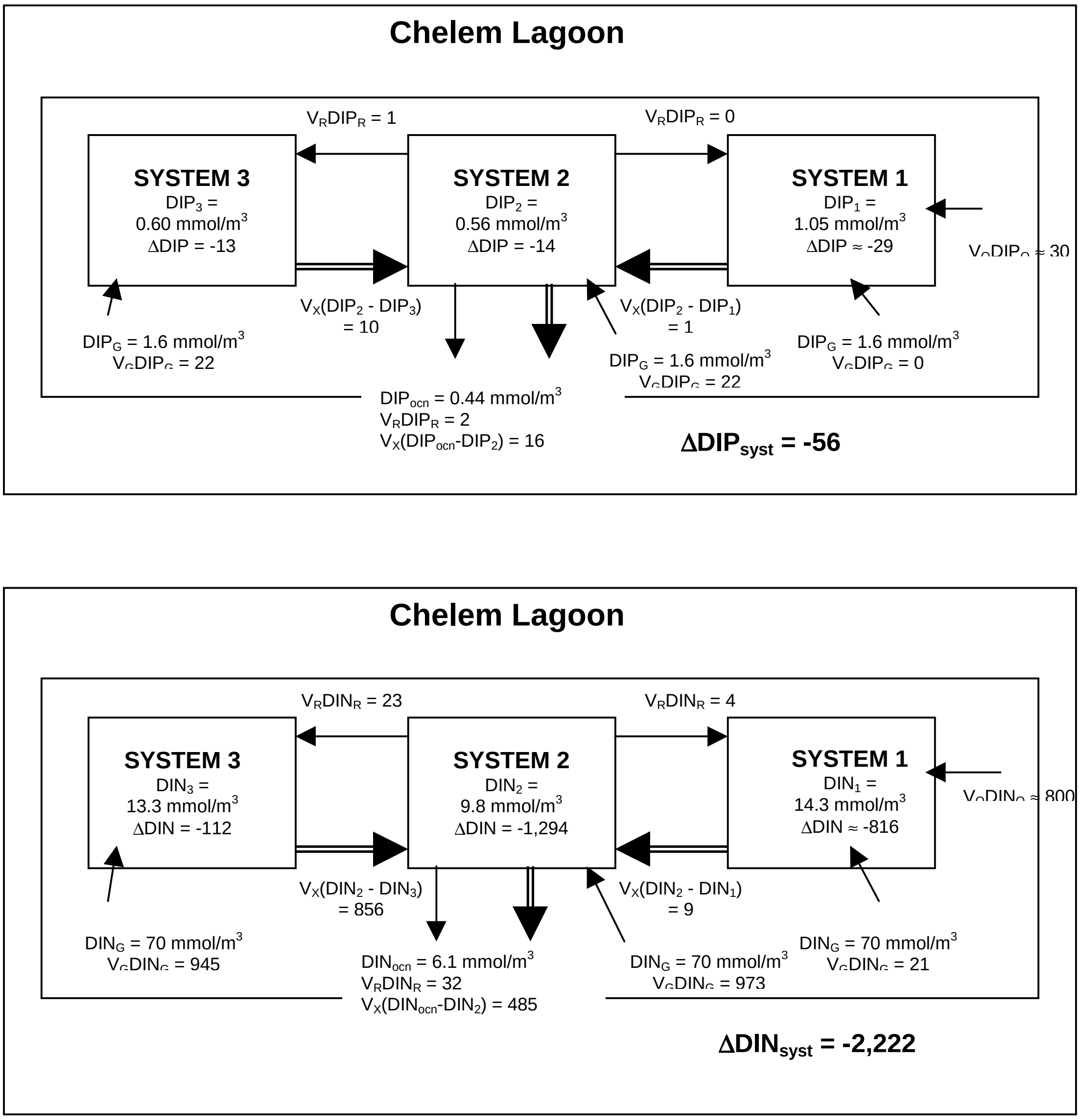

Figure 2.13. DIP and DIN budgets for Chelem Lagoon. Fluxes in 10^3 mol yr^{-1}. Note that the arrows indicate the direction of material fluxes between boxes.

2.2.3 Ría Lagartos Lagoon, Yucatan

David Valdes

<u>Study area description</u>

Ria Lagartos coastal lagoon, on the northern coast of the Yucatan Peninsula in the Gulf of Mexico (Figure 2.14) (22.58°N; 87.03°W), is under pressure from several human activities (stock-breeding, salt extraction, craft fisheries) as well as natural processes. These, combined with the climate (low precipitation, high evaporation) and the geology (karstic region), make it susceptible to marked eutrophication, due to elevated levels of nitrogen and phosphorus responsible for primary production, and consequent negative effects such as anoxic conditions in the water column (Justic *et al.* 1995). The lagoon is very shallow (0.5-1.0 m), 80 km long, and 94 km^2 surface area. In the western zone, the lagoon has three permanent mouths (one natural and two artificial) that permit exchange of water with the Gulf of Mexico.

The lagoon can be divided into four basins or subsystems: 1) San Felipe, the western zone, near the mouths, influenced by two fishing villages and groundwater springs (we do not have data of the flow of freshwater in these springs); 2) Coloradas basin, a wide zone, with macrophytes in the bottom, high salinity and many man-made transformations (e.g., evaporation ponds for the industrial extraction of salt); 3) El Cuyo basin, the second widest zone of the lagoon, with still higher salinity and microbial paths in the bottom; and 4) Flamingos basin, a semi-isolated zone of the lagoon (by the road that crosses to El Cuyo town) with the highest salinity levels and much suspended organic matter.

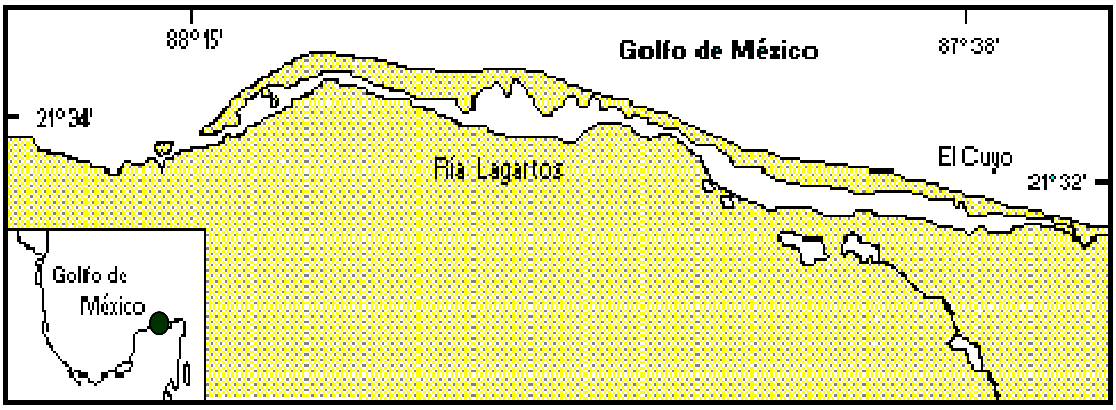

Figure 2.14. Generalised map of Ria Lagartos Lagoon.

Data are available from lagoonal samples (water and sediment) 3 times over a year (every 4 months), at 30 locations. We also have 24-hour measurements of water flux, salinity and nutrients at the mouth. Mean characteristics of each zone are summarised in Table 2.7.

Table 2.7. Water composition of the various subsystems of Ria Lagartos Lagoon.

	Mouth	System 1 San Felipe	System 2 Coloradas	System 3 El Cuyo	System 4 Flamingos
Area (10^6 m^2)		15.8	40.8	28.2	13.2
Volume (10^6 m^3)		15.8	40.8	28.2	13.2
Salinity (psu)	37.0	35.6	55.4	98.3	122.1
Ammonium (µM)	3.0	3.1	3.1	3.1	4.4
Nitrate (µM)	0.4	1.2	0.5	0.2	0.4
Phosphate (µM)	0.01	0.16	0.01	0.02	0.18
Silicate (µM)	12	26	50	56	62
POM (mg l^{-1})	3.0	2.5	8.3	56.6	94.8
PON (µg l^{-1})	26.5	29.1	109.8	507.7	1078

Water and salt budgets

The lagoon is in a karstic region; surface rivers do not exist, and groundwater flow is very localised in the western portion of the lagoon. Direct precipitation averages about 600 mm yr^{-1}. Evaporation is high (~2,000 mm yr^{-1}).

Salinity and silicate increase from the mouth to the inner zones of the lagoon. The ocean mouth salinity, as estimated from a 24-hour sampling, is apparently higher than the salinity in the western zone (San Felipe). The silicate distribution tends to suggest that San Felipe and Coloradas account for most of the silicate elevation in the entire lagoonal system.

This information is used along with the equation derived in Appendix II to estimate the groundwater input to the system. Groundwater salinity and silicate concentrations of 2 psu and 200 µM, respectively, are used to estimate groundwater flow; the calculations are not very sensitive to the exact values employed. This calculation yields small negative groundwater flux into El Cuyo and Flamingos sub-systems. Changing estimated groundwater salinity (between 0 and 10 psu) and silicate (between 100 and 500 µM) has little effect on estimated groundwater input, so these values are simply treated as 0. An estimated $9x10^6$ m^3 yr^{-1} of groundwater flows into Coloradas, and $316x10^6$ m^3 yr^{-1} into San Felipe. These estimates are not sensitive to estimated groundwater salinity, although they respond somewhat to changing the estimated silicate.

These calculations support and quantify the observation that groundwater flow is apparently localised into the western portion of the lagoon. Moreover, the total groundwater inflow estimate ($325x10^6$ m^3 yr^{-1}) into a lagoon which is approximately 80 km in length yields a flow of about $4.1x10^6$ m^3 km^{-1} yr^{-1}. Comparing this rate with an estimate of $8.6x10^6$ m^3 km^{-1} yr^{-1} for the northern portion of the Yucatan Peninsula (Hanshaw and Back 1980) emphasises both that the Lagartos lagoon as a whole is indeed a region of relatively low flow compared to the average, and that the flow is relatively heterogeneous on scales as large as 80 km.

Figure 2.15 illustrates the water and salt budgets for the system. While the inner portion of the system is net evaporative, groundwater flow for the system as a whole (mostly in the western portion, near the mouth) actually exceeds net evaporation.

Budgets of nonconservative materials

Figure 2.16 illustrates the budgets of DIP and DIN in the system. Estimates of nutrient concentrations in the groundwater are taken from Herrera-Silveira *et al.* (1998).

P balance

It can be seen that there is some variation in P flux along the length of the lagoon. Over the area of the entire system, ΔDIP is $+114\text{x}10^3$ mol yr^{-1}. This represents a net source of only 1 mmol m^{-2} yr^{-1}. In any case, estimated ΔDIP is sensitive to the apparently large groundwater-associated flux in the western portion of the system. It seems safe to conclude that ΔDIP of this system is near 0.

N balance

The system also shows variability in N flux along its length, with the rates apparently strongly influenced by groundwater input of DIN in the western portion of the lagoon. Over the entire system ΔDIN is $-19\text{x}10^6$ mol yr^{-1} (-198 mmol m^{-2} yr^{-1}). Again, groundwater-associated flux appears large. In the case of ΔDIN, it seems unlikely that an uncertainty in groundwater flux would reverse the rather large estimated uptake.

Stoichiometric calculations of aspects of net system metabolism

Stoichiometric estimates can be based on the molar C:N:P ratio of material likely to be reacting in the system. We assume that this material is plankton, with a Redfield C:N:P molar ratio of 106:16:1.

An estimate of nitrogen fixation minus denitrification (*nfix-denit*) is established as the difference between observed and expected ΔDIN, where the expected ΔDIN is ΔDIP multiplied by the Redfield N:P ratio of 16: $\Delta DIN_{exp} = 16\text{x}(+114\text{x}10^3 \text{ mol yr}^{-1}) = +2\text{x}10^6 \text{ mol yr}^{-1}$. Thus (*nfix-denit*) = $-19\text{x}10^6 - (2\text{x}10^6) \text{ mol yr}^{-1} = -21\text{x}10^6 \text{ mol yr}^{-1}$. This is equivalent to a system-average rate of -223 mmol m^{-2} yr^{-1}. This rate of net denitrification is moderate, and it seems likely that a higher rate of groundwater DIN supply would continue to result in a large proportion of DIN loss to denitrification.

An estimate of primary production minus respiration (*p-r*) is derived on the assumption that ΔDIP represents net organic reaction according to the Redfield C:P ratio of 106: Thus (*p-r*) = $-106 \text{ x } (+114\text{x}10^3) \text{ mol yr}^{-1} = -12\text{x}10^6 \text{ mol yr}^{-1}$. This is equivalent to a rate of about -128 mmol m^{-2} yr^{-1}. This is a slow rate of net organic respiration.

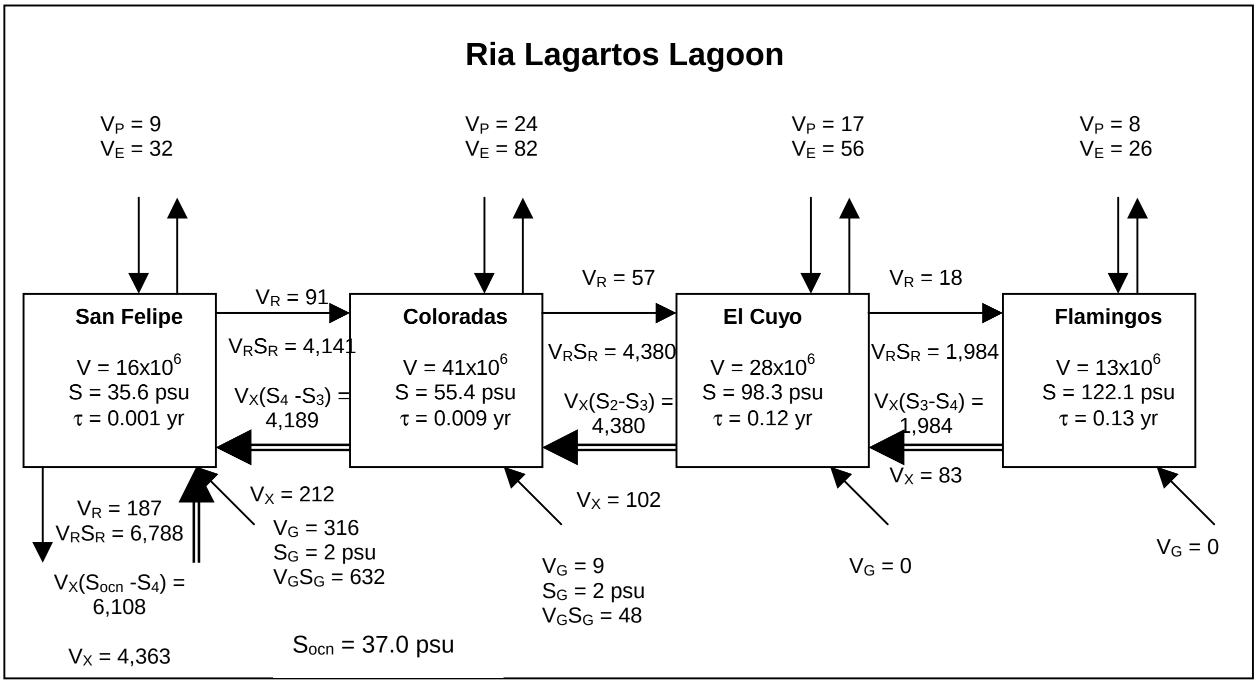

Figure 2.15. Water and salt budgets for the Ria Lagartos Lagoon. Water fluxes in 10^6 m^3 yr^{-1}; water fluxes in 10^6 psu m^3 yr^{-1}. The arrows indicate the direction of fluxes; in the case of the mixing arrows, the directions indicated are directions of net salt flux.

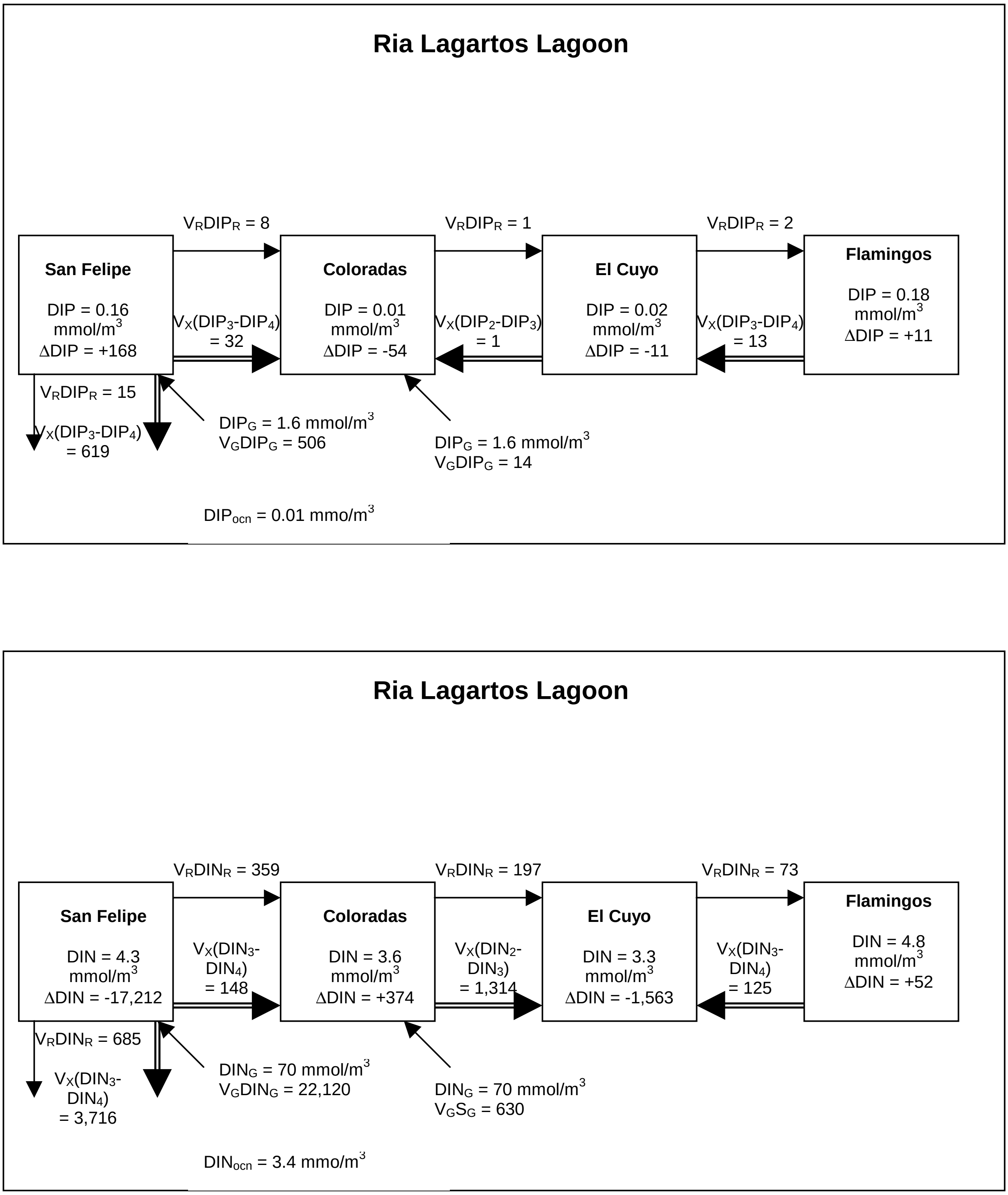

Figure 2.16. DIP and DIN budgets for Ria Lagartos Lagoon. Fluxes in 10^3 mol yr^{-1}. The arrows indicate the direction of the fluxes.

2.2.4 Nichupté Lagoonal System, Quintana Roo

Martin Merino Ibarra

<u>*Study area description*</u>

The Nichupté Lagoonal System (NLS) is located in the north-eastern corner of the Yucatan Peninsula (21.1°N; 86.8°W) (Figure 2.17). The tourist zone of Cancun has been constructed on the sand bar that separates Nichupté from the sea. The Nichupté system is formed from a principal lagoon that contains three separate basins and various lagoons of minor size connected with the principal lagoon. Nichupté is approximately rectangular, with dimensions of 12x5 km. The lagoonal system is connected to the sea through two narrow channels (20-40 m wide), located at the extreme north and south of the system. The total area of the system is 50×10^6 m^2. The lagoons are shallow, with a maximum depth of 5 m and mean depth of only 2.2 m. The volume of the system is 110×10^6 m^3 (Merino *et al.* 1990).

Figure 2.17. Map of the Nichupté Lagoonal System.

<u>*Water and salt budgets*</u>

Due to the karstic nature of the calcareous rocks that form the Yucatan Peninsula, as well as the small relief of the landscape, rainfall is rapidly filtered into the subsoil, and there is no surface drainage. Because of this, even though rainfall is abundant (about 1,100 mm yr^{-1}), there are no rivers draining into Nichupté.

The rainfall which filters into the ground throughout the Peninsula is an important source of freatic water which eventually discharges through the coastal zone into the ocean. It has been calculated that the average discharge along this coast is approximately 8.6×10^6 m^3 yr^{-1} (Hanshaw and Back 1982). From this estimate the Nichupté system should be receiving about 100×10^6 m^3 yr^{-1} of groundwater discharge. It is probable that the salinity of the groundwater is significantly different from 0 psu. In the preliminary model here we have used the average value of 1.65 psu reported for groundwater in the Yucatan Peninsula by Doehring and Buttler (1974), but direct measurement of the salinity of groundwater discharges to the NLS will be done in the near future to improve the model.

The salt and water balance was obtained from a hydrological study (Merino *et al.* 1990) in which the NLS was sampled near to monthly in 1982-1983 (Table 2.8). Evaporation in the region is approximately 1,800 mm yr^{-1} and rainfall is about 1,100 mm yr^{-1}. However, because of groundwater discharge, the Nichupté system behaves like an estuary. The average lagoonal salinity is about 28 psu, with minimum of about 22 in December and maximum of about 35 in May. There are no significant vertical gradients in salinity; the system appears well mixed. There are, however, significant horizontal gradients. In general, the salinity increases from west to east. The lowest values observed are about 8 psu in the western portion after intense rains, while near the mouths on the east the salinities approach adjacent oceanic salinity values of 35.7 (Merino and Otero 1991). In some regions the salinity can be elevated up to 37 psu due to evaporation.

It can be seen in Table 2.8 that there is considerable variation in water exchange over an annual cycle. From these data the mean annual water exchange for the NLS was calculated to be 0.30 yr (110 days) (Figure 2.18). If the calculation is based on the averaged fluxes, instead of the average concentrations and the summed fluxes, exchange time is 0.24 yr.

Table 2.8. Salt and water balance data and calculations for periods between samplings of the NLS. V_G is figured at a nominal rate of 100×10^6 m^3 yr^{-1} (based on Hanshaw and Back 1980).

Period	**Days**	$\mathbf{V_E}$ 10^6 m^3	$\mathbf{V_P}$ 10^6 m^3	$\mathbf{S_{NLS}}$ (psu)	$\mathbf{S_R}$ (psu)	$\mathbf{V_G}$ 10^6 m^3	$\mathbf{V_R}$ 10^6 m^3	$\mathbf{V_X}$ 10^6 m^3
21Apr-11May '82	20	-5.7	2.2	33.5	34.6	6	-2	38
11May-30June '82	50	-14.2	24.4	28.4	32.1	14	-24	110
30June-8Aug '82	39	-11.1	0.7	26.2	31.0	11	-1	4
8Aug-7Sept '82	30	-6.5	4.8	29.9	32.8	9	-7	40
7Sept-17Nov '82	71	-13.0	11.6	28.4	32.1	20	-19	86
17Nov-15Dec '82	28	-5.1	4.4	26.7	31.2	8	-7	26
15Dec82-21Jan '83	37	-7.4	11.4	24.9	30.3	10	-14	42
21Jan-17Feb '83	27	-5.4	2.3	24.5	30.1	8	-5	13
17Feb-18Mar '83	29	-6.8	4.2	26.0	30.9	8	-6	19
18Mar-8May '83	51	-14.5	2.4	28.4	32.1	14	-2	13
TOTAL/AVE.	382	-89.6	68.2	27.7	31.7	108	-87	390
Adjusted for 365 days:		**-86**	**65**			**100**	**-83**	**-370**

Budgets of nonconservative materials

The available nutrient data for the budgets were measured in 1986 by Gonzalez (1989). Average dissolved phosphate in the NLS is 0.7 µM. Total dissolved inorganic nitrogen (DIN) is 6.5 µM. The adjacent oceanic nutrient concentrations are 0.2 µM for DIP and 2.5 µM for DIN (Merino and Otero 1991). Groundwater concentrations were estimated with the measurements of Alcocer *et al.* (1999) and Alcocer (unpublished data) at the Casa Cenote, which, due to its location on the same coast, is expected to receive groundwater similar to the NLS. Groundwater DIP was taken as 1.6 µM and DIN as 19 µM. Actual groundwater nutrient levels will be measured in the near future to improve this budget.

Sewage discharges from the tourist zone built on the island are probably a important source of DIP, DOP, DIN and DON for the lagoon system (Merino *et al.* 1992), but at present there are no data to estimate these discharges.

P balance

The system is a net source of DIP (Figure 2.19). While the lagoon's rate of nonconservative flux is small (ΔDIP= +22,000 mol yr^{-1} = +0.4 mmol m^{-2} yr^{-1}) when compared with other coastal lagoons, it seems significant for a lagoon that does not receive river inputs. There is considerable uncertainty in the value because of an uncertain groundwater concentration (and water flux) as well as the probable contribution of both organic and inorganic phosphorus by sewage input.

N balance

The Nichupté Lagoon System seems to be a slight sink of DIN (Figure 2.20), although the rate of nonconservative DIN flux is relatively small (ΔDIN = -376,000 mol yr^{-1} = -8 mmol m^{-2} yr^{-1}). ΔDIN could be underestimated if the nitrogen input due to groundwater is underestimated or if sewage is important.

Stoichiometric calculations of aspects of net system metabolism

Nitrogen fixation minus denitrification (*nfix-denit*) was calculated as the difference between observed and expected ΔDIN. Expected ΔDIN is ΔDIP multiplied by the N:P ratio, assuming that the Redfield ratio for phytoplankton (16:1) was appropriate.

The estimate of (*nfix-denit*) (-728x10^3 mol yr^{-1} = -15 mmol m^{-2} yr^{-1}) is about double the ΔDIN. This occurs because the system is a slight net source of DIP yet is consuming DIN. The estimated rate of (*nfix-denit)* is actually quite low. It would not be surprising if considerably more DIN is delivered via sewage or groundwater and lost by denitrification in this system.

Similarly, net ecosystem metabolism (*p-r*) was estimated as the negative of the nonconservative DIP flux multiplied by the C:P ratio of the reacting organic matter. Since in the NLS the dominant primary producer is *Thalassia testudinum*, a C:P ratio of 106:1 was used. The system appears to be slightly net heterotrophic; that is (*p-r*) = -9x10^6 mol yr^{-1} = -0.009 mol m^{-2} yr^{-1}.

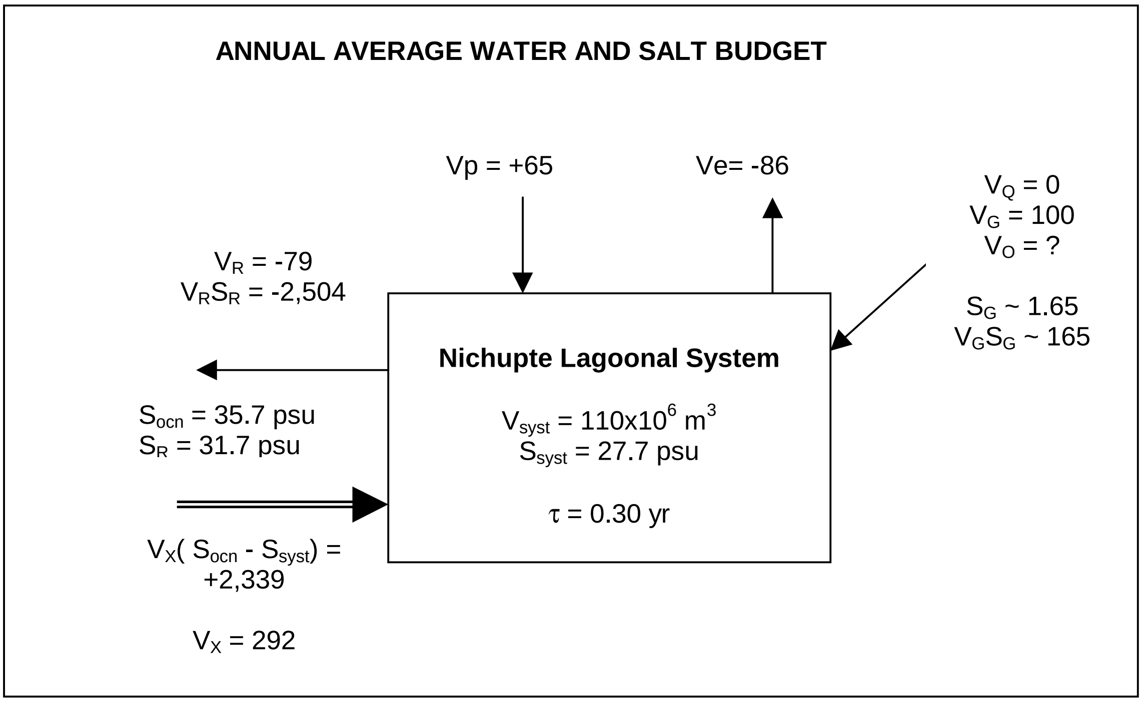

Figure 2.18. Water and salt budget for NLS, using average salinity, rainfall, and evaporation number and a guessed value for groundwater flow. Fluxes of water in 10^6 m^3 yr^{-1}. Fluxes of salt in 10^6 psu m^3 yr^{-1}.

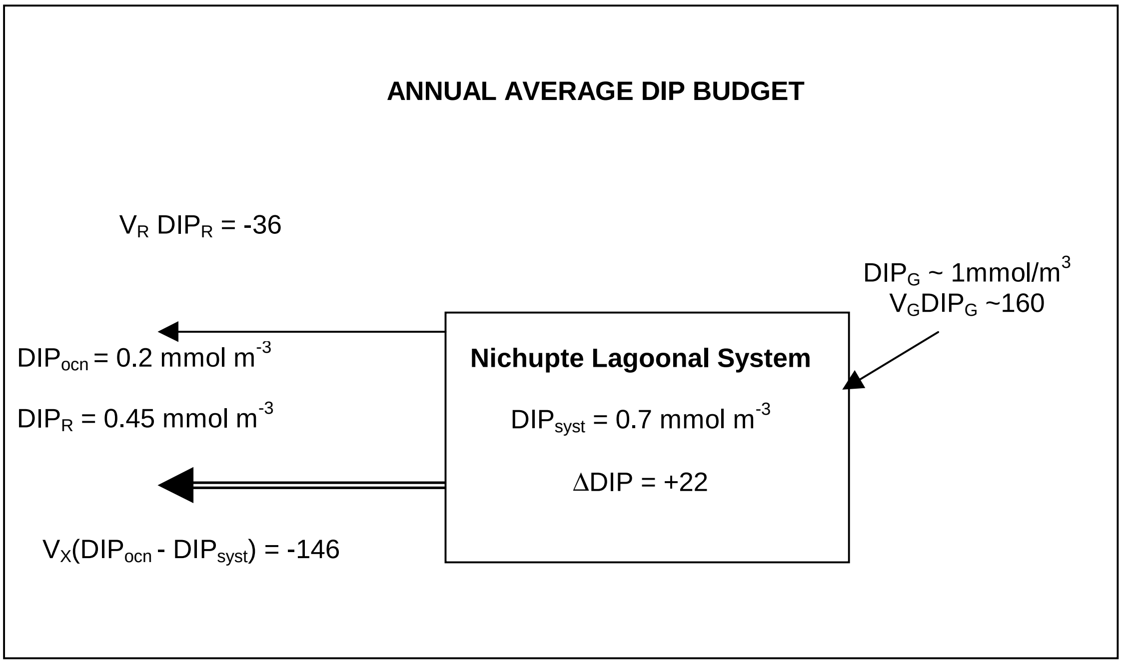

Figure 2.19. Average annual DIP budget for NLS. Fluxes in 10^3 mol yr^{-1}.

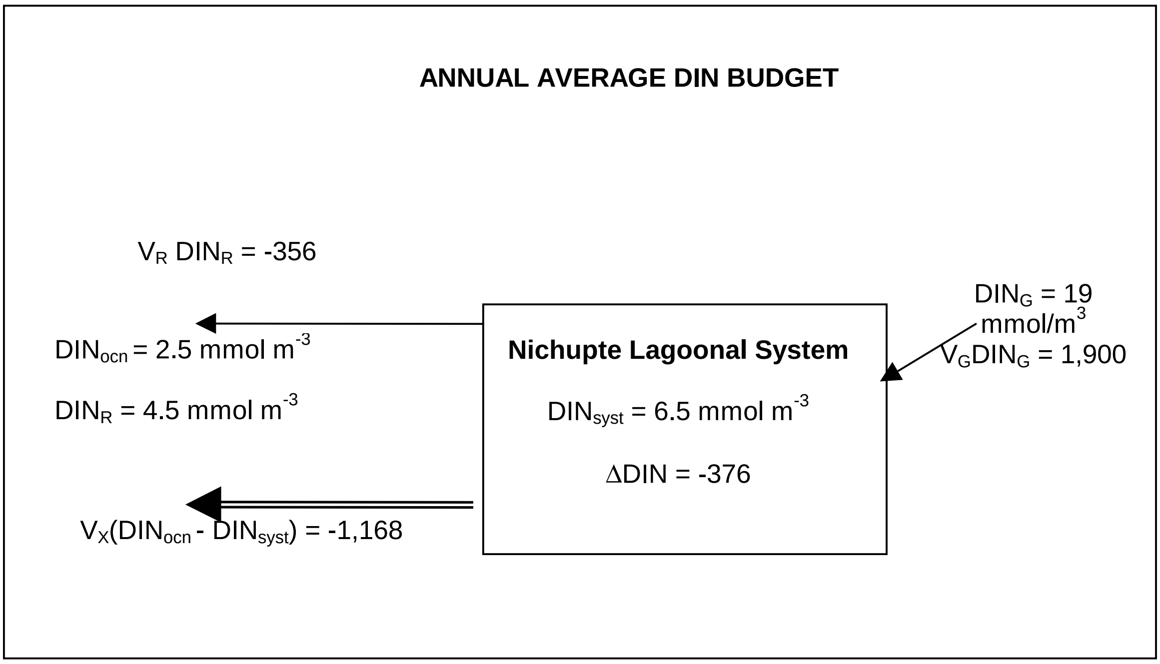

Figure 2.20. Average annual DIN budget for NLS. Fluxes in 10^3 mol yr^{-1}.

2.2.5 Dzilam Lagoon, Yucatán

Jorge A. Herrera-Silveira, Luis Troccoli Ghinaglia, Javier Ramíez Ramirez and Arturo Zaldivar Jimenez

Study area description

Dzilam Lagoon is located in the central region of the Yucatán coast (21.5°N; 88.7°W) (see Figure 2.21). Its geomorphological classification is as a barrier island lagoon (Lankford 1974). It is parallel to the coastline, shallow (0.5-2.1 m) with an inlet in the middle of the system and two arms. The total surface is of 9.4 km^2, with a mean depth of 1.1m. This central region experiences a precipitation between 750-900 mm yr^{-1} and very high evaporation (1,400-1,550 mm yr^{-1}). In spite of this water deficit, the salinity of the lagoon is lower than the adjacent sea, due to groundwater discharges as a consequence of the karstic limestone of the region.

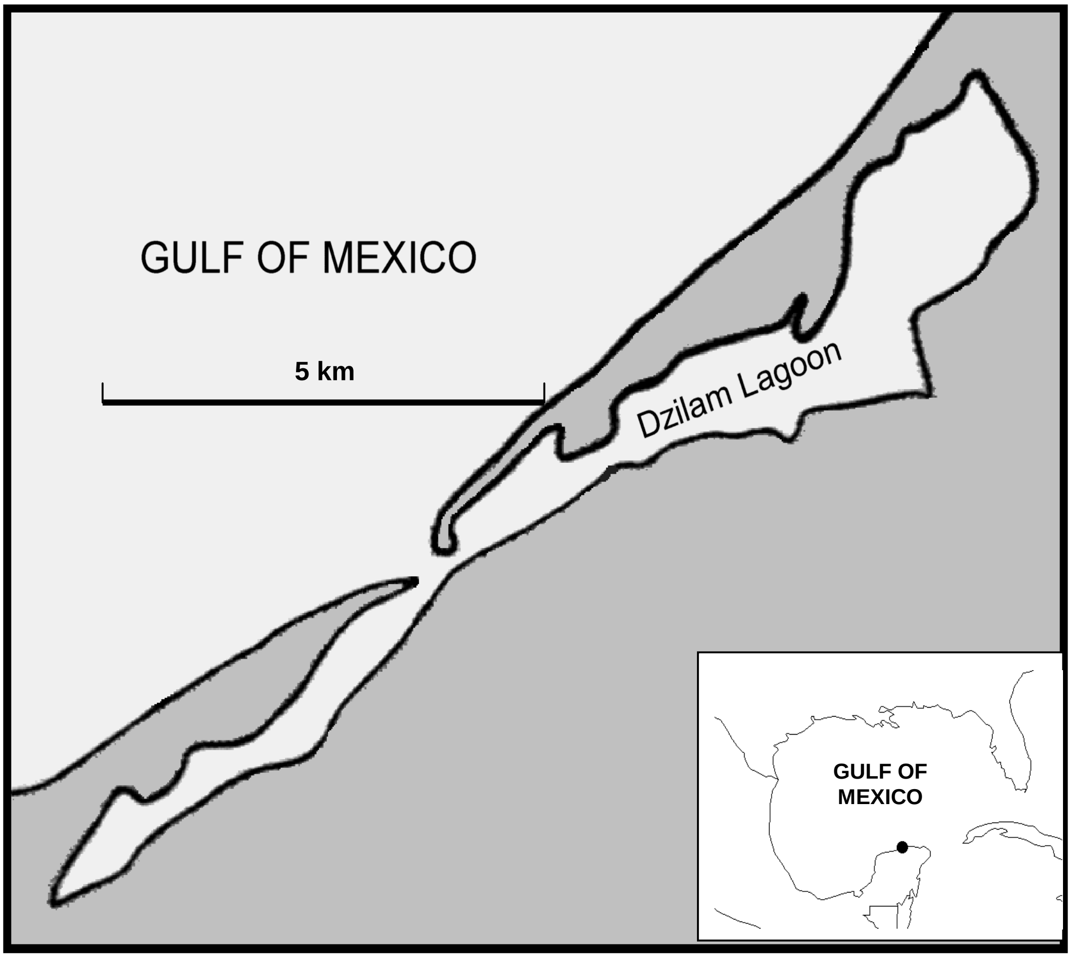

Figure 2.21. Map of Dzilam Lagoon.

About 90% of the bottom is covered by submerged aquatic vegetation dominated by *Halodule wrightii*, *Ruppia maritima, Thalassia testudinum* and *Batophora oerstedi*. The shores of the lagoon are covered by mangrove vegetation (*Rhizophora mangle, Avicennia germinans* and *Laguncularia racemosa*). The lagoon is located in a State Protected Area, and is probably the best-preserved ecosystem of the whole state because there is no human development in the surrounding areas. Access to the lagoon is from the sea, and no roads exist (Herrera-Silveira *et* *al.* 1999). From the hydrological gradient and circulation pattern, Dzilam lagoon can be divided into three systems, the east arm (4.6 km^2), the west arm (3 km^2) and the central zone (1.8 km^2) that opens to the sea.

Ten stations along Dzilam Lagoon were sampled in March, April, August and October of 1994, and January and February of 1995, thus covering a complete annual cycle. Table 2.9 summarises means for various properties in the three subsystems, as well as coastal ocean. With these space patterns the water balance, salt balance and nutrient budgets were carried out in an annual context.

Table 2.9. Mean annual chemical composition of Dzilam Lagoon and coastal ocean.

Property	**Ocean**	**West (3)**	**Central (2)**	**East (1)**	**Groundwater**
Salinity (psu)	36.8	32.6	35.6	30.1	8
DIN (μM)	4.7	6.1	5.1	6.3	3.1
DIP (μM)	0.03	0.12	0.07	1.20	0.03
Silicate (μM)	16	75	61	77	150

Salt and water budgets

As the lagoon is located in a karstic region, surface discharges of freshwater as rivers don't exist. However, groundwater discharges are located at both zones (east and west) of the lagoon. We used the salinity-silicate method presented in Appendix II to estimate groundwater discharge to the entire system (based on groundwater silicate and salinity, on the rainfall minus evaporation, and on the exchange of salt and silicate at the mouth). We then apportioned the total-system estimate of groundwater flux according to the lengths of the three sub-systems. The total groundwater discharge is estimated 25 000 m^3 day^{-1}, or 9.1x10^6 m^3 yr^{-1}. Over the 15 km length of the system, this is an estimated annual discharge of about 0.6x10^6 m^3 km^{-1}. This is about 8% of the discharge estimated by Hanshaw and Back (1980) for the northern portion of the Yucatán Peninsula. During the sampling year, direct precipitation was 820 mm yr^{-1}, while evaporation was 1,420 mm yr^{-1}.

Based on these data, the water and salt budgets were calculated and are illustrated in Figure 2.22. Note that the central zone is both in contact with the sea and receives the influence from the east and west zones. Water exchange times in the east and west zones are very long (206 and 550 days, respectively). These long exchange times for these arms are not particularly reliable because of the near balance between salt inflow with the groundwater and outflow as residual flow. As a result, the calculations of V_X are unreliable and extremely sensitive to the exact salinity of the groundwater (here estimated at 8 psu). The central zone exchanges much more rapidly (18 days), and the overall exchange time for the system is 120 days. This latter rate is also rather sensitive to the groundwater salt inflow.

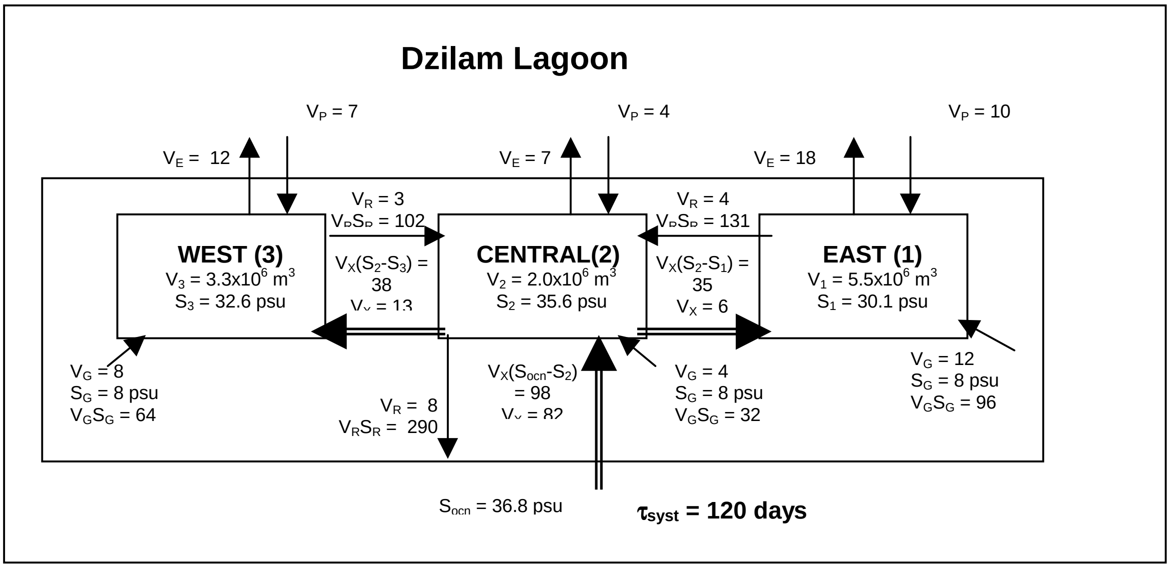

Figure 2.22. Water and salt budgets for the three subsystems of Dzilam Lagoon. Water fluxes in 10^3 m^3 day^{-1}; salt fluxes in 10^3 psu m^3 d^{-1}. The arrows indicate the direction of the fluxes; in the case of the mixing arrows, the directions indicated are the directions of net salt flux.

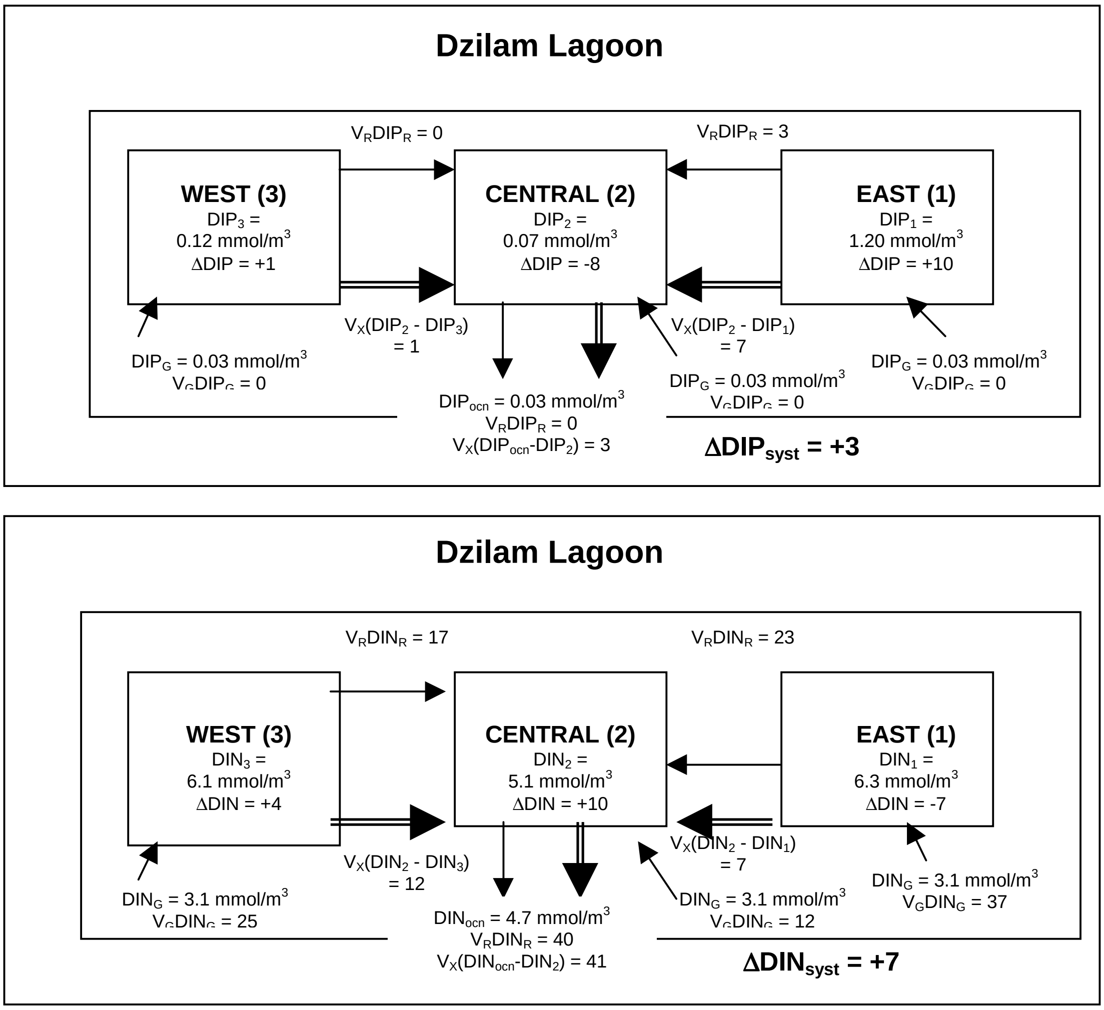

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Figure 2.23. DIP and DIN budgets for Dzilam Lagoon. Fluxes in mol day^{-1}. Note that the arrows indicate the direction of material fluxes between boxes.

P balance

ΔDIP for this system totals only +3 mol day^{-1}, over the entire area of the lagoon (9.4 km^2). This is equivalent to a net annual flux of 1,100 mol yr^{-1}, or +0.12 mmol m^{-2} yr^{-1}. DIP in this system appears to be in near balance between inflow and outflow.

N balance

The ΔDIN balance for the system is also in near balance, showing an apparent net ΔDIN of +7 mol d^{-1}, or +2,600 mol yr^{-1} (+0.28 mmol m^{-2} yr^{-1}).

Stoichiometric calculations of aspects of net system metabolism

Stoichiometric estimates can be used on the molar C:N:P ratio of material likely to be reacting in the system. We assume that this material is dominated by plankton, with a Redfield C:N:P molar ratio of 106:16:1.

Net nitrogen fixation minus denitrification (*nfix-denit*) is estimated as the difference between observed and expected ΔDIN, where ΔDIN_{exp} is estimated as ΔDIP multiplied by the Redfield N:P ratio of the inferred reacting organic matter. Thus:

$$(nfix\text{-}denit) = +0.28 - 16\text{x}(+0.12) \text{ mmol m}^{-2} \text{ yr}^{-1}, \text{ or } +2.2 \text{ mmol m}^{-2} \text{ yr}^{-1}.$$

The system is apparently fixing nitrogen, but this rate is near 0.

Similarly, net ecosystem metabolism (*p-r*) is estimated as ΔDIP multiplied by the assumed reacting organic matter C:P ratio:

$$(p\text{-}r) = -0.12\text{x}106 \text{ mmol m}^{-2} \text{ yr}^{-1} = -13 \text{ mmol m}^{-2} \text{ yr}^{-1}.$$

The system appears to be net heterotrophic, but at a rate near 0.

3. BUDGETS FOR GULF OF MEXICO

The estuarine area of the Gulf of Mexico is the largest in Mexico, with about 24% of the national total, and about 30 coastal lagoons and estuaries. Summer is the rainy season, when the large rivers of the region flow strongly. Precipitationa and runoff are important contributors to estuarine budgets, as are groundwater runoff and storage. The region has oil and natural gas, cattle, shrimp fisheries, tourism and apopulation of more than 10 000 000, all factors contributing pressures and pollution to the coastal systems.

3.1 Carmen-Machona Lagoon, Tabasco

David Valdes

<u>Study area description</u>

This coastal system is formed by two lagoons: Carmen and Machona, on the coast of Tabasco State, Mexico, in the Gulf of Mexico (Figure 3.1). Carmen Lagoon (18.28°N; 93.82°W) has an area of 91 km^2 and a mean depth of 1.8 m. Machona Lagoon (18.37°N; 93.83°W) has an area of 76 km^2, and a mean depth of 2.5 m. The two lagoons are connected by a channel called the Pajonal Lagoon; in this analysis, this third lagoon is treated simply as the channel of flow and mixing between the two major lagoons. The hydrodynamics of the system have been discussed by Vazquez-Gutierrez (1994). The system is under pressure from several natural processes and

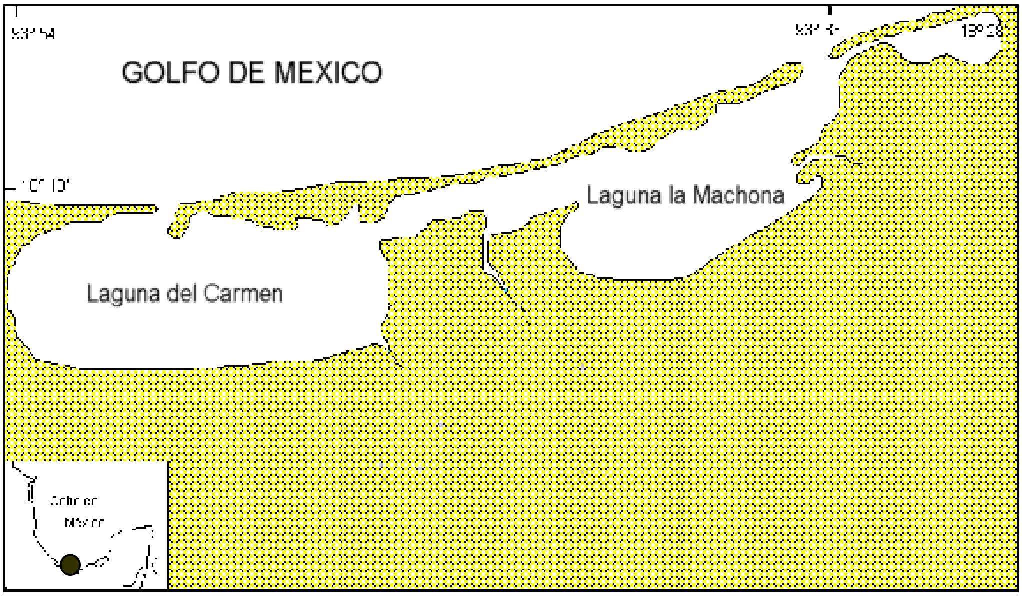


Figure 3.1. Map of the Carmen-Machona Lagoon system.

human activities (cattle farms, oil extraction, oyster fisheries). These conditions, combined with the climate (high precipitation, high evaporation) and the geology (region of heavy fluvial deposition), make this a fragile ecosystem.

Both lagoons are of the type II-A (Lankford 1977), associated with fluvial deltas. Freshwater inputs are from two rivers and water from the surrounding wetlands. The rivers are the San Felipe in the south-east of Carmen Lagoon, and the Santana in the south-east of Machona Lagoon. The system has permanent communication with the sea through the Santana River's mouth in the western extreme of Carmen Lagoon. In 1975 an artificial mouth was opened in the eastern zone of Machona Lagoon, but littoral and aeolian transport have almost closed this inlet; it is ignored in the budget. The system is bordered by mangroves, and large oyster banks exist on the lagoon floor. Water composition data from near the mouth of the San Felipe River are used for both river inputs.

The lagoons were sampled in 1992, 3 times over a year, at 24 locations. Mean characteristics of each zone are summarised in Table 3.1.

Table 3.1. Water composition of the Carmen-Machona Lagoonal system, including the mouth and the major river inflow.

	Santana Mouth	**System 1 Carmen**	**System 2 Machona**	**San Felipe River**
Area (10^6 m^2)		91	76	
Volume (10^6 m^3)		164	190	
Salinity (psu)	31.2	22.3	27.5	0
Ammonium (µM)	3.8	5.4	4.9	9.9
Nitrate (µM)	0.3	1.1	0.9	3.7
Phosphate (µM)	0.3	5.9	3.2	10.9
Silicate (µM)	30	140	94	331
POM (mg l^{-1})	3.7	5.0	5.1	4.4

Water and salt budgets

We made an estimate of the annual input of the San Felipe and Santana rivers to the lagoons with the area of the respective basins and with the annual precipitation and the reported runoff.

Direct precipitation averages about 2,050 mm yr^{-1}. Evaporation is high: ~1,600 mm yr^{-1}, and runoff is 300 mm yr^{-1} from a combined watershed area of about 2,500 km^2 (Secretaria de Programacion y Presupuesto 1981). Figure 1 summarises the water and salt budgets. Machona, which is relatively isolated from the ocean and has rather low river inflow, has an exchange time of 0.17 yr (about 60 days). Carmen, which connects with the sea, exchanges with Machona, and has high river flow, has an exchange time of 0.04 yr (about 15 days). The combined exchange time for the entire system is 0.11 yr, or about 40 days (Figure 3.2).

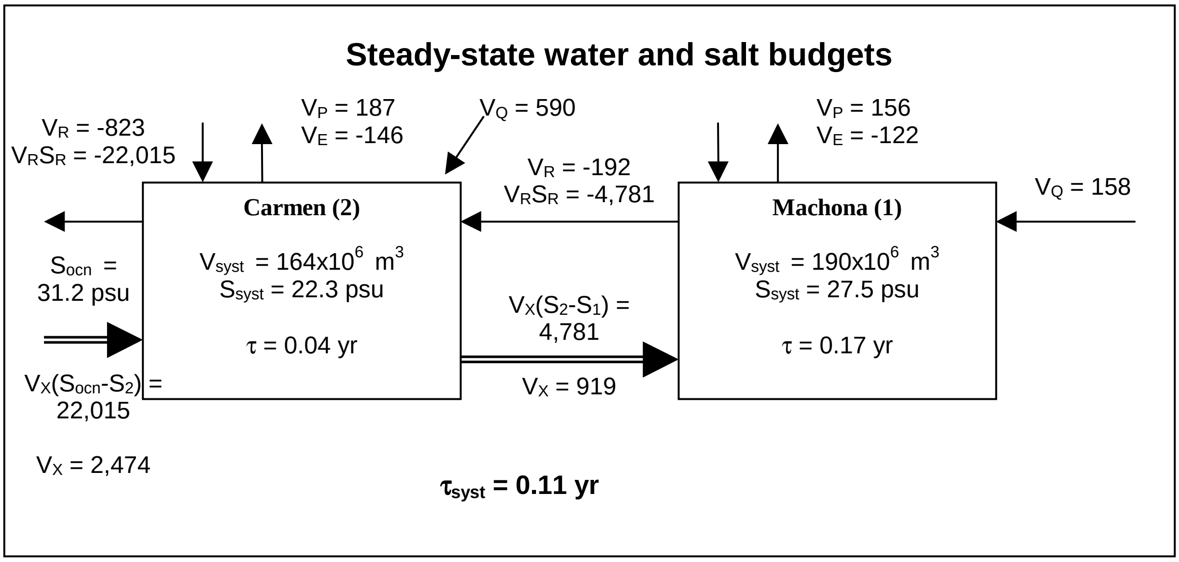


Figure 3.2. Steady state water and salt budgets for Carmen and Machona Lagoons. Note that the conventions are to calculate fluxes as positive inward. However, the arrows on a multiple box diagram are drawn to illustrate the direction of both water and salt flux (for V_R) or the direction of salt flux (for V_X, which has no net water flux). Water fluxes in 10^6 m^3 yr^{-1} and salt fluxes in 10^6 psu m^3 yr^{-1}.

Budgets of nonconservative materials

Figure 3 illustrates the budgets of DIP and DIN in the system.

P balance

Over the area of both lagoons, ΔDIP is +9x10^6 mol yr^{-1} (+54 mmol m^{-2} yr^{-1}). There is slight DIP uptake in Machona, and substantial release in Carmen. This pattern seems consistent with river delivery of particulate materials to the system.

N balance

ΔDIN in the system is 0, with slight net uptake in Machona and release in Carmen. This pattern also seems consistent with delivery of river-borne materials.

Stoichiometric calculations of aspects of net system metabolism

Stoichiometric estimates can be based on the molar C:N:P ratio of material likely to be reacting in the system. We assume that this material is plankton, with a Redfield C:N:P molar ratio of 106:16:1.

An estimate of nitrogen fixation minus denitrification (*nfix-denit*) is established as the difference between observed and expected ΔDIN, where the expected ΔDIN is ΔDIP multiplied by the Redfield N:P ratio of 16:1 for the two systems combined, ΔDIN_{exp} =16x(+9x10^6 mol yr^1) = +144x10^6 mol yr^{-1}. Since ΔDIN_{obs} is 0, (*nfix-denit*) = -144x10^6 mol yr^{-1}. This is equivalent to a system-average net denitrification rate of -862 mmol m^{-2} yr^{-1}. This rate of net denitrification is reasonable for a system receiving moderately high delivery of reactive organic matter.

An estimate of primary production minus respiration (*p-r*) is derived on the assumption that Δ*DIP* represents net organic reaction according to the Redfield C:P ratio of 106:1 thus (*p-r*) = -106x(+9x10^6) mol yr^{-1} = -954x10^6 mol yr^{-1}. This is equivalent to a rate of about -5.7 mol m^{-2} yr^{-1}. This rate of net heterotrophy is also consistent with delivery of river-borne organic detritus.

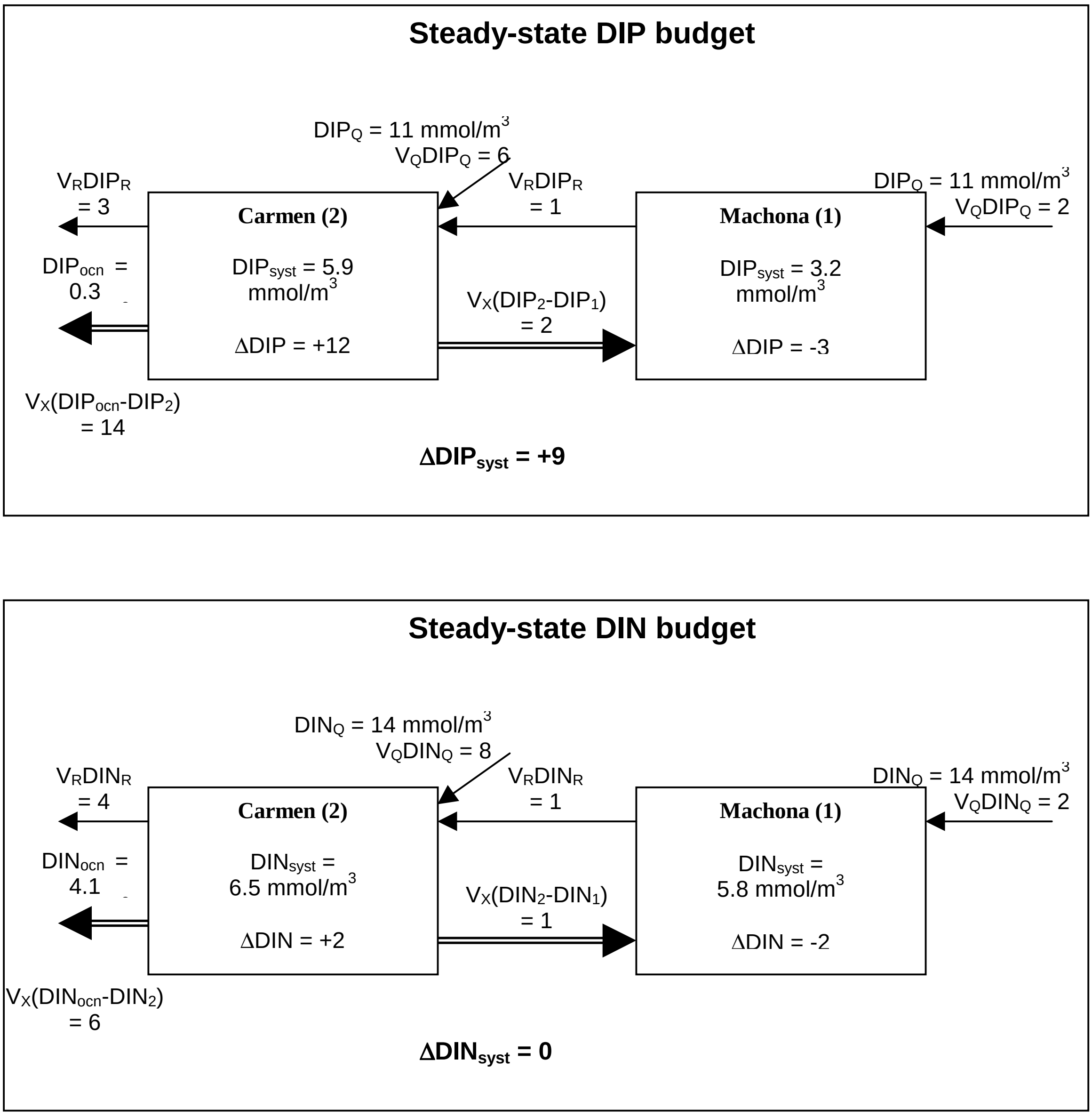


Figure 3.3. Steady state DIP and DIN budgets for Carmen and Machona Lagoons. Note that the conventions are to calculate fluxes as positive inward. However, the arrows on a multiple box diagram are drawn to illustrate the direction of fluxes. Fluxes in 10^6 mol yr^{-1}.

3.2 Mecoacan Lagoon, Tabasco

David Valdes

Study area description

Mecoacan lagoon is located on the coast of Tabasco State, Mexico, in the Gulf of Mexico (Figure 3.4) (18.38°N; 93.15°W), is under pressure from several natural processes and human activities (oil extraction, craft oyster fisheries). The lagoons have an area of 50 km^2 and a mean depth of 1 m.

The lagoon is of the type II-A (Lankford 1977), associated with fluvial deltas. The system has permanent communication with the sea through the Dos Bocas natural mouth in the northern extreme of Mecoacán lagoon. An important PEMEX installation for the oil that is extracted in the Campeche Sonda is situated in this mouth. The system is bordered by mangrove, and in the bottom exist many oyster banks (*Crassostrea virginica*). Galaviz-Solis *et al.* (1987) have described the physical characteristics of this lagoon.

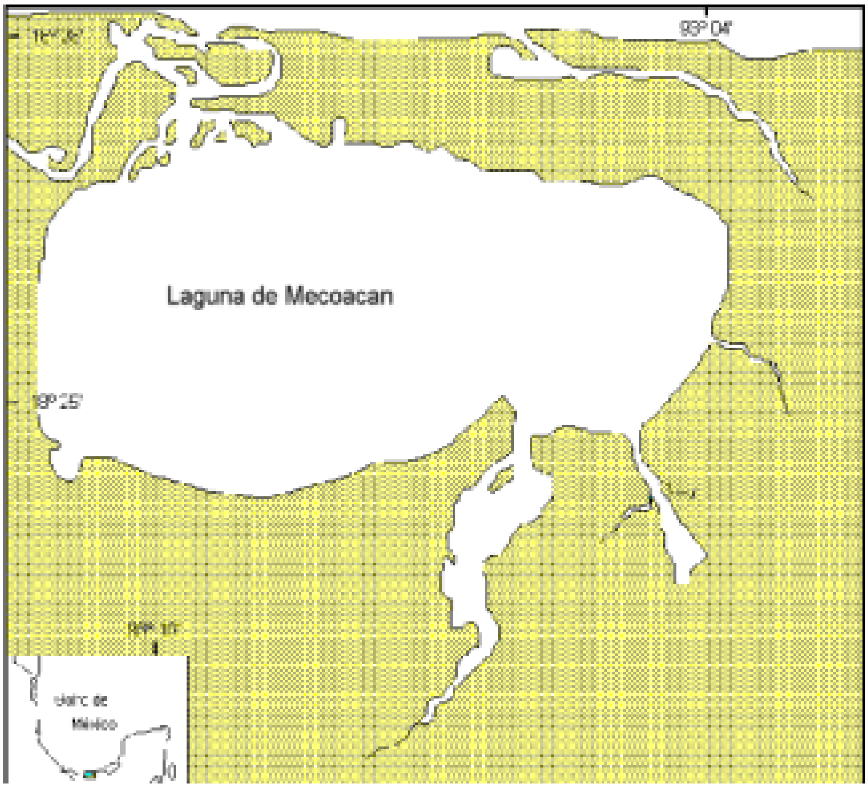


Figure 3.4. Map of Mecoacán Lagoon.

Freshwater inputs are from four rivers and the direct inlet of water from the wetlands. The rivers are Rio Seco in the north of Mecoacán lagoon, Cuxcuchapa in the south-east and Escarbado and González in the east of the estuarine system.

The lagoons were sampled in 1992, at 10 locations. Mean characteristics are summarised in Table 3.2.

Table 3.2. Mean concentrations of materials in Mecoácan Lagoon, its mouth, and a 'near-river' station.

	Dos Bocas Mouth	Mecoacán Lagoon	Near-river station
Salinity (psu)	13	9	0
Ammonium (µM)	7.8	7.0	16.3
Nitrate (µM)	1.4	1.0	2.5
Phosphate (µM)	4.4	5.6	12.5
Silicate (µM)	188	200	319
POM (mg l^{-1})	2.3	3.2	3.7

Water and salt budgets

We made an estimate of the annual freshwater input of the four rivers to the lagoon with the area of the respective basins and with the annual precipitation and the reported drainage basin area.

Direct precipitation averages about 1,800 mm yr^{-1}. Evaporation is 1,600 mm yr^{-1}, and estimated runoff is 300 mm yr^{-1} over an area of about 440 km^2 (Secretaria de Programacion y Presupuesto 1981).

Figure 3.5 summarises the salt and water budgets which arise from these estimates. The water exchange time is about 0.09 yr (~33 days), with residual flow and exchange flow being about the same magnitude.

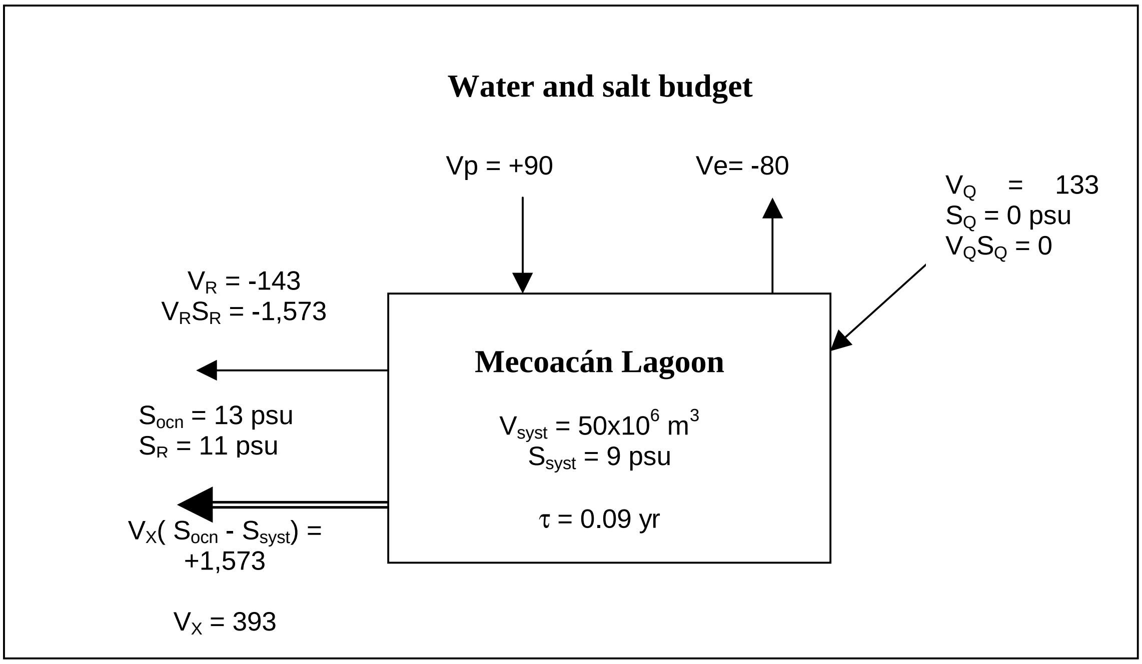


Figure 3.5. Annual average water and salt budgets for Mecoacán Lagoon. Water fluxes in 10^6 m^3 yr^{-1}; salt fluxes in psu m^3 yr^{-1}.

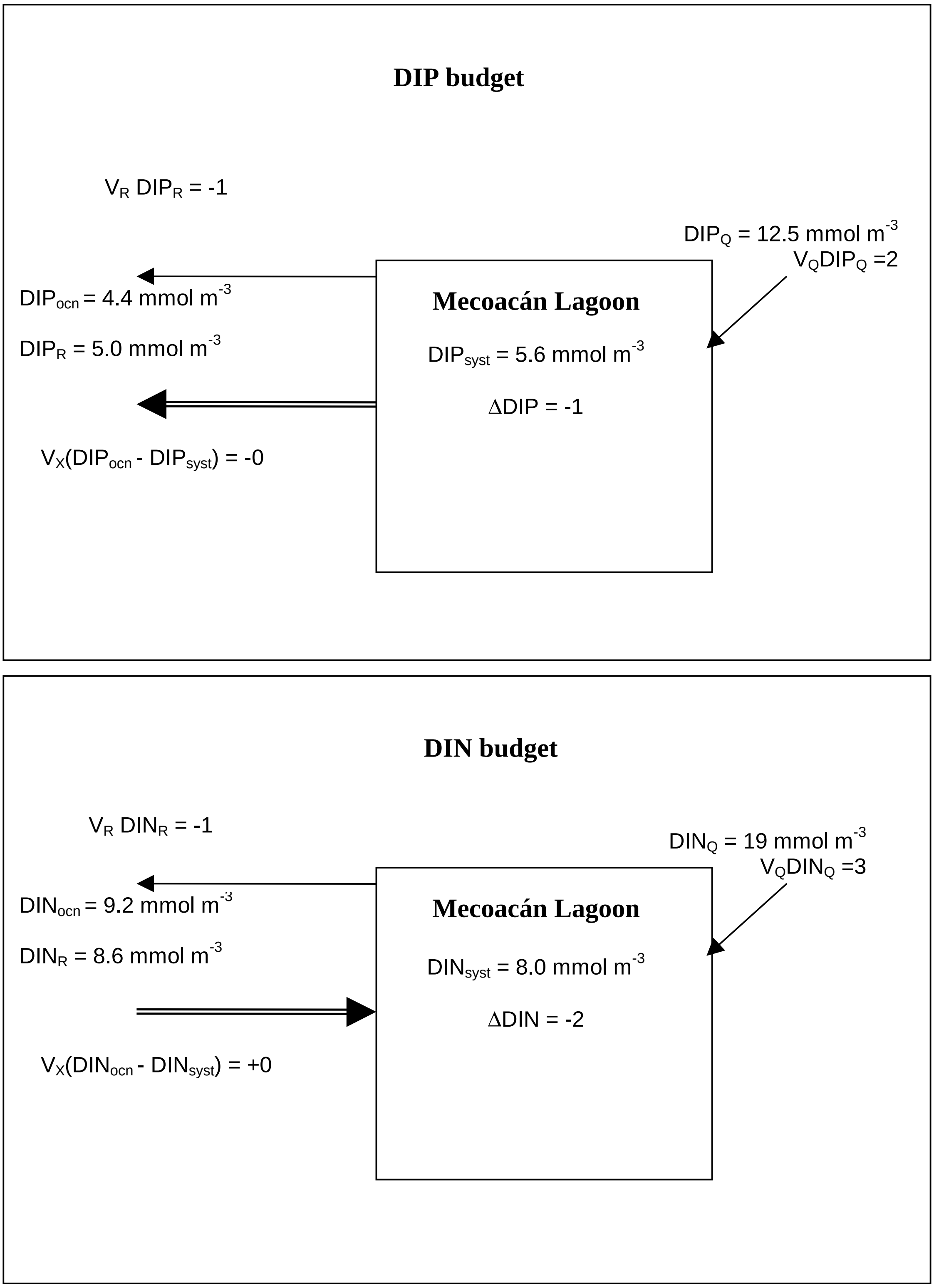


Figure 3.6. DIP and DIN budgets for Mecoacán Lagoon. Fluxes in 10^6 mol yr^{-1}.

Budgets of non-conservative materials

Figure 3.6 summarises the budgets of nonconservative materials in this system.

P balance

As shown in Figure 3.6, ΔDIP is approximately -1x10^6 mol yr^{-1}. Averaged over the lagoon area of 50 km^2, this is an uptake rate of about -20 mmol m^{-2} yr^{-1}.

N balance

Figure 3.6 shows ΔDIN to be approximately -2x10^6 mol yr^{-1}. Over the lagoon area, this uptake is about -40 mmol m^{-2} yr^{-1}.

Stoichiometric calculations of aspects of net system metabolism

Net nitrogen fixation minus denitrification (*nfix-denit*) is calculated as ΔDIN_{obs} minus ΔDIN_{exp}, where ΔDIN_{exp} is ΔDIP multiplied by the N:P ratio of the reacting particulate material (assumed to be 16:1). Thus, (*nfix-denit*) is estimated to be +280 mmol m^{-2} yr^{-1}. This system appears to fix nitrogen at a relatively slow rate.

Net ecosystem metabolism, the difference between primary production and respiration (*p-r*) is estimated as - ΔDIP multiplied by the C:P ratio of the reacting organic material (assumed to be 106:1). Thus, (*p-r*) is estimated to be approximately +2.1 mol m^{-2} yr^{-1}. The system appears to be net autotrophic.

4. BUDGETS FOR GULF OF CALIFORNIA & BAJA CALIFORNIA

Estuarine systems on the Gulf of California and Baja California have been the subject of earlier LOICZ assessments (Smith *et al*. 1997). Here, we add a further two major systems to that group of examples for the region, and update the assessment for Bahia San Quintin.

The relatively arid land climate and an array of population pressures in the Gulf of California, within the estuaries and the catchment basins, contribute to a picture of systems performance that has major importance for global comparisons, as well as being of intrinsic interest in the regional understanding under development by LOICZ. The coastal lagoons and estuaries in the region represent about 17% of Mexico's total and number about 40 systems. Impacts from human use - fisheries and aquaculture, agrochemical pollution, increasing human settlement, tourism, industrial and urban wastewater discharge - are clearly evident. These pressures, associated with significant modification of water resources (groundwater and the limited surface waters), have the potential to yield a more synoptic understanding of the role of people on the biogeochemical processes of the regional estuarine systems.

4.1 Estero El Sargento, Sonora

Cesar Almeda

<u>Study area description</u>

Estero El Sargento, Sonora, is a typical desert coastal lagoon on the north-west of Mexico (29.3°N; 112.3°W) in the southern portion of the northern zone of the Gulf of California. It lies to the north of canal del Infiernillo, which separates Isla Tiburón from the continent (Figure 4.1).

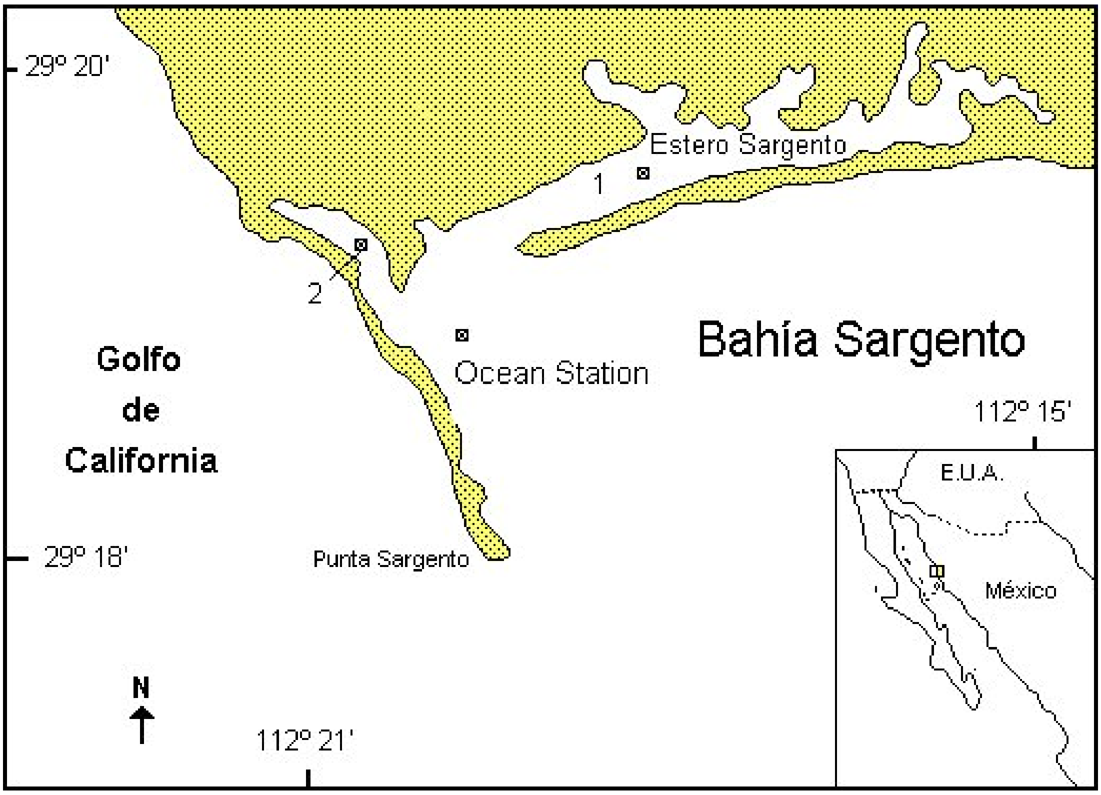


Figure 4.1. Map of Estero El Sargento, Sonora and sampling stations.

El Sargento is characterised as a coastal lagoon with no freshwater input; thus, the lagoon can be classified as an anti-estuarine system (Pritchard 1967). It has a length of 7 km and an area of $11x10^6$ m^2, with an average depth of 1.4m ($15x10^6$ m^3). It is isolated from the adjacent sea by a sandbar 6 km in length. The mouth is 1 km wide and is permanent; most of the sediment is coarse sand. The lagoon has no anthropogenic impact.

The lagoon is located in a region with two pronounced seasons: summer, from May to October, with high temperatures reaching 33°C; and winter, from November to April with temperatures reaching 11°C. Rainfall is scarce; thus evaporation exceeds precipitation by an order of magnitude. Values for salinity are 35 to 45 psu. Seston values are in the range of 50 mg m^{-3} in summer (maximum) and minimum values (14 mg m^{-3}) in spring. In general, there is a well-defined space-time variation, and a strong influence by the tide in the nutrient variability (Valdez and Botello 1990).

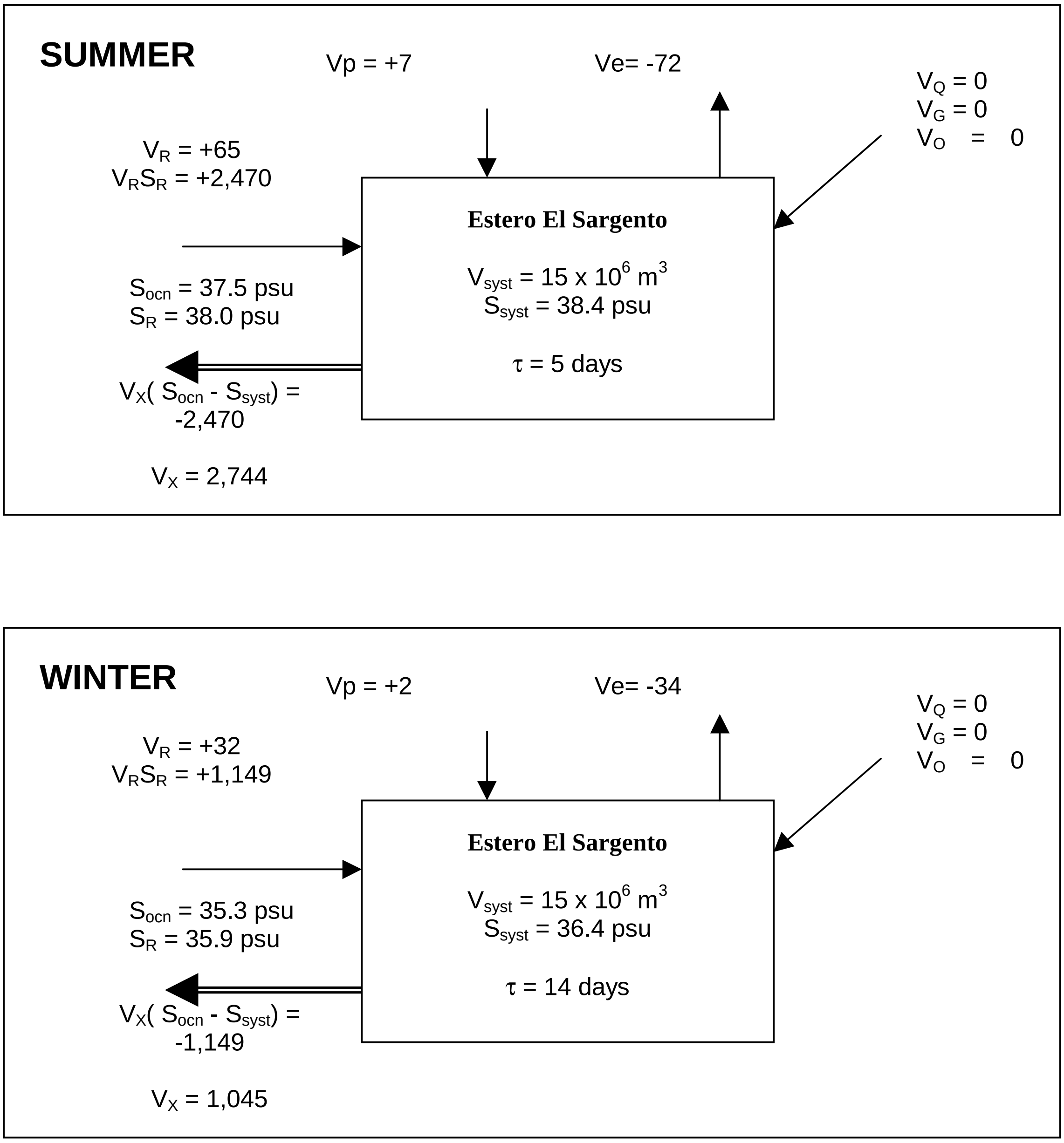


Figure 4.2. Water and salt budgets for Estero El Sargento, during summer and winter. Water fluxes in $10^3 m^3 d^{-1}$; salt fluxes in 10^3 psu m^{-3} d^{-1}.

Water and salt budgets

Figure 4.2 summarises the water and salt budgets for the summer and winter. Groundwater input (V_G), River inflow (V_Q) and V_O are considered 0. Precipitation (V_P) is highly seasonal and very low and evaporation (V_E) exceeds the freshwater throughout the year. The water exchange time was 5 days in summer and 14 days in winter.

The water, salt, N and P budgets presented here are based on data collected during a one year time period, with sampling performed in three stations (Figure 4.1) inside the two arms of the coastal lagoon and in the adjacent sea (Ocean station). The data were split into two data sets representing summer (April-September) and winter (November-March).

Budgets of nonconservative materials

The balance of nonconservative fluxes for DIP and DIN for summer period are illustrated in Figures 4.3 and 4.4.

P balance

The nonconservative flux of dissolved inorganic P, ΔDIP, in Estero El Sargento for the summer period is :

ΔDIP = +4,227 mol day^{-1} (+0.38 mmol m^{-2} day^{-1}),

and for the winter:

ΔDIP = -881 mol day^{-1} (-0.08 mmol m^{-2} day^{-1})

In summer the system is a net DIP source, while in winter there is a slight net sink for this material. The average is +1,673 mol day^{-1} (+0.15 mmol m^{-2} day^{-1}). Therefore, averaged over an annual cycle, the system is a net phosphorus source.

N balance

The system is a slight net nitrogen sink during both and winter:

Summer ΔDIN = -1,228 mol day^{-1} (-0.11 mmol m^{2} day^{-1}),
Winter ΔDIN = -228 mol day^{-1} (-0.02 mmol m^{2} day^{-1}),
Average ΔDIN = -728 mol day^{-1} (-0.07 mmol m^{2} day^{-1}).

Stoichiometric calculations of aspects of net system metabolism

The rates of nonconservative DIP and DIN flux can be used to estimate the apparent rates of nitrogen fixation minus denitrification *(nfix-denit)* as the difference between observed and expected DIN production (ΔDIN_{obs}-ΔDIN_{exp}), where ΔDIN_{exp} is estimated as ΔDIP multiplied by the N:P ratio of the reactive particle organic matter. We assume that this reaction ratio is the Redfield N:P ratio of 16:1, for plankton. Thus:

Summer (*nfix-denit*) = -1228 mol d^{-1} -16 x (4,227) mol d^{-1} = -66,404 mol d^{-1}
(-6.0 mmol m^{-2} d^{-1}),
Winter (*nfix-denit*) = -228 mol d^{-1} -16 x (-881) mol d^{-1} = +13,868 mol d^{-1}
(+1.3 mmol m^{-2} d^{-1}),
Average (*nfix-denit*) = -728 mol d^{-1} -16 x (1,673) mol d^{-1} = -27,496 mol d^{-1}
(-2.5 mmol m^{-2} d^{-1}).

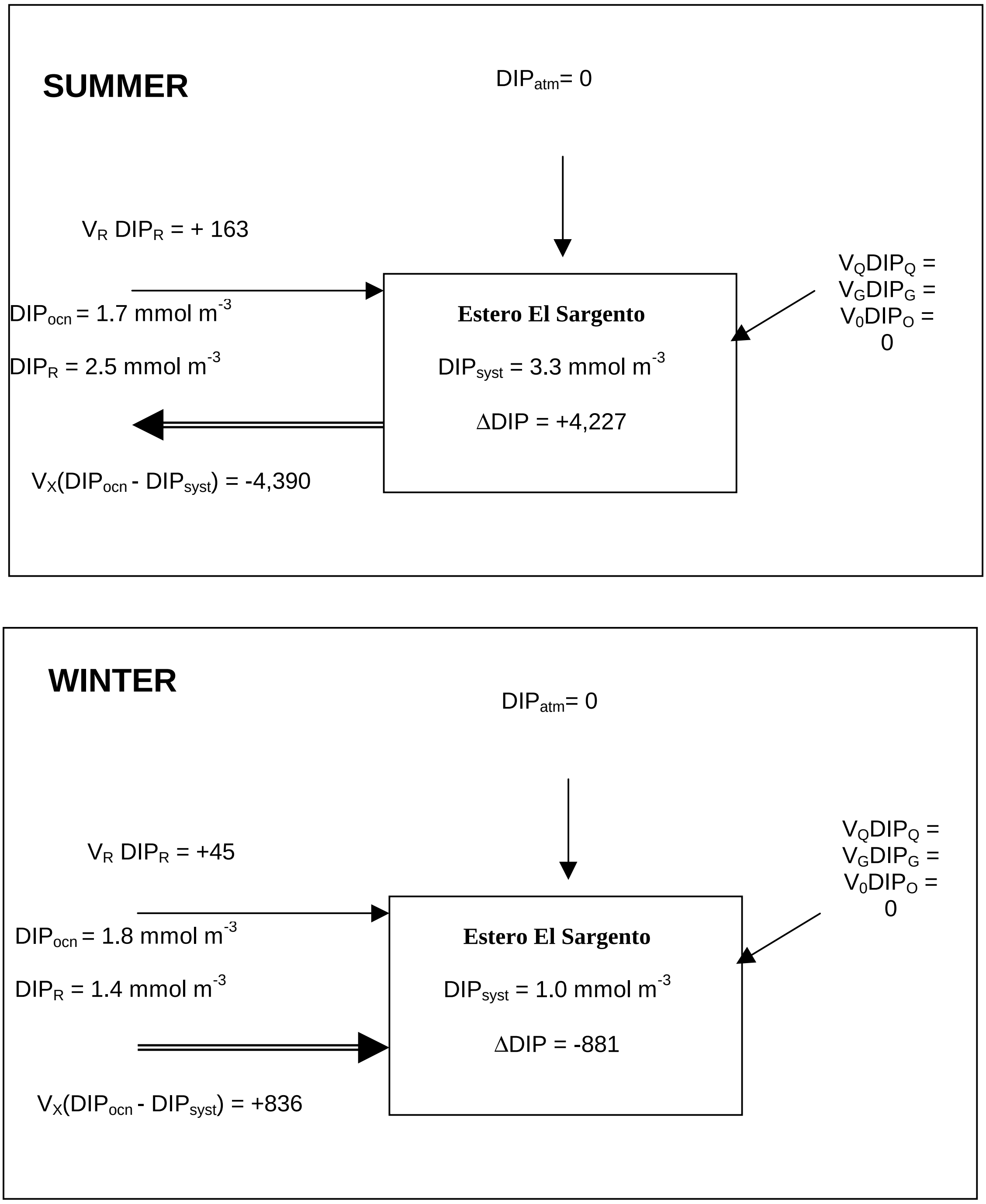


Figure 4.3. Summer and winter DIP budgets for Estero El Sargento.

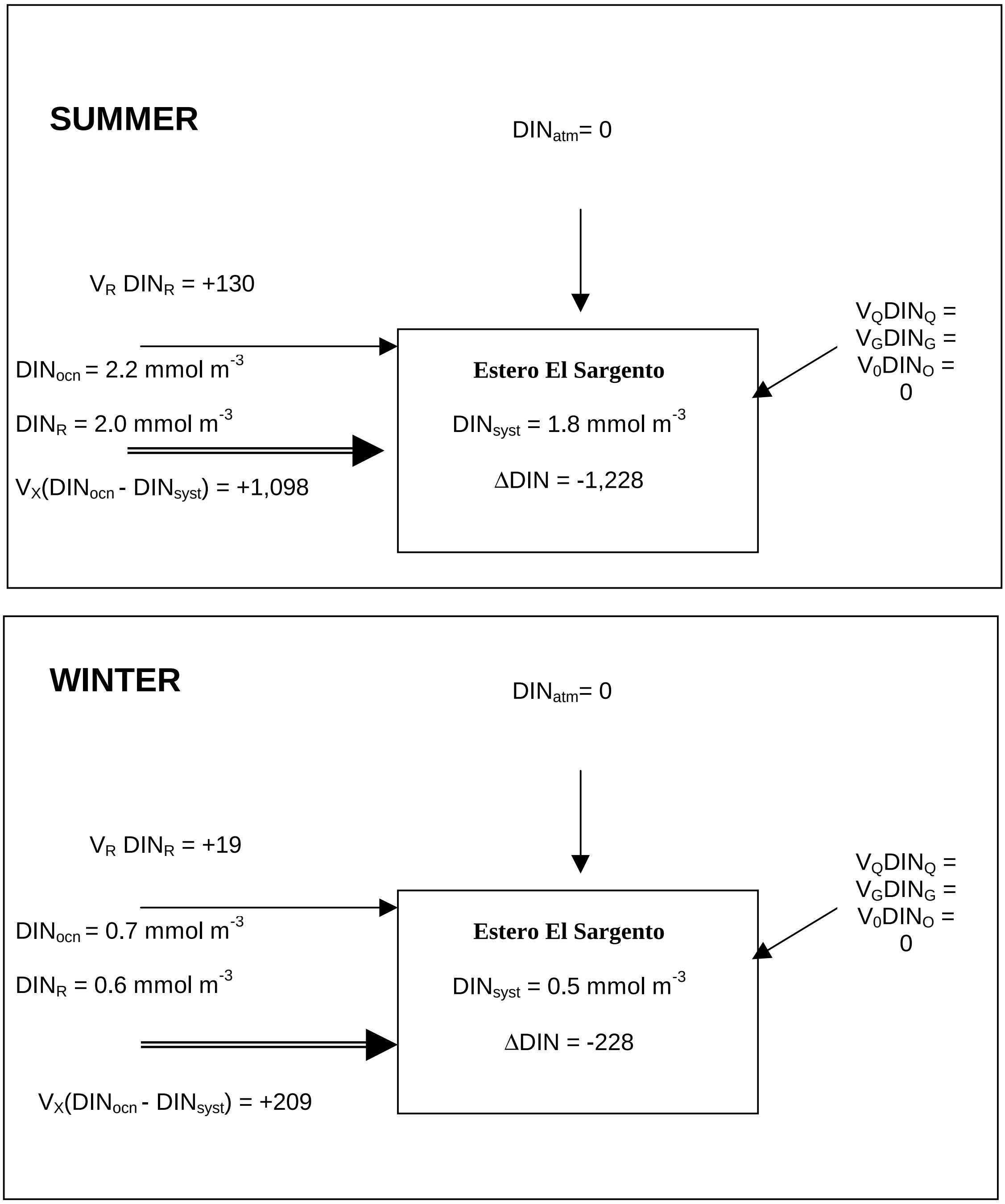


Figure 4.4. Summer and winter DIN budgets for Estero El Sargento.

Over an annual cycle, the system appears to be a net denitrifying system, with a suggestion of some nitrogen fixation during the winter.

In a similar fashion, calculations can be made of net ecosystem metabolism (*NEM* = [*p*-*r*]) based on ΔDIP and the C:P ratio of material which is reacting. We assume the reacting material has a C:P ratio equal to the Redfield ratio of 106:1. Therefore (*p*-*r*) = -106 x ΔDIP. Thus:

Summer (*p*-*r*) = -106 x (4,227) mol d^{-1} = -448,000 mol d^{-1} (-41 mmol m^{-2} d^{-1}),
Winter (*p*-*r*) = -106 x (-881) mol d^{-1} = +93,000 mol d^{-1} (+8 mmol m^{-2} d^{-1}),
Average (*p*-*r*) = -106 x (1,673) mol d^{-1} = -177,000 mol d^{-1} (-16 mmol m^{-2} d^{-1}).

The system appears to be very strongly net heterotrophic in the summer, net autotrophic (at a considerably slower rate) in the winter, and on average net heterotrophic.

4.2 Colorado River Delta

F. Muñoz-Arriola, J. Carriquiry-Beltran, E. Nieto-García and M. Hernandez-Ayon

The Colorado River empties its water and materials load into the Gulf of California, forming a deltaic system with the morphological attributes typical of those dominated by tidal forces (e.g., Carriquiry and Sanchez 1999). The Colorado river is the largest fluvial system in the south-west of the USA, supplying water to 20 million people in the USA as well as to agricultural, industrial, recreational and municipal activities in seven states of the USA, and two countries (USA and Mexico). Fluvial discharge into the Gulf of California at the turn of the century was in the order of $21x10^9$ m^3 yr^{-1}. After dam construction early in the 1960's, fluvial discharge decreased to about $0.9x10^9$ m^3 yr^{-1} (Baba *et al*. 1991); discharge ever since has been about 5% of the original. Although a water quota was established for delivery to Mexico, this quota is just enough to support domestic and agricultural activities in the Mexicali valley, without any significant water discharge into the Gulf of California. Present conditions of fluvial discharge into the Colorado delta are nil. However, during extraordinarily wet years in which rainfall in the lower basin of the Colorado River Basin (in the USA) exceeds storage capacity, catastrophic floods occur in the Mexican side of the hydrologic basin, delivering water into the delta system at a rate of $35x10^9$ m^3 yr^{-1} (Cupul-Magana 1994).

Discharge loss into the deltaic system of the Colorado River has produced significant changes in the hydrology, hydrography and ecology of this region. Some of the most evident changes include shifting the system from a brackish-estuarine environment into a hypersaline system (e.g., Hernandez-Ayon *et al*. 1993); changing from net depositional to a net erosional sedimentary system and changing the hydrographic circulation from a long-basinal to a cross-basinal pattern of materials transport (Carriquiry and Sanchez 1999). This system is now largely hydrographically controlled by tidal processes. Although the materials exchange pattern at the land-ocean interface, at the Colorado River Delta, may well have changed, this is an initial attempt to estimate present conditions of materials budget between the hydrologic basin of the Colorado River and the Gulf of California.

Study area description

The Colorado River Delta is located in the upper Gulf of California, México (31.75N; 114.70W; Figure 4.5). The climatic system is characterised by extreme aridity, with average temperatures in the summer and winter of 32°C and 12°C and extremes in the summer and winter of 52°C and -2°C, respectively. The average annual evaporation and precipitation rates are 900 and 70 mm yr^{-1}, respectively. The system is macrotidal (7-9 m range) characterised by semidiurnal tides; tidal forcing controls the variability of materials concentrations (Cupul Magaña 1994). The Delta is an hypersaline system responsible for the formation of the water mass of the Gulf of California (Roden and Groves 1959; Alvarez-Borrego and Schwartlose 1979, Torres-Orozco 1993, Lavin *et al.* 1995, 1997). The estuarine system is typically a negative estuary, with salinity decrease directed to the physiographic end of the Delta - the mouth of the estuary (typically from 38 to 36 psu; and between summer and winter (39 to 37 psu). The area of the Delta region included in this study is 450 km^2 (volume $\approx 1,660x10^6$ m^3).

The system is macro-tidal with 7-9 m tidal range and semidiurnal tides, which control the variability of the material concentrations (Cupul Magana 1994).

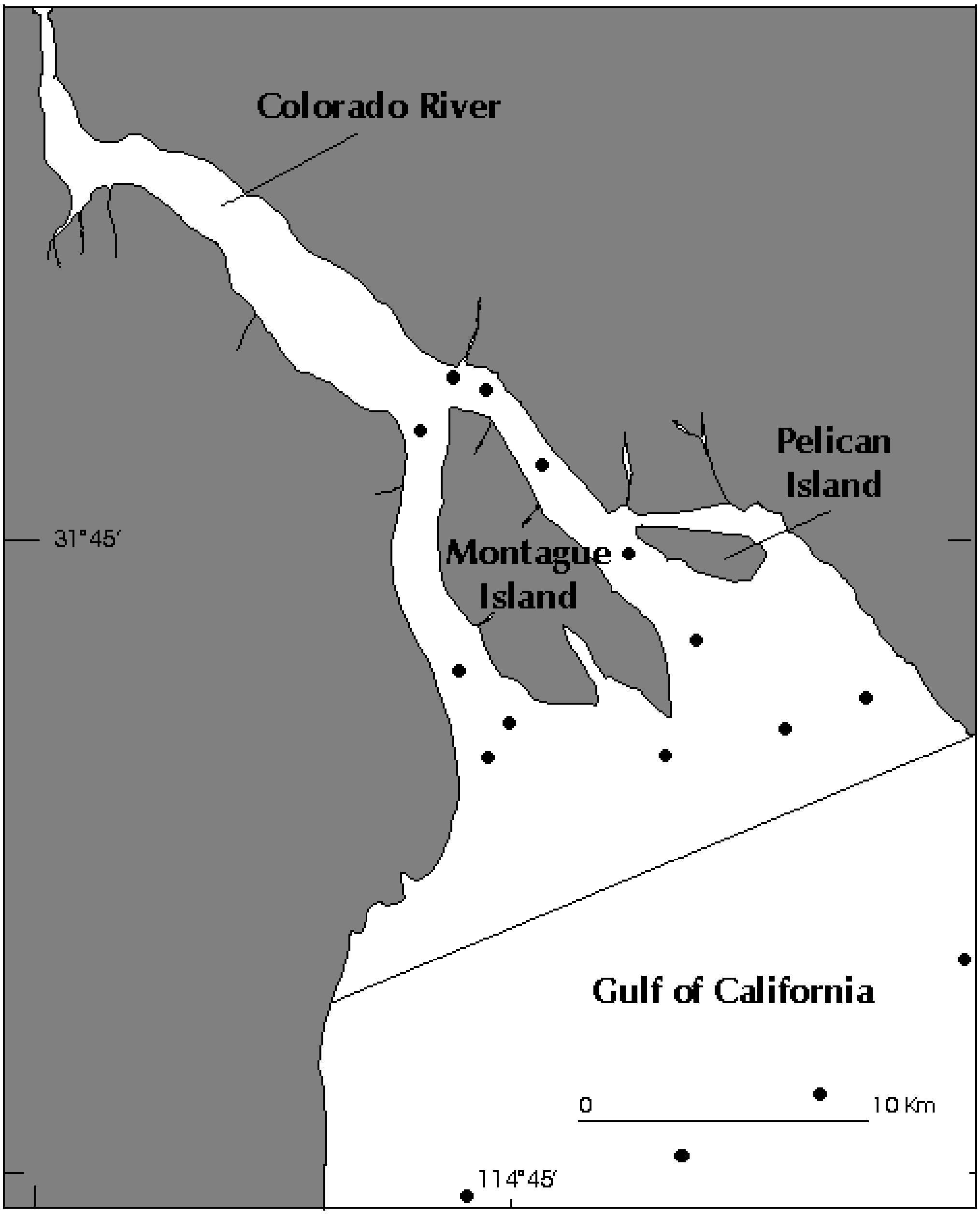


Figure 4.5. Northern section of the Gulf of California and the Colorado River Delta.

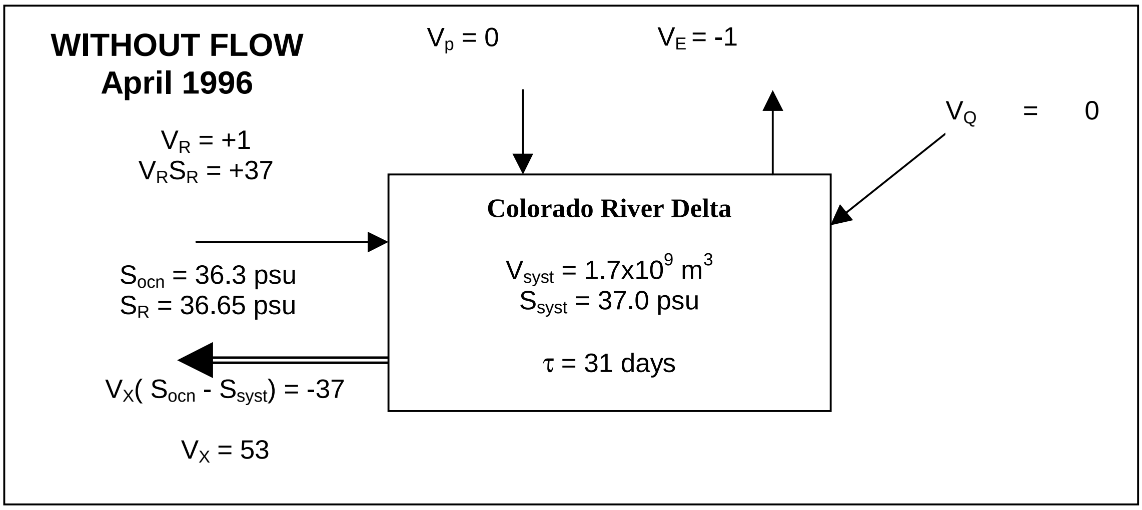
The Colorado River Delta is a fertile coastal zone. It is an area of reproduction and nursery for many fish species, some mammals and commercial crustaceans; some of these are considered to be in danger of extinction like the *totoaba* (*Totoaba macdonaldi*) and a small dolphin known as the 'v*aquita*' (*Phocoena sinus*) (Hernandez-Ayon 1993, Zamora-Casas 1993).

The input changes of the Colorado River have a great impact on the variability and distribution of suspended materials, sediments, nutrients and salinity in the Delta Region and upper Gulf of California (Hernandez-Ayon *et al.* 1993, Cupul Magana 1994, Nieto-García 1998). In general, the dissolved nutrients in the upper Gulf of California are not limiting for phytoplankton because concentrations are high (Alvarez-Borrego and Lara-Lara 1991).

This study makes use of the data presented in several other studies in the region dealing with changes in the materials supplied by the Colorado River. These studies include data from Hernandez-Ayon (1991), Hernandez-Ayon *et al.* (1993), Zamora-Casas (1993), Cupul-Magaña (1994) and Nieto-García (1998). The calculations presented here examine the system during the same month (April) in two contrasting conditions of Colorado River discharge (one with, and the other without, river discharge).

Water and salt budgets

The difference between the two periods is based on runoff (V_Q), which occurs only when the dams release excess water and the Colorado River becomes an input to the Delta. Groundwater discharge (V_G) is unknown and is probably small, due to impermeable sediments. There are no



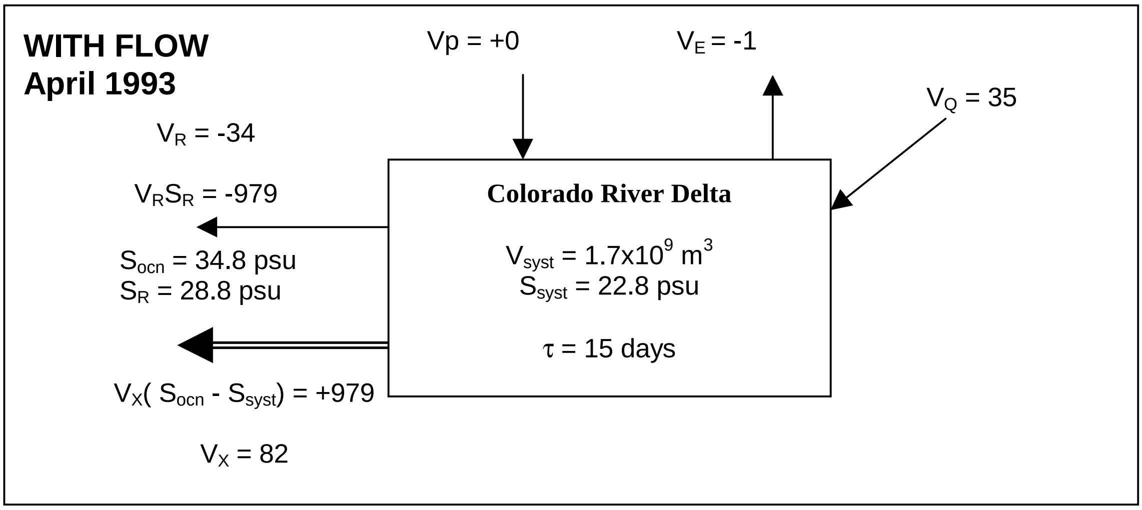


Figure 4.6 Water and salt budgets for the Colorado River Delta during periods without and with river flow. Water fluxes in $10^6\ m^3\ d^{-1}$; salt fluxes in 10^6 psu $m^3\ d^{-1}$.

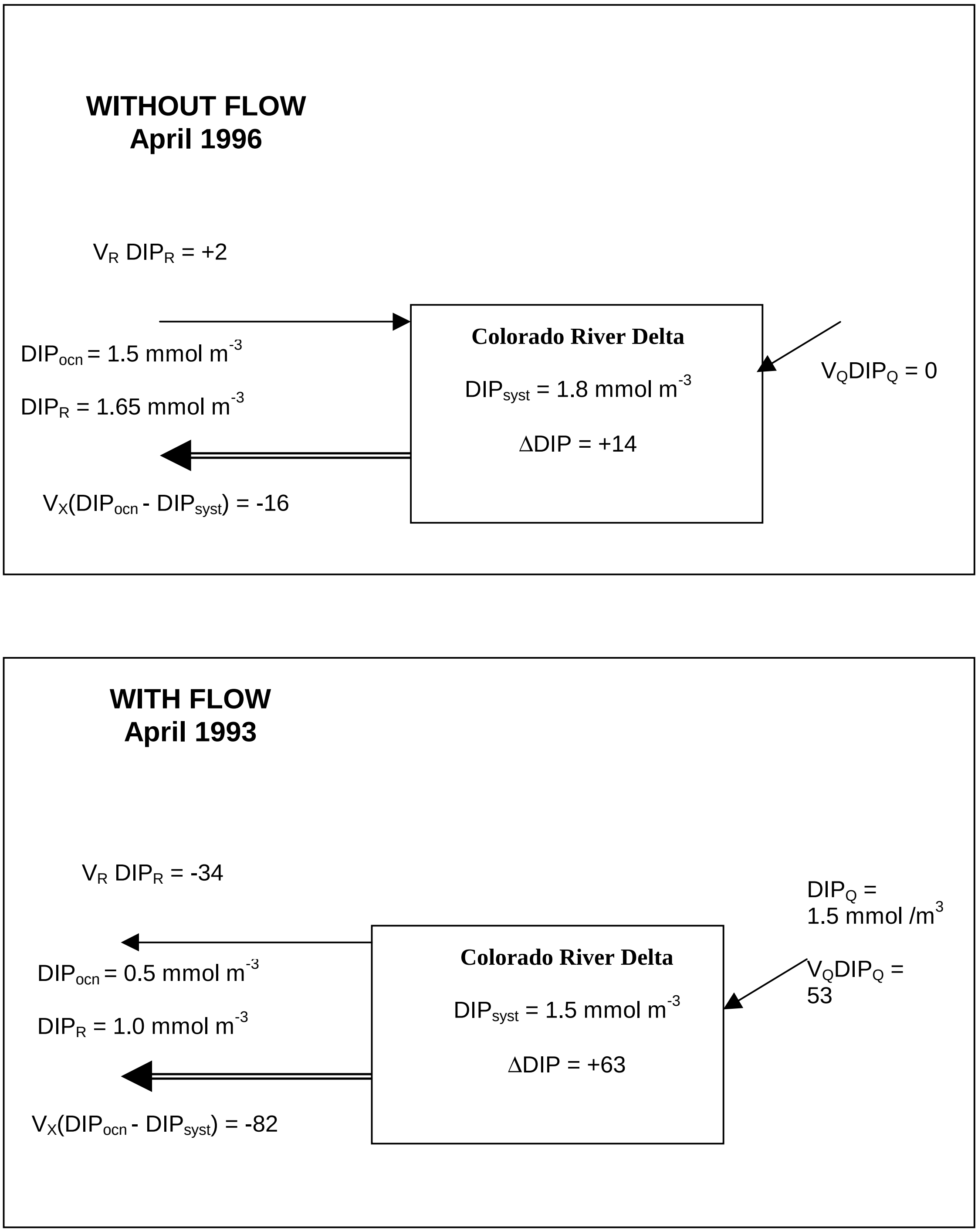


Figure 4.7. DIP budgets for the Colorado River Delta without and with river flow. DIP fluxes in 10^3 mol d^{-1}.

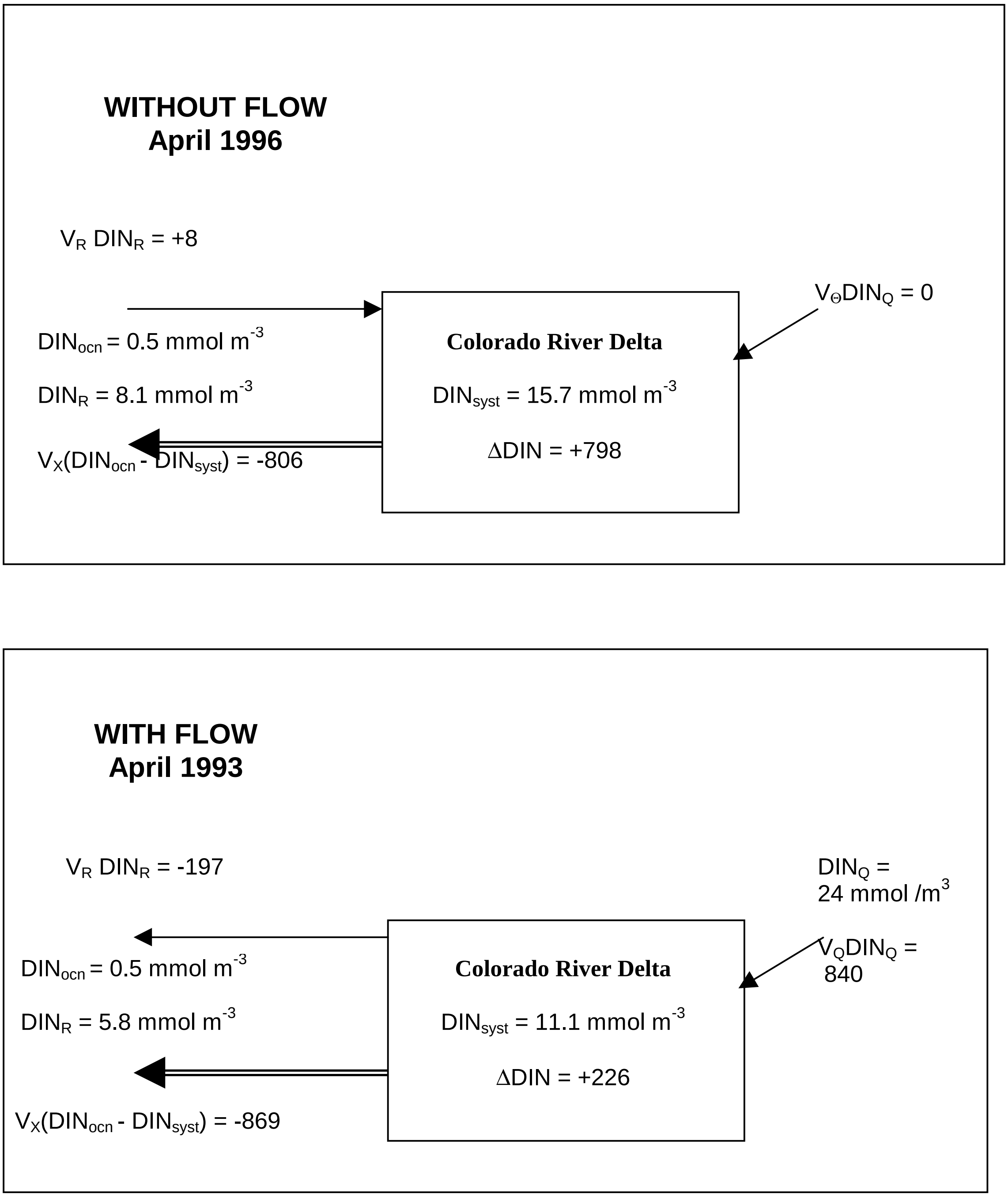


Figure 4.8 DIN budgets for the Colorado River Delta without and with river flow. DIN fluxes in 10^3 mol d^{-1}.

outfalls in the delta, so V_O is 0. So, during the first period V_O=V_Q=V_G=0 (without river discharge), and during the second one V_O=V_G=0, although there is river discharge. Precipitation (V_P) is highly seasonal but generally low. On the other hand, evaporation is very high and has its maximum effect in the first case, resulting in high salinity values. The exchange (V_X) flow was calculated using the salinity differences between the Delta and the adjacent upper Gulf of California; although the salinity gradients reversed, V_X was the main route of material transport in both cases. The exchange time ranged from about 31 days without to 15 days with discharge (Figure 4.6).

Budgets of nonconservative materials

P balance

Figure 4.7 contains the DIP budgets. In both cases Δ*DIP* was slightly positive. It was higher with river flow (+63x10^3 mol d^{-1}; 0.14 mmol m^{-2} d^{-1}) than without flow (+14x10^3 mol d^{-1}; +0.03 mmol m^{-2} d^{-1}).

N balance

The concentration of NO_3 was used as a measure of DIN because the NH_4 data are not available (they are probably low). Δ*DIN* was positive during the dry period (+798x10^3 mol d^{-1}; +1.8 mmol m^{-2} d^{-1}) and almost four times the value for the period of river flow (+226x10^3 mol d^{-1}; 0.5 mmol m^{-2} d^{-1}) (Figure 4.8).

Stoichiometric calculations of aspects of net system metabolism

The rates of DIP and DIN fluxes (Δ*DIP,* Δ*DIN*) in the Colorado River Delta are used to estimate nitrogen fixation minus denitrification (*nfix-denit).* Δ*DIP* scaled by the Redfield N:P ratio (16:1) is an estimate of expected Δ*DIN* associated with the oxidation of organic matter. The difference between observed Δ*DIN* and the expected value is an estimate of (*nfix-denit*), which was +1.4 mmol m^{-2} d^{-1} during the period without flow and -1.2 mmol m^{-2} d^{-1} during high flow. Because low flow periods presently dominate this system, the low-flow conditions are considered to represent the usual rate of (*nfix-denit*) for this system.

Similarly, Δ*DIP* multiplied by the negative of the Redfield C:P ratio is an estimate of net organic metabolism. During the 0-flow period, (*p-r*) was -3.2 mmol m^{-2} d^{-1}; during the high flow, it was -14.8 mmol m^{-2} d^{-1}. Again, the rate associated with low flow conditions is considered to be the typical rate. The system appears to be net heterotrophic.

4.3 Bahía San Quintín, Baja California: N/P Budgets within Compartments in a Coastal Lagoon

V.F. Camacho-Ibar, J.D. Carriquiry and S.V. Smith

Budgets of dissolved inorganic nitrogen and phosphorus for the whole of the Bahía San Quintín system were presented in some detail as a teaching example of multiple-complartment budgeting in Camacho-Ibar *et al.* (1997). The conclusion of the calculations was that Bahía San Quintín is a net heterotrophic system throughout the year. That is, the system apparently oxidises more organic matter than it produces over an annual cycle. The net metabolism estimated for the winter ($p\text{-}r \cong -1$ mmol C m^{-2} day^{-1}) was approximately an order of magnitude lower than the net system metabolism during summer ($p\text{-}r \cong -18$ mmol C m^{-2} day^{-1}).

From a global perspective, estimating the metabolism of whole systems is useful for the integration of worldwide data. However, the whole system values are more accurate if they are based on a summation of distinct sub-system values (see Webster *et al*. 1999). Here we give an example of partitioning a system into obvious sub-systems. Moreover, we also show that the stoichiometrically linked water-salt-nutrient budget models presented in the LOICZ Modelling Guidelines (Gordon *et al.* 1996) are also useful from a local perspective. The partition of a system into two or more sub-systems can help in describing details of how different parts of a system work from a net metabolism perspective.

Study area description

Many details of Bahía San Quintín (Baja California, México) relevant to budget calculations were described in Camacho-Ibar *et al.* (1997); those details will not be repeated here. For the exercise presented here, the system is divided in three sections (Figure 4.9): Bahía Falsa (BFa), Bahía San Quintín (BSQ) and the mouth of the bay (MoB). The area corresponding to each section is BFa = 9 km^2, BSQ = 15 km^2 and MoB = 18 km^2. Due to the lack of a detailed bathymetry, a mean depth of 2 m is assumed for all of the sections even though the inner arms of the bay may be shallower than the mouth section. This assumption doesnot affect the net water, salt and nutrient flux estimates, but influences the residence time calculations. Numbers on the map (Figure 4.9) correspond to sampling stations of August 1995, most of which were sampled at the surface and near the bottom. The mean salinity and nutrient concentrations in the ocean, BFa, BSQ and MoB were obtained from a total of 8, 12, 16 and 16 data points.

Consider a simplified view of the exchange of water within this system. The Y-shaped geometry of the bay allows only for the exchange of materials between the following subsystems: BFa-MoB, BSQ-MoB and MoB-Ocean. The boundaries between sub-systems were determined from the spatial clustering of salinity distribution. This clustering should represent ‘cells’, with more internal mixing than exchange across the cell boundaries.

Notation for mass balances presented here follows from Gordon *et al.* (1996).

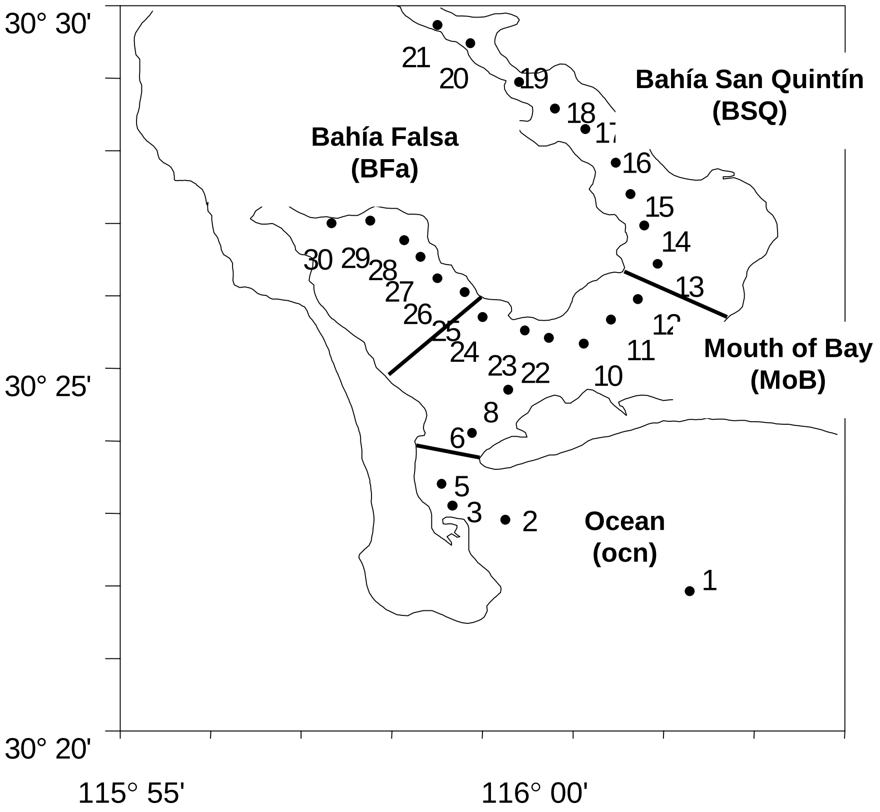


Figure 4.9. Bahía San Quintín subsystems as used for the 3-box model construction. Numbers indicate sampling stations during August 1995.

Water budget

Bahía San Quintín is a simple system in terms of freshwater balances, because several of the terms in the general water balance equation:

$$dV/dt = V_Q + V_P + V_G + V_O + V_E + V_R \qquad (1)$$

are negligible, where *dV/dt* represents the volume of the system; the remaining *V's* stand for volume fluxes, and the subscripts *Q, P, E, G,* and *R* represent river flow, precipitation, evaporation, groundwater flux and 'residual flow' (i.e., net flow through the bay mouth to balance the water volume) respectively.

San Quintín is located in an arid region in which surface runoff and groundwater flows are negligible most of the time, particularly during the summer. Direct sewage inputs through outfalls are also negligible. Therefore, the terms V_Q , V_G and V_O have been explicitly excluded from the calculations; and Equation (1) can be reduced to:

$$dV/dt = V_P + V_E + V_R \qquad (2)$$

For steady state conditions (i.e. $dV/dt = 0$), the residual volume (V_R) for BSQ and BFa becomes a function only of the balance between evaporation (V_E) and precipitation (V_P) (Figure 2):

$$V_R = - V_P - V_E \qquad (3)$$

Fluxes to the system of interest are positive; therefore V_E (that is, evaporation) is a term which will always have a negative value (see Table 4.1), as the process of evaporation removes water from the system.

Table 4.1. Freshwater flows, surface area and chemical composition of the different compartments in Bahía San Quintín. Data are for August 1995.

	V_P (10^3 m^3 d^{-1})	**V_E (10^3 m^3 d^{-1})**	**V_G (10^3 m^3 d^{-1})**	**Area (km^2)**	**S (psu)**	**DIP (mmol m^{-3})**	**DIN (mmol m^{-3})**
BSQ	1.5	-60	0	15	35.08	2.24	0.87
BFa	0.9	-36	0	9	34.57	1.89	1.62
MoB	1.8	-72	0	18	34.31	1.71	0.63
WHOLE	4.2	-168	0	42	34.66	1.95	0.99
OCEAN					33.78	0.80	1.87

In the case of the MoB sub-system, it is important to notice that the volume conservation (dV/dt) equation becomes more complex than that for BSQ and BFa (Figure 4.10). This balance includes not only the 'standard' residual flow with respect to the ocean, but also flow between MoB and both BSQ ($V_{R(MoB\text{-}BSQ)}$) and BFa ($V_{R(MoB\text{-}BFa)}$). Thus:

$$dV/dt = V_P + V_E + V_{R(ocn\text{-}MoB)} + V_{R(MoB\text{-}BSQ)} + V_{R(MoB\text{-}BFa)} \qquad (4)$$

For steady state conditions, the residual flow from the ocean to the MoB is

$$V_{R(ocn\text{-}MoB)} = - V_P - V_E - V_{R(MoB\text{-}BSQ)} - V_{R(MoB\text{-}BFa)} \qquad (5)$$

It must be noticed that, as in the case of V_E, the terms $V_{R(MoB\text{-}BSQ)}$ and $V_{R(MoB\text{-}BFa)}$ must be substituted in equations 4 and 5 with a negative value, because the flows represent outputs of water from the MoB sub-system (Figure 4.11). In cases of a graphical representation of multiple boxes such as this, it is useful to note the actual direction of flow between the boxes by the direction of the arrows between the boxes.

Salt budget

The equations to estimate the mixing volume (V_X) through salt budgets for each subsystem are shown in Figure 4.12. For the inner sub-systems, BFa and BSQ, the general salt balance equation is simple and similar to the single box model:

$$d(VS)/dt = V_P S_P + V_E S_E + V_R S_R + V_X (S_2 - S_1) \qquad (6)$$

As the salinities of rain water (S_P) and evaporated water (S_E) are close to 0 psu and assuming steady state ($d(VS)/dt = 0$), V_X is solved as follows:

$$V_X = - V_R S_R / (S_2 - S_1) \qquad (7)$$

The notation used in this example for the mixing volume between the subsystems BSQ-MoB, BFa-MoB and MoB-ocn was $V_{X(MoB\text{-}BSQ)}$, $V_{X(MoB\text{-}BFa)}$ and $V_{X(ocn\text{-}MoB)}$, respectively. Similar subscripts were used for other variables (Figure 4).

In the case of the MoB subsystem, the salt conservation equation

$$\begin{aligned} d(VS)/dt \;=\; & + V_R S_{R(ocn\text{-}MoB)} - V_R S_{R(MoB\text{-}BFa)} - V_R S_{R(MoB\text{-}BSQ)} \\ & + V_{X(ocn\text{-}MoB)} (S_{ocn} - S_{MoB}) \\ & + V_{X(MoB\text{-}BFa)} (S_{MoB} - S_{BFa}) \\ & + V_{X(MoB\text{-}BSQ)} (S_{MoB} - S_{BSQ}) \qquad (8) \end{aligned}$$

shown in Figure 4.12 is, in appearance, more complex than Equation 6. We have left explicit all of the inputs and outputs of salt to this sub-system, to demonstrate why the exchange volume of water between the MoB sub-system ($V_{X(ocn\text{-}MoB)}$) estimated from Equation 9:

$$V_{X(ocn\text{-}MoB)} = - V_R S_{R(ocn\text{-}MoB)} / (S_{ocn} - S_{MoB}) \qquad (9)$$

is independent of the mixing volumes between the BFa-MoB ($V_{X(MoB\text{-}BFa)}$) and the BSQ-MoB sub-system. As shown in Equation 5, this was not the case for the estimation of the residual flow between the MoB and the ocean ($V_{R(ocn\text{-}MoB)}$) which is a function of the residual flow between the BFa-MoB ($V_{R(MoB\text{-}BFa)}$) and the BSQ-MoB ($V_{R(MoB\text{-}BSQ)}$) sub-systems, neither the case of the nonconservative material fluxes (see Figure 4.13).

The salt conservation equation (Equation 8) for the MoB, explicitly included the terms: (a) $- V_R S_{R(MoB\text{-}BFa)}$ representing the export of salt from the MoB to BFa associated with the residual flow; (b) $+ V_{X(MoB\text{-}BFa)} (S_{MoB} - S_{BFa})$ representing the import of salt from BFa into the MoB associated with the mixing volume; (c) $- V_R S_{R(MoB\text{-}BSQ)}$ representing the export of salt from the MoB to BSQ associated with the residual flow; and (d) $+ V_{X(MoB\text{-}BSQ)} (S_{MoB} - S_{BSQ})$ representing the import of salt from BSQ into the MoB associated with the mixing volume. From Equation (7), it must be remembered that, by definition, the terms (a) and (b) are equivalent; thus they cancel out in Equation (8); so can the terms (c) and (d), because they are also equivalent. That is, to maintain the steady state condition assumed in equation (7), the salt which is gained in the BFa and BSQ sub-systems from the import of water through a residual flow is balanced by a net export of the same amount of salt through mixing. In other words:

$$V_{X(MoB\text{-}BFa)} (S_{MoB} - S_{BFa}) = - V_R S_{R(MoB\text{-}BFa)}, \text{ and}$$

$$V_{X(MoB\text{-}BSQ)} (S_{MoB} - S_{BSQ}) = - V_R S_{R(MoB\text{-}BSQ)}$$

Therefore, under the assumption of steady state, there is effectively no net exchange of salt between the MoB-BFa and the MoB-BSQ sub-systems.

The clarification above is important because, in the case of the nonconservative material budgets, the terms for the MoB shown in Figure 4.13, equivalent to the terms (a), (b), (c) and (d) indicated above, do not cancel out.

Water exchange time (τ) in each box follows the standard formulation. In the case of BFa, τ is the system volume divided by the sum of $V_{X(MOB\text{-}BFa)}$ and the absolute value for $V_{R(MoB\text{-}BFa)}$, that is:

$$\tau = \mathrm{V}_{\mathrm{BFa}}/(V_{X(MoB\text{-}BFa)} + |V_{R(MoB\text{-}BFa)}|) \qquad (10)$$

Note that V_P and V_E do not get included in the calculation. Water is exchanged by the combination of residual flow through the system (i.e., advection) plus mixing back and forth between one system and the adjacent system. The 'easy' way to remember this is to count the water flowing only in one direction - into the box. The formulation for BSQ is exactly analogous and need not be laid out. The value for τ between MoB and the other boxes is somewhat more difficult, because the calculation is based on all of the V_X values, but only V_R between the ocean and MoB. The reason is exactly analogous to the reason to ignore V_P and V_E in calculating τ for BFa and BSQ. That is, residual flow between these systems and MoB is already handled as water flow in $V_{R(ocn\text{-}MoB)}$. Thus, for MoB:

$$\tau = \mathrm{V}_{\mathrm{MoB}}/(V_{X(ocn\text{-}MoB)} + V_{X(MoB\text{-}BFa)} + V_{X(MoB\text{-}BSQ)} + |V_{R(ocn\text{-}MoB)}|) \qquad (11)$$

Budgets of nonconservative materials

Figure 4.13 shows the mass conservation equations for nonconservative materials in each sub-system. In this case, the general equation for budgets in BFa and BSQ

$$d(VY)/dt = V_R Y_R + V_X (Y_2 - Y_1) + \Delta Y \qquad (12)$$

is equivalent to the single box budget (see Camacho-Ibar *et al.* 1997) and simpler than the budget for the MoB

$$\begin{aligned} d(VY)/dt = \; & + V_R Y_{R(ocn\text{-}MoB)} - V_R Y_{R(MoB\text{-}BFa)} - V_R Y_{R(MoB\text{-}BSQ)} \\ & + V_{X(ocn\text{-}MoB)} (Y_{OC} - Y_{MoB}) \\ & + V_{X(MoB\text{-}BFa)} (Y_{MoB} - Y_{BFa}) \\ & + V_{X(MoB\text{-}BSQ)} (Y_{MoB} - Y_{BSQ}) \\ & + \Delta Y_{(MoB)} \end{aligned} \qquad (13)$$

In the case of the MoB, the nonconservative fluxes ($\Delta Y_{(MoB)}$) shown in Figures 4.14 and 4.15 are a function of the outputs of Y associated with the residual flows from the MoB to BFa ($V_R Y_{R(MoB\text{-}BFa)}$) and from the MoB to BSQ ($V_R Y_{R(MoB\text{-}BSQ)}$) and of the inputs of Y from the BFa and BSQ subsystems associated with the exchange flows $V_{X(MoB\text{-}BFa)} (Y_{MoB} - Y_{BFa})$ and $V_{X(MoB\text{-}BSQ)} (Y_{MoB} - Y_{BSQ})$ respectively. In constrast with salt (or any other conservative property), the inputs and outputs of Y between the MoB and BFa and the MoB and BSQ do not cancel out, i.e.:

$V_{X(MoB\text{-}BFa)} (Y_{MoB} - Y_{BFa}) \neq - V_R Y_{R(MoB\text{-}BFa)}$, and

$V_{X(MoB\text{-}BSQ)} (Y_{MoB} - Y_{BSQ}) \neq - V_R Y_{R(MoB\text{-}BSQ)}$

Therefore, in this example there was a net exchange of Y between the MoB-BFa and the MoB-BSQ subsystems as $\Delta Y_{(BFa)}$, $\Delta Y_{(BSQ)}$ and $\Delta Y_{(MoB)}$ were different from zero.

Results and discussion

The results of the budgets are summarised in Figures 4.12, 4.14, 4.15 and 4.16 and in Tables 4.2 and 4.3.

Table 4.2. Estimates of the residual volume flow (V_R), exchange volume flow (V_X), and water exchange time (τ) obtained from the water and salt budgets for the different compartments in Bahía San Quintín. Data are for August 1995. The values for BSQ, BFa, and MoB are the results of the 3-box calculations presented here; 'Bay Sum' is based on V_X and V_R and MoB only, while the 'WHOLE' number is the result of the earlier 1-box model (Camacho-Ibar *et al.* 1997).

	V (1000 m^3)	**V_R (1000 m^3 d^{-1})**	**V_X (1000 m^3 d^{-1})**	**τ (days)**
BSQ	30 000	59	2,636	11
BFa	18 000	35	4,650	4
MoB	36 000	164	10 536	2
Bay Sum	84 000	164	10 536	8
WHOLE	84 000	164	6,350	13

Table 4.3. Estimates of the surface area normalised nonconservative DIP and DIN fluxes, the difference between N fixation and denitrification, and of the net metabolism of the different compartments in Bahía San Quintín. Data are for August 1995. The values for BSQ, BFa, MoB are the results of the 3-box calculations presented here; 'Bay Sum' is the area weighted mean of the 3-box model; and 'WHOLE' is the result of the earlier 1-box model (Camacho-Ibar *et al.* 1997).

	ΔDIP (mmol $m^{-2}d^{-1}$)	**ΔDIN (mmol $m^{-2}d^{-1}$)**	**(*nfix-denit*) (mmol $m^{-2}d^{-1}$)**	**(*p-r*) (mmol $m^{-2}d^{-1}$)**
BSQ	+0.09	+0.04	-1.4	-10
BFa	+0.09	+0.51	-0.9	-10
MoB	+0.41	-1.02	-7.6	-43
Bay Sum	+0.21	-0.32	-3.7	-22
WHOLE	+0.17	-0.14	-2.8	-18

Table 4.2 includes the results from the water and salt budgets for each of the sub-systems and for the whole system. These results show that the residence time of the whole Bahia San Quintín, estimated from a 1-box model, is about 13 days for August 1995. After partitioning the system, however, it can be seen that the MoB and the BFa subsystems are more dynamic, with residence times of less than 4 days. On the other hand, the residence time of the BSQ subsystem is nearly 3 times longer than those for the other sub-systems.

Our previous estimate of the net metabolism of the whole Bahía San Quintín system (Table 4.3), allowed to conclude that it is a net heterotrophic system with a (p-r) = -18 mmol m^{-2} day^{-1}. However, partitioning the bay into sub-systems allows us to observe that heterotrophy is four times more intense at the MoB ([p-r] = -43 mmol m^{-2} day^{-1}) than at the inner arms ([p-r] = -10 mmol m^{-2} day^{-1}). The closer balance between p and r in BSQ and BFa is probably due to the photosynthetic activity of seagrasses covering most of the subtidal sediments. The results from partitioning the system imply that a significant amount of the OC imported from the ocean is probably oxidised in the sediments of the MoB, where the limited seagrass coverage allows a greater imbalance between p and r. The whole Bahía San Quintín is a net denitrifying system; however, the 3-box model allows us to observe that denitrification at the MoB is approximately 7 times more intense than at the inner arms (see Figure 4.16).

A further point emerges in the comparison of the ‘Bay Sum’ values with the ‘WHOLE’ bay values. Although the trends remain qualitatively the same, the Bay Sum estimate based on the three box model gives higher results than the results obtained from the single box model. If the data set is sufficient to allow such partitioning, the multiple box model should give a more representative approximation of the bay performance than the single box model. Often, of course, the available data simply do not justify this higher resolution.

Summary and conclusions

In summary, the two advantages to the multiple-box model over the single-box model are resolution of spatial differences (and similarities) in the comparison among different parts of the system, and a more accurate resolution of whole-system performance by the addition of fluxes among different compartments of the system. This system is not vertically stratified to any significant extent, but in a similar fashion, a vertically stratified system should be divided into vertically resolved boxes. Discussion by Webster *et al.* (1999) helps to clarify the mathematics behind these points.

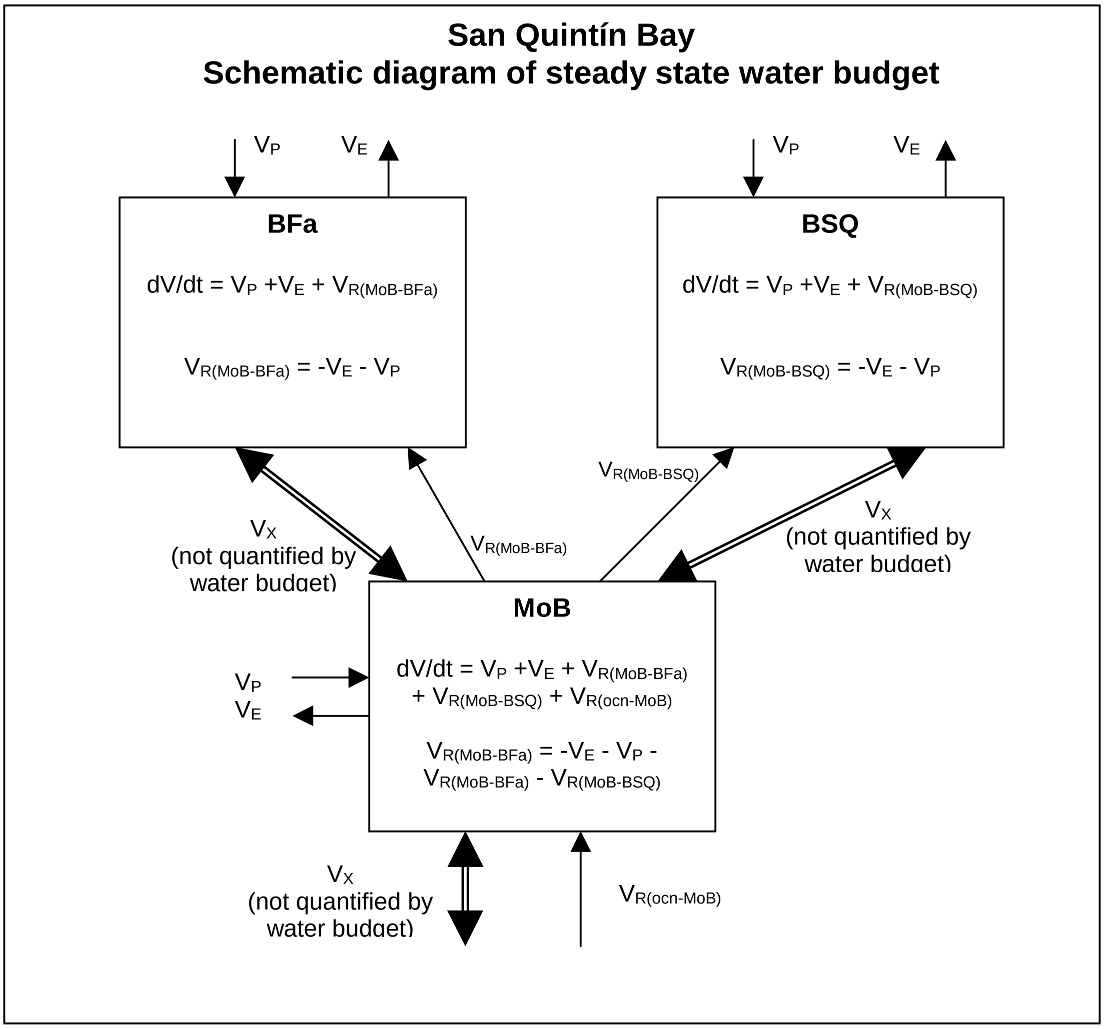


Figure 4.10. Schematic diagram of steady state water budget for a 3-box model of San Quintín Bay. The known quantities are V_P and V_E (precipitation, evaporation). The V_R values (residual flow) are unknown and derived from the water budget, and the mixing terms (V_X) are not solved from the water budget.

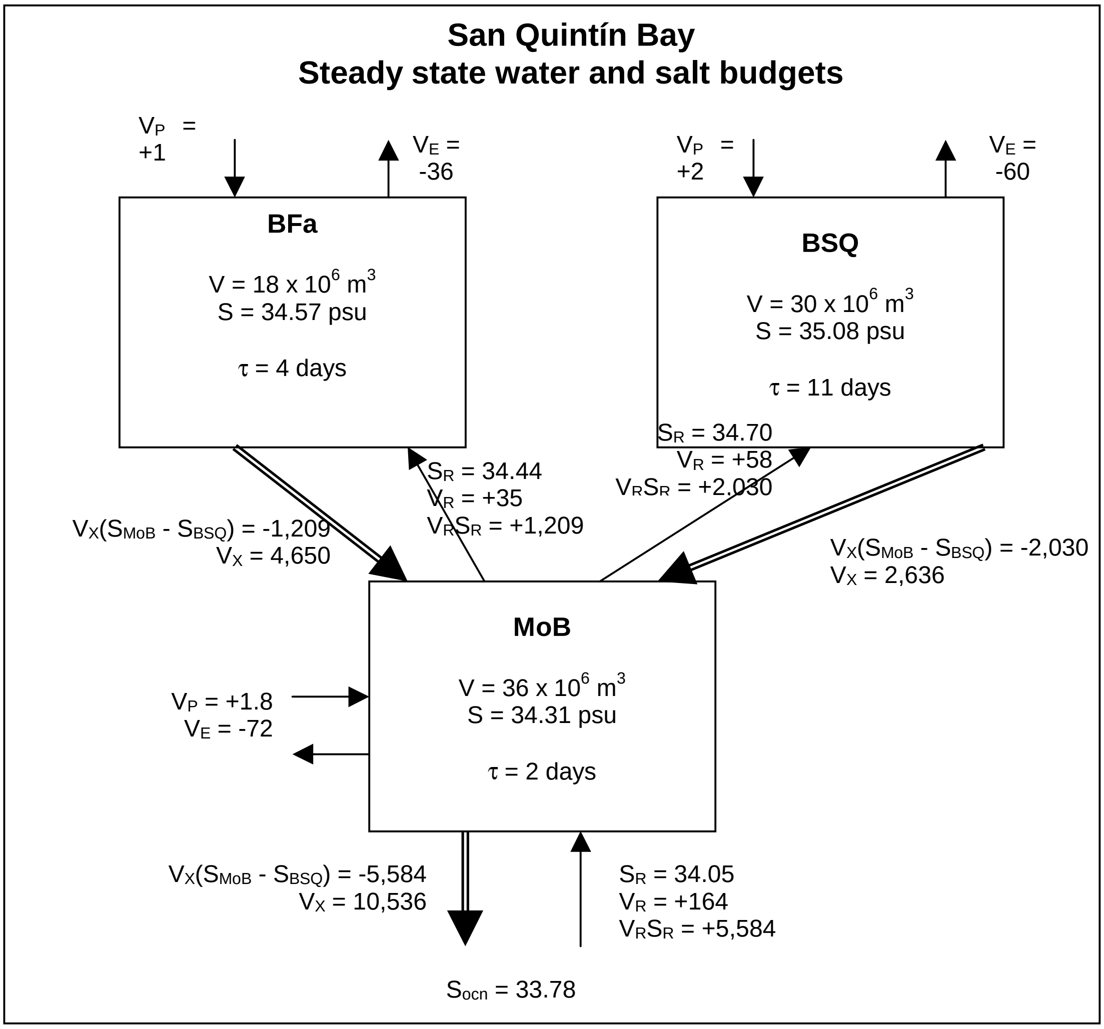


Figure 4.11. Steady state water and salt budgets for the 3-box model of San Quintín Bay. The known quantities are V_P, V_E, and the salinity values. The V_R values (residual flow) are unknown and derived from the water budget, and V_X terms are solved to balance the salt budget. Note that the conventions are to calculate fluxes as positive inward. However, the arrows on a multiple box diagram are drawn to illustrate the direction of both water and salt flux (for V_R) or the direction of salt flux (for V_X, which has no net water flux). Water fluxes in 10^3 m^3 d^{-1}, and salt fluxes in 10^3 psu m^3 d^{-1}.

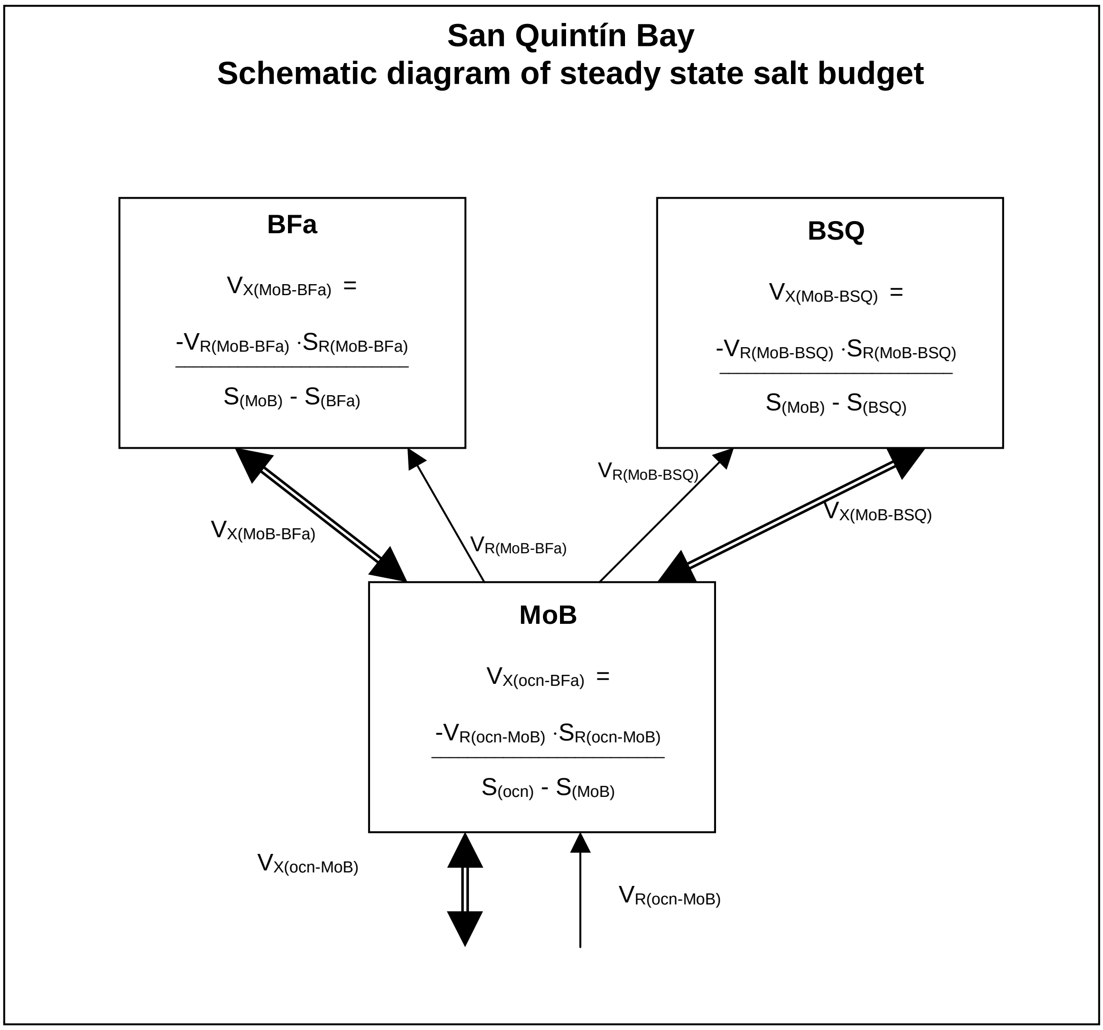


Figure 4.12. Schematic diagram of steady state salt budget for a 3-box model of San Quintín Bay. The V_R values derived from the water budget. Salinity (S) is known for each box. S_R, the residual salinity, is the average salinity between adjacent boxes. The mixing terms (V_X) are the unknowns and are derived to balance the salt fluxes.

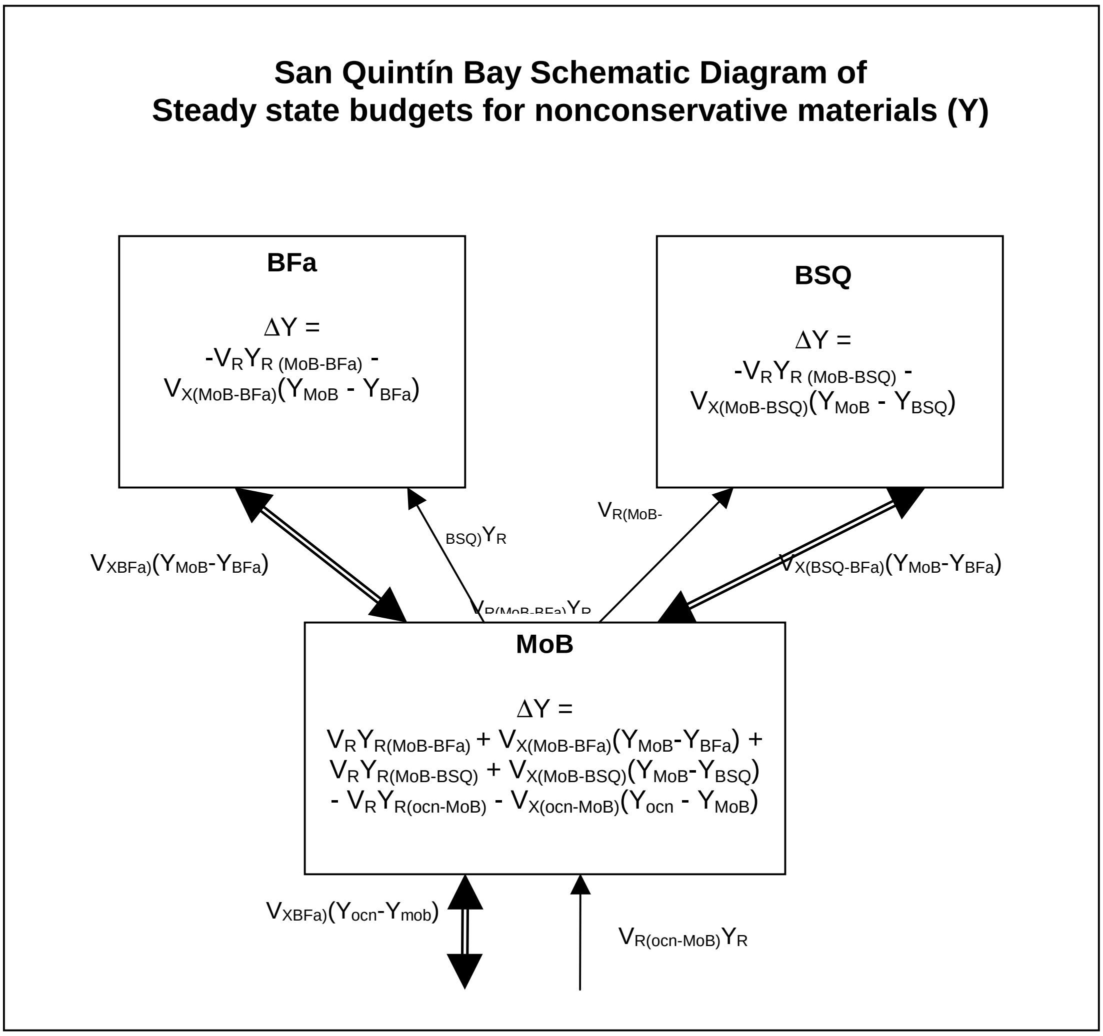


Figure 4.13. Schematic diagram of steady state budget of a nonconservative material (Y) for a 3-box model of San Quintín Bay. The V_R and V_X values are derived from the water and salt budgets. Note that the conventions are to calculate fluxes as positive inward. However, the arrows on a multiple box diagram are drawn to illustrate the direction of material flux. The concentration of Y is known for each box. Y_R, the residual value of Y, is the average Y between adjacent boxes. The values Δ*Y* are the unknowns and represent the release (+) or uptake (-) of Y within each box.

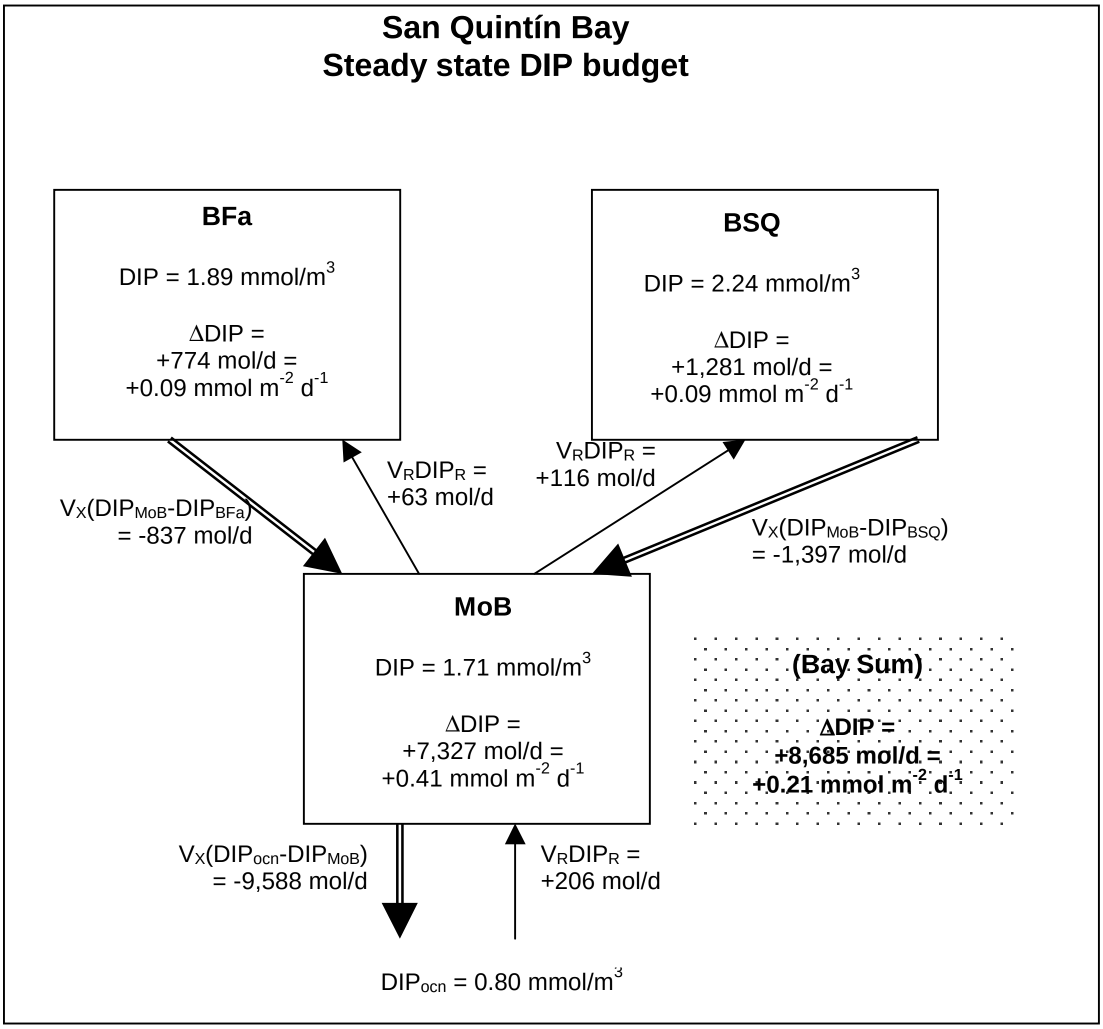


Figure 4.14. Steady state DIP budget for the 3-box model of San Quintín Bay. The known quantities are the *V* values (from the water and salt budgets) and the DIP concentrations. The residual DIP values (DIP_R) are the average of DIP for adjacent boxes. Note that the conventions are to calculate fluxes as positive inward. However, the arrows on a multiple box diagram are drawn to illustrate the direction of material flux.

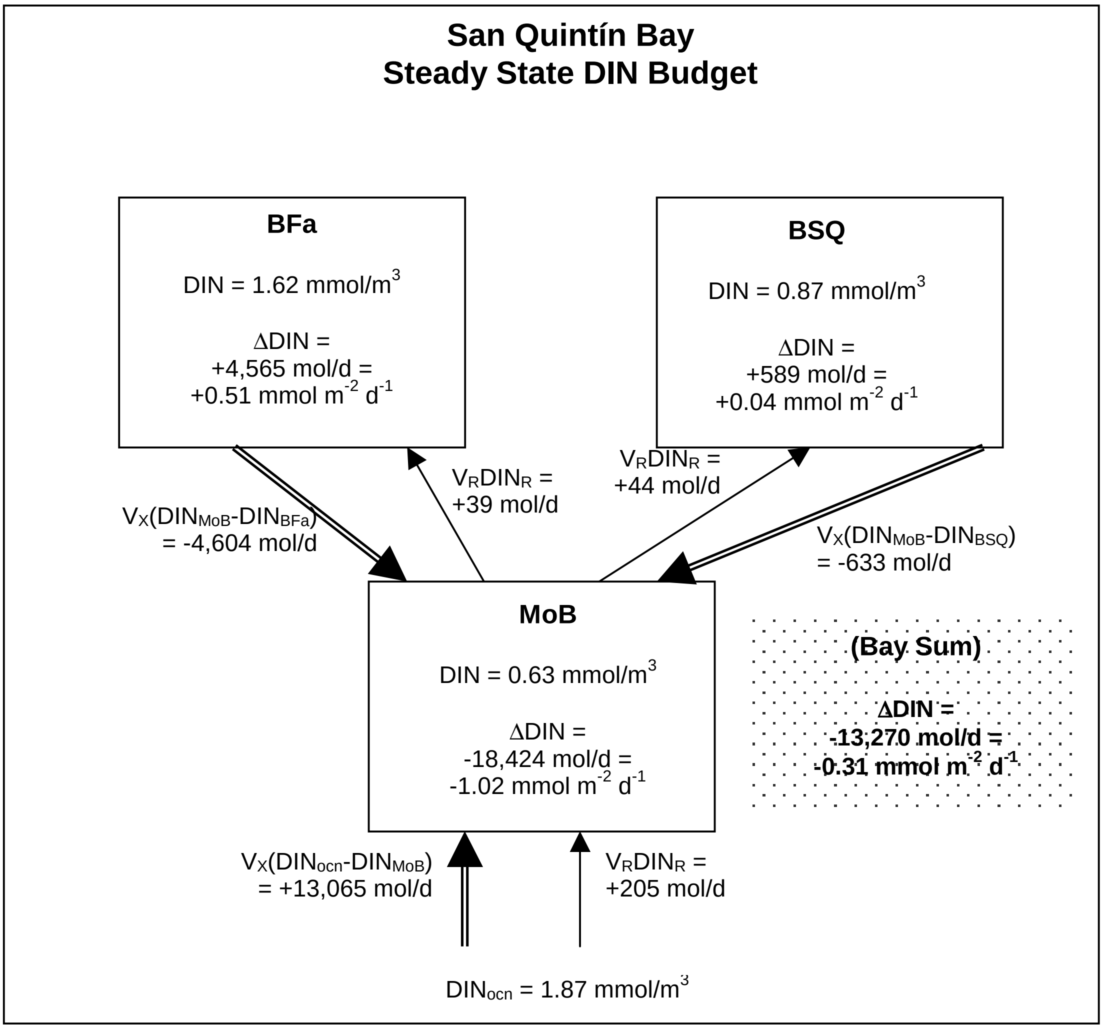
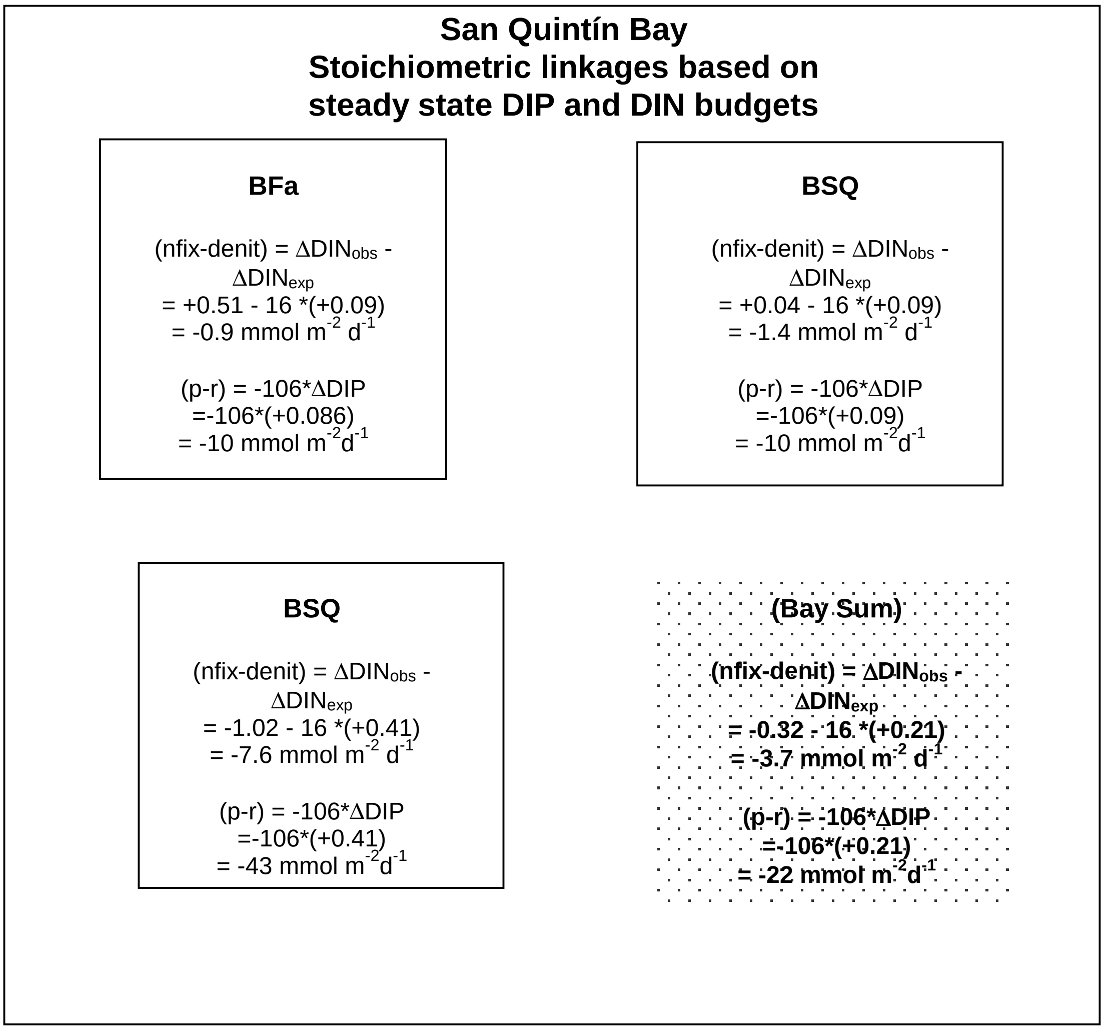


Figure 4.15. Steady state DIN budget for the 3-box model of San Quintín Bay. The known quantities are the *V* values (from the water and salt budgets) and the DIN concentrations. The residual DIN values (DIN_R) are the average of DIN for adjacent boxes. Note that the conventions are to calculate fluxes as positive inward. However, the arrows on a multiple box diagram are drawn to illustrate the direction of material flux.



San Quintín Bay
Stoichiometric linkages based on
steady state DIP and DIN budgets

BFa

(nfix-denit) = ΔDIN_{obs} - ΔDIN_{exp}
= +0.51 - 16 *(+0.09)
= -0.9 mmol m^{-2} d^{-1}

(p-r) = -106*ΔDIP
=-106*(+0.086)
= -10 mmol $m^{-2}d^{-1}$

BSQ

(nfix-denit) = ΔDIN_{obs} - ΔDIN_{exp}
= +0.04 - 16 *(+0.09)
= -1.4 mmol m^{-2} d^{-1}

(p-r) = -106*ΔDIP
=-106*(+0.09)
= -10 mmol $m^{-2}d^{-1}$

BSQ

(nfix-denit) = ΔDIN_{obs} - ΔDIN_{exp}
= -1.02 - 16 *(+0.41)
= -7.6 mmol m^{-2} d^{-1}

(p-r) = -106*ΔDIP
=-106*(+0.41)
= -43 mmol $m^{-2}d^{-1}$

(Bay Sum)

(nfix-denit) = ΔDIN_{obs} - ΔDIN_{exp}
= -0.32 - 16 *(+0.21)
= -3.7 mmol m^{-2} d^{-1}

(p-r) = -106*ΔDIP
=-106*(+0.21)
= -22 mmol $m^{-2}d^{-1}$

Figure 4.16. Stoichiometric calculations based on steady state DIP and DIN budgets for the 3-box model of San Quintín Bay.

5. BUDGETS FOR OTHER CENTRAL AMERICAN SITES

The Central American region has a diverse climatic regime and a large number of estuarine systems, whose ecology and biogeochemical performance has potential to contribute significantly to the LOICZ objectives. While there are many universities and research agencies in the coastal nations, the availability of information from ecosystem assessments remains sparse within the global literature. The work in this Workshop represents a small step in bringing together information and, importantly, raising the awareness and skills for further research on system function and change. LOICZ expects to build on this work through subsequent workshops and collaborative efforts with the research community in order to obtain a broader view of the status and regimes of change influencing the diverse coastal lagoons and estuarine systems.

5.1 Laguna de La Restinga, Venezuela

Luis Troccoli Ghinaglia, Jorge A. Herrera-Silveira and Julio Salazar López

Study area description

Laguna de La Restinga (area 26×10^6 m^2; depth 1.5 m; volume 39×10^6 m^3) is a coastal lagoon located on Margarita Island, Venezuela, in the southeast Caribbean (Figure 5.1). The lagoon has a triangular shape, and communication with the sea is by an open mouth (200 m wide) on the south side. The lagoon has no river discharge; the only source of water exchange is the open sea. The southern portion is separated from the open ocean by a sand barrier (Zarzosa 1974). The lagoon is hypersaline and considered a negative estuary (Gómez-Gaspar 1983). It is surrounded by mangrove vegetation (*Rhizophora mangle*, *Avicennia germinans* and *Laguncularia racemosa*). The bottom has some areas of seagrass (*Thalassia testudinum*) near the mouth and *Halodule* in the inner zone. The average precipitation of Margarita Island is about 400 mm yr^{-1} and the evaporation rate is about 1,100 mm yr^{-1}. The tidal range is 50 cm. The range of primary production is 60-180 g m^{-2} yr^{-1} (Gómez-Gaspar 1983).

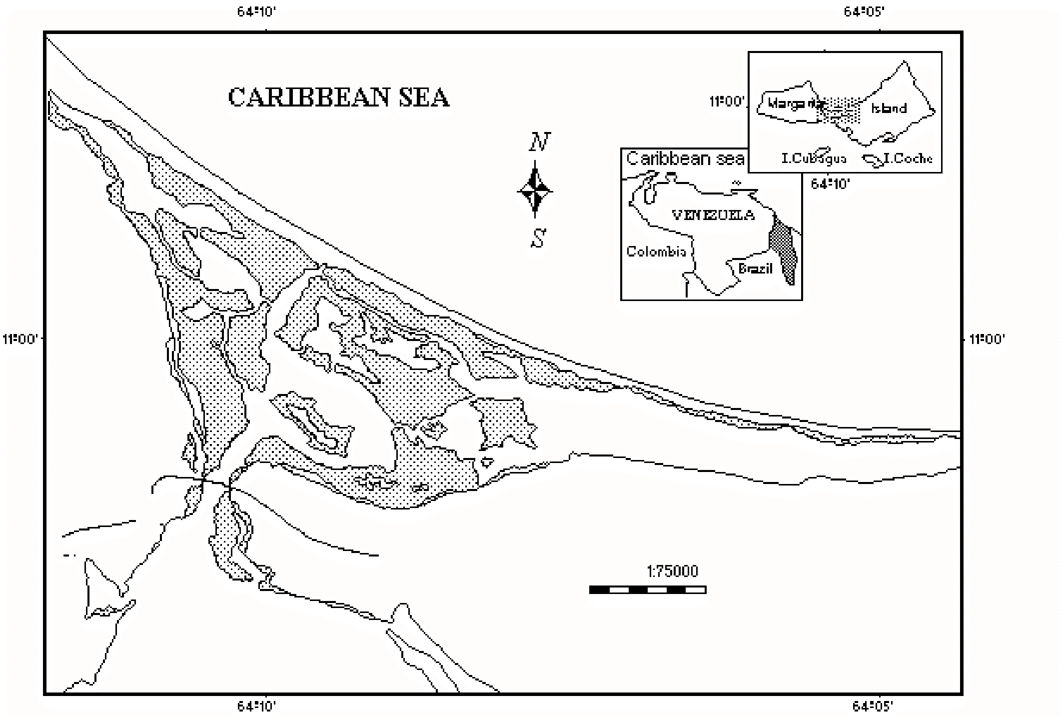


Figure 5.1. Map of Laguna La Restinga, Margarita Island, Venezuela.

The climatic conditions of the area are separated according to Herrera and Febres (1975) into the dry season, when coastal upwelling occurs in the adjacent ocean, and the rainy season when the wind speed is very low. In the budgets presented here, we separate the two seasons: from November to March (dry), and from April to October (wet). The analyses are based on studies of Gomez and Chanut (1993), Monente (1978) and Salazar (1996). Water composition, average rainfall and average evaporation in the two seasons are summarised on the figures illustrating the budgets.

Water and salt budgets

The water and salt budgets are shown in Figure 5.2. These calculations are based on the average rainfall, evaporation, and salinity during the five-month dry season and seven-month

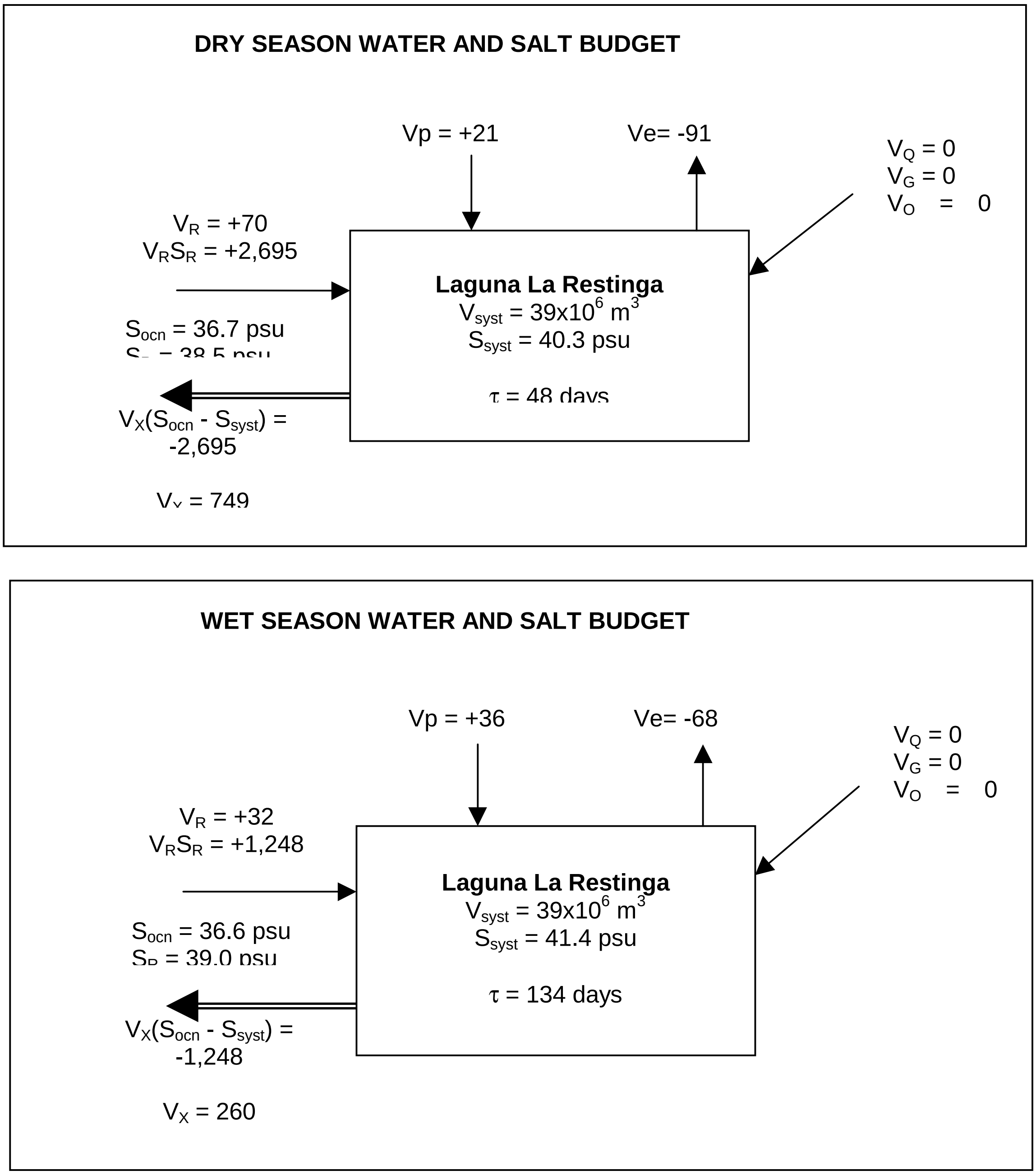


Figure 5.2. Water and salt budgets for Laguna la Restinga, separated into the wet and dry seasons. (Water fluxes in 10^3 m^3 day^{-1}; salt fluxes in 10^3 psu m^3 day^{-1}.)

wet season. During both seasons, evaporation substantially exceeds rainfall. Mixing (V_X) appears to be more rapid during the dry season, apparently because of the higher winds. Water exchange time (τ) can be calculated as $V_{syst}/(V_X + |V_R|)$. During the dry season the exchange time is about 48 days, during the wet season it is about 134 days. If the calculation is weighted by the lengths of the two seasons, the annual average value for τ is 84 days.

Budgets of nonconservative materials

P balance

Figure 5.3 illustrates the budgets of DIP and DIN in this system for the wet and dry seasons. Both residual flow (driven inward by net evaporation) and mixing (from high-phosphorus ocean water to lower phosphorus lagoon water) deliver DIP to this system, where it is taken up. ΔDIP in the dry season is -132 mol day^{-1}; in the wet season it is -44 mol d^{-1}. If the data are weighted by the length of the seasons, the annual average value for ΔDIP is -81 mol d^{-1}. This is equivalent to the very slow uptake rate of 0.003 mmol m^{-2} d^{-1}. Despite the low rate, the system gradients strongly support the idea that DIP is taken up in this system.

N balance

Similarly, the balance for DIN (Figure 5.4) implies a DIN sink of -667 mol d^{-1} during the dry season, -470 during the wet season, and an annual average ΔDIN of -552 mol day^{-1}. This is equivalent to an uptake rate of -0.02 mmol m^{-2} d^{-1}.

Stoichiometric calculations of aspects of net system metabolism

Stoichiometric estimates can be based on the molar C:N:P ratio of material likely to be transported into this system and reacting there. We assume that this material is plankton, with a C:N:P ratio of 106:16:1.

An estimate of nitrogen fixation minus denitrification (*nfix-denit*) is established as the difference between observed and expected ΔDIN, where the expected ΔDIN is 16xΔDIP: (*nfix-denit*) =
-552 mol d^{-1}-16x(-81) mol d^{-1} = +744 mol d^{-1}. According to this stoichiometric assumption, this system appears to be fixing nitrogen at the very slow rate of +0.03 mmol m^{-2} d^{-1}. This rate is probably indistinguishable from 0.

An estimate of net ecosystem metabolism or production minus respiration (*NEM*=[*p-r*]) is derived from the assumption that ΔDIP reflects release from plankton organic matter. Thus, (*p-r*) = -106xΔDIP = -106x(-81 mol d^{-1}) = -8,600 mol d^{-1}. According to this assumption, primary production exceeds respiration by about 0.3 mmol m^{-2} d^{-1} (*p-r*) . It was stated in the introduction that primary production in this system lies between about 80 and 160 g C m^{-2} yr^{-1}. If we take the average of these numbers and express them on a daily rate, they are equivalent to a primary production rate of about 30 mmol m^{-2} d^{-1}. From the calculation of (*p-r*), we can see that primary production exceeds respiration by about 1%.

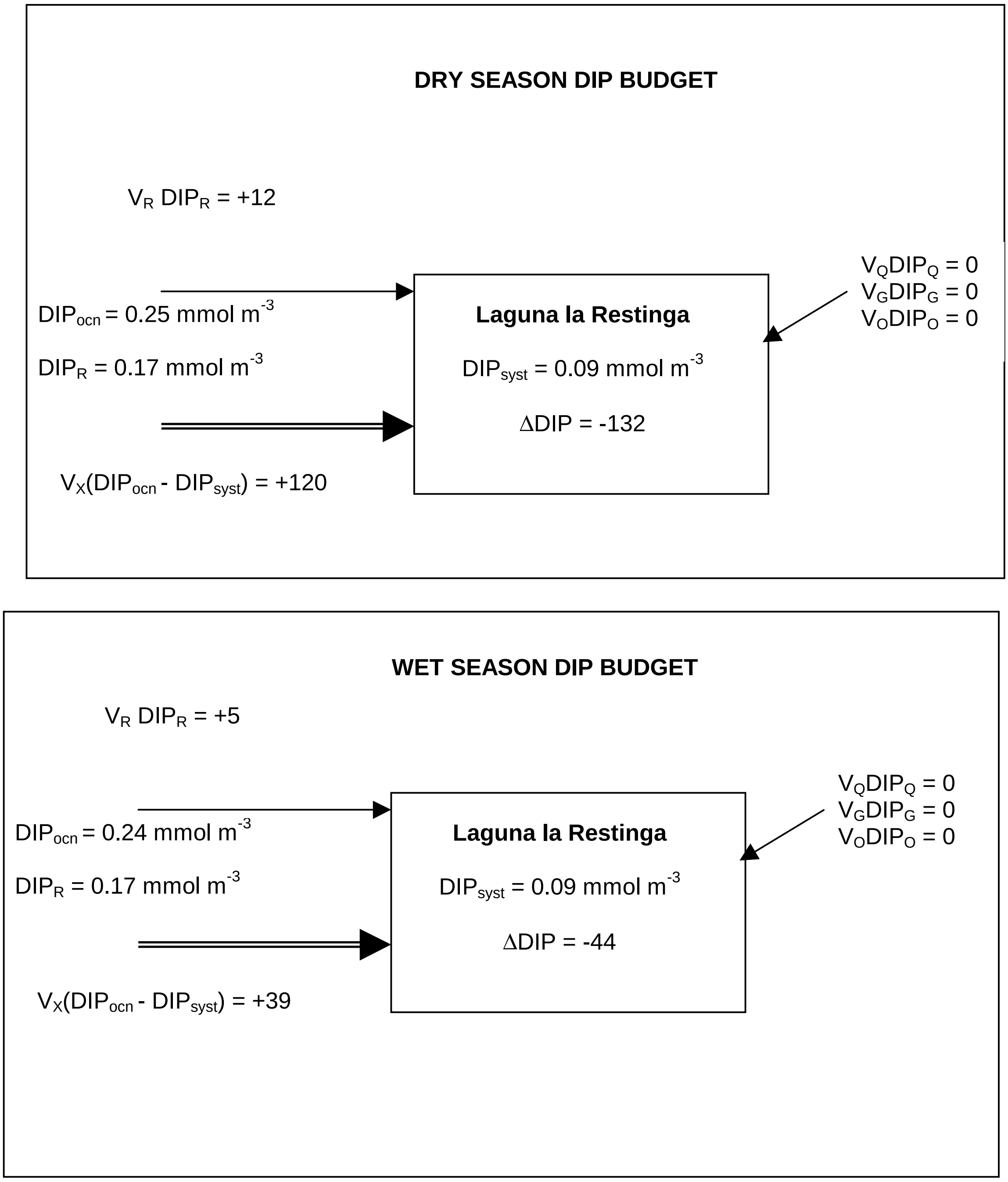


Figure 5.3. Dry season and wet season DIP budgets for Laguna la Restinga. Fluxes in mol day^{-1}.

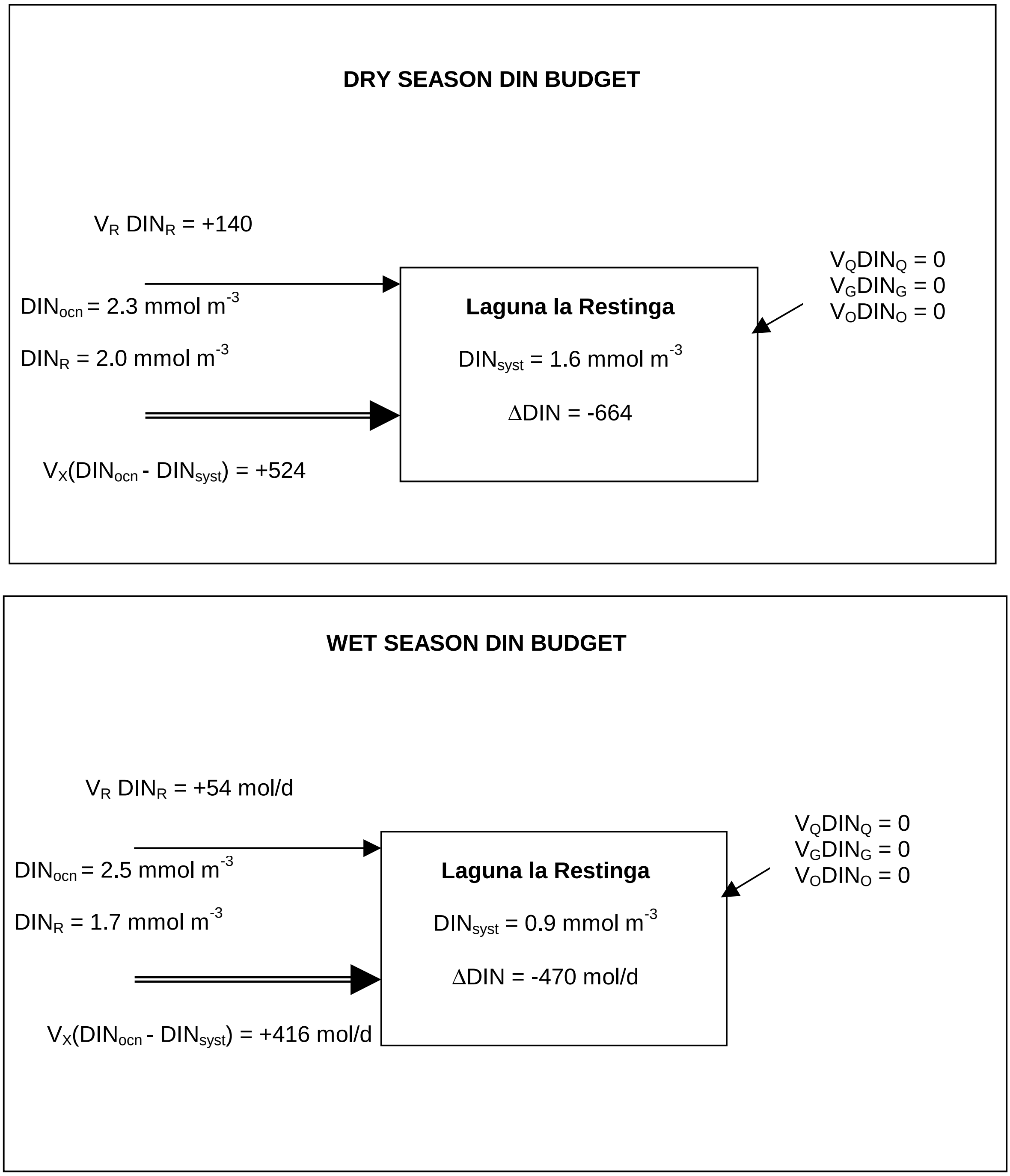


Figure 5.4. Dry season and wet season DIN budgets for Laguna la Restinga. Fluxes in mol day^{-1}.

5.2 Gulf of Nicoya, Costa Rica

S.V. Smith and C.J. Crossland

<u>*Study area description*</u>

The Gulf of Nicoya (10°N; 85°W) is a large estuary located on the Pacific Ocean coast of Costa Rica (Figure 5.5). The estuary is 25 km long (surface area 525 km^2; volume 5.5 km^3) and shows positive estuary characteristics in its discharge of waters through a stratified gulf connecting with the adjacent deep and low-nutrient waters of the Pacific Ocean (Epifanio *et al.* 1983). Depth increases (6-40m) from the Rio Tempisque to the mouth of the estuary, between San Lucas Island and the Puntarenas Peninsula. A small sill (28m depth) occurs outside the estuary in the Gulf, delineating the vertically mixing waters of the estuary from the stratified waters of the Gulf. Mangrove systems occur within the estuary, and seasonally-elevated primary production in the water column and organic loads from mangrove systems and the Rio Tempisque have been inferred (Epifanio *et al.* 1983). Significant amounts of sewage are discharged into the estuary from the city of Puntarenas (about 50 000 population).

The seasonal pattern of rainfall has a marked effect on the characteristics of the waters of the estuary, seen particularly in the elevation of DIN concentrations during the wet season. Seasonal rainfall is 50 mm per month during the 'dry' season: December to April and >600 mm per month during the 'wet' season: May to November. This influences freshwater input to the

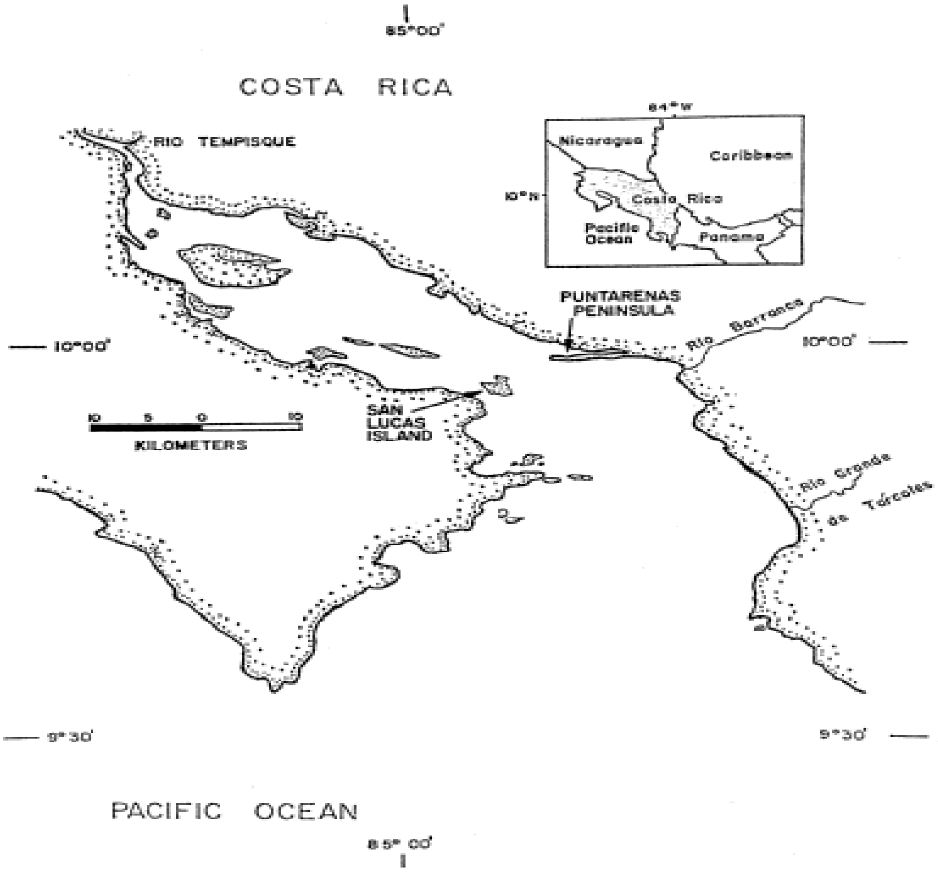


Figure 5.5. Map of Gulf of Nicoya, Costa Rica (from Epifanio *et al.* 1983).

estuary, which is dominantly from river flow out of the Rio Tempisque whose peak discharges range from 40 to 60 m^3 sec^{-1}. In the wet season, average salinity of the estuary falls from around $33^{o}/_{oo}$ to $31^{o}/_{oo}$, and rarely falls below $25^{o}/_{oo}$ (Epifanio *et al.* 1983). DIN concentrations in the estuary are elevated 10-fold during the wet season, but phosphorus levels are only marginally affected. The two seasons have been separately considered in developing the budget presented herein.

Water and salt budgets

Calculation of water and salt budgets (Figure 5.6) is based on average rainfall and salinity during the five-month dry season and seven-month wet season. Evaporation is assumed to be at a constant rate of 1,000 mm per year, in keeping with other systems from the region. Additional characteristics of river inputs were derived from Meybeck *et al.* (1989).

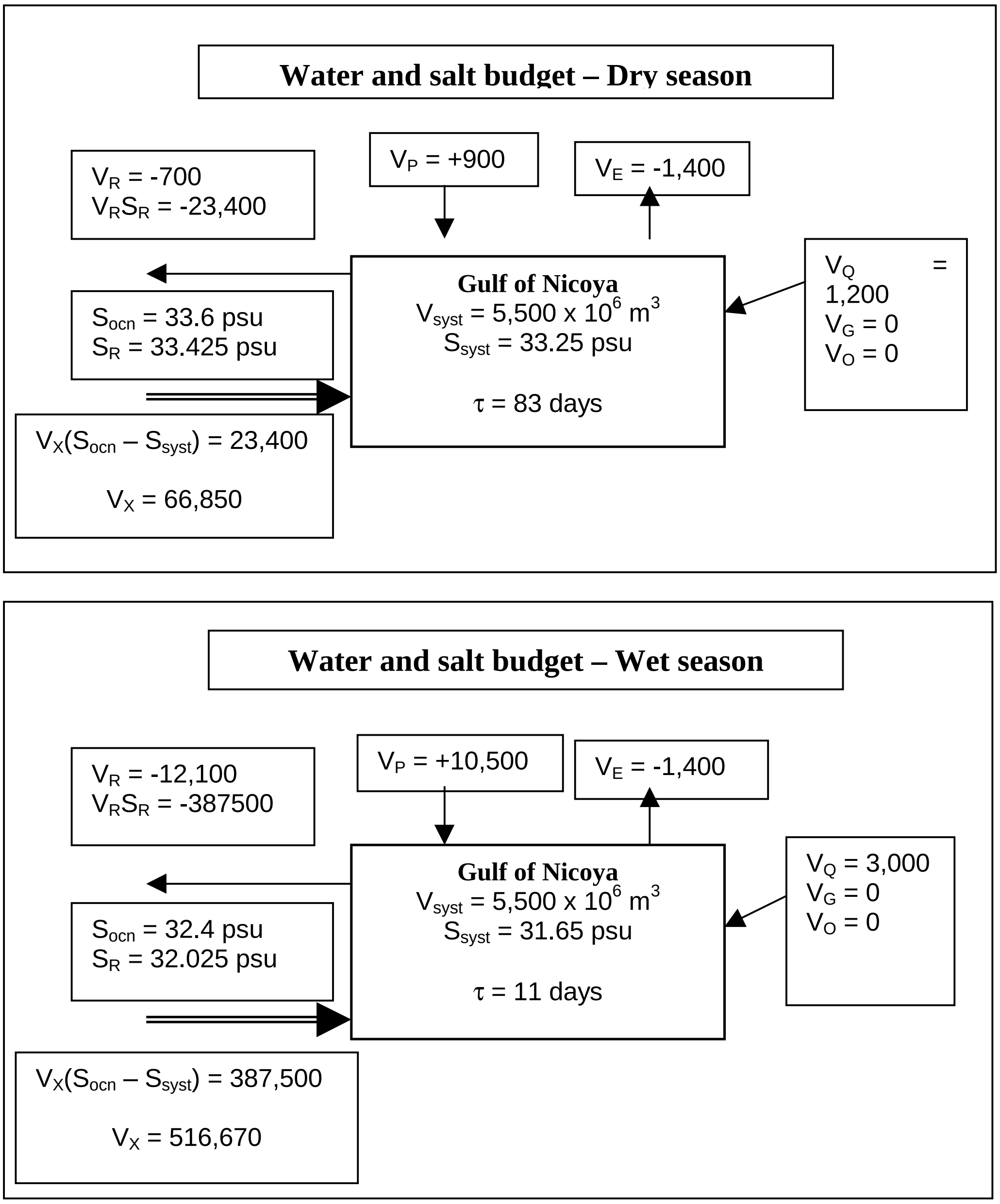


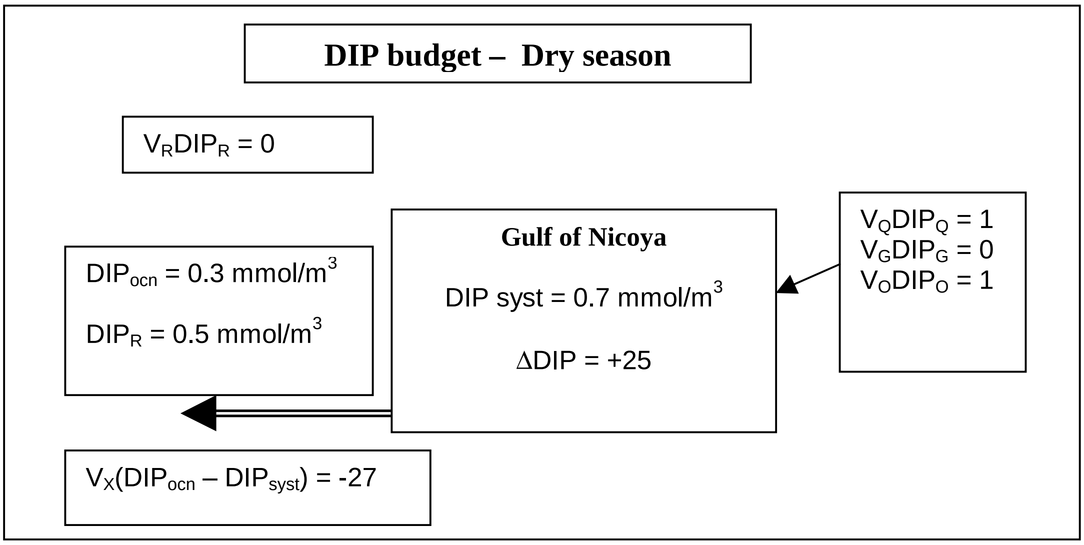
Figure 5.6. Water and salt budgets for Gulf of Nicoya, during dry and wet seasons. (Water fluxes in 10^3 m^3 day^{-1}; salt fluxes in 10^3 psu m^3 day^{-1}.)

The system is increasingly dynamic during the wet season with elevated rainfall and surface water runoff, mainly from the Rio Tempisque. There is a concomitant increase in the mixing term (V_x) and water exchange time (τ) decreases from about 83 days in the dry season to about 11 days in the wet season. Weighting these calculations by the length of the seasons yields an estimated average annual water exchange time of 41 days.

Budgets of nonconservative materials

P balance

Estimated DIP budgets (Figure 5.7) show a net efflux of phosphorus from the estuarine system, almost an order of magnitude greater in the wet season than in the dry season. ΔDIP for the system shows a similar pattern with values of 25×10^3 mol day^{-1} (dry season) and 211×10^3 mol day^{-1} (wet season). These values equate to a release rate for the system of about 0.05 mmol m^{-2} day^{-1} (dry season) and 0.4 mmol m^{-2} day^{-1} (wet season), and an annual average value of about 0.25 mmol m^{-2} day^{-1}.



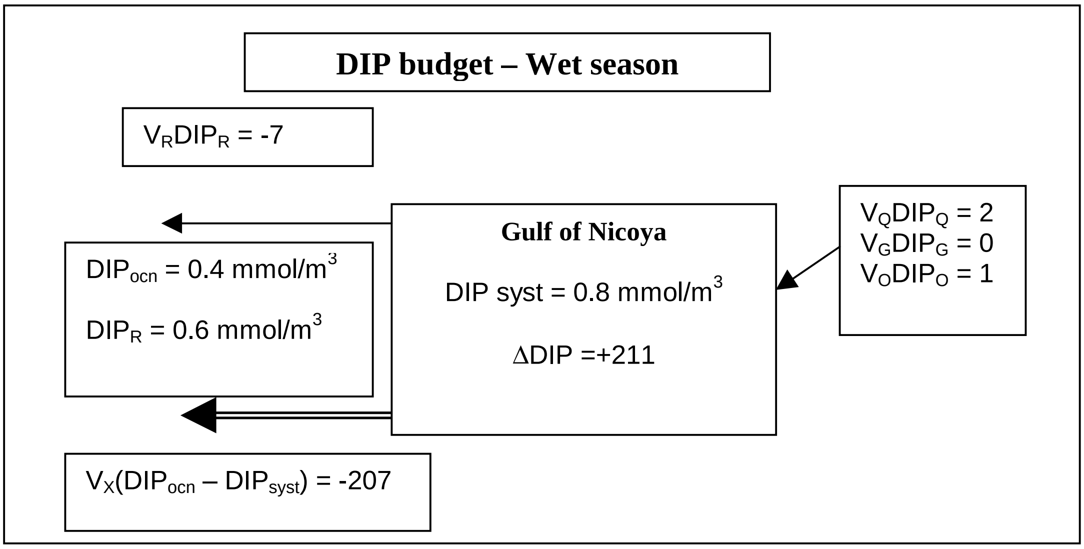


Figure 5.7. DIP budgets for Gulf of Nicoya during dry and wet seasons.
Fluxes in 10^3 mol day^{-1}

N balance

The Gulf of Nicoya estuary is a net source of DIN yielding 53x10^3 mol d^{-1} in the dry season and a greatly elevated level (3058x10^3 mol.day^{-1}) in the wet season. This is equivalent to 0.1 mmol. m^{-2} day^{-1} (dry season), 5.82 mmol m^{-2} day^{-1} (wet season) and an annual average value of about 3.44 mmol m^{-2} day^{-1} (Figure 5.8).

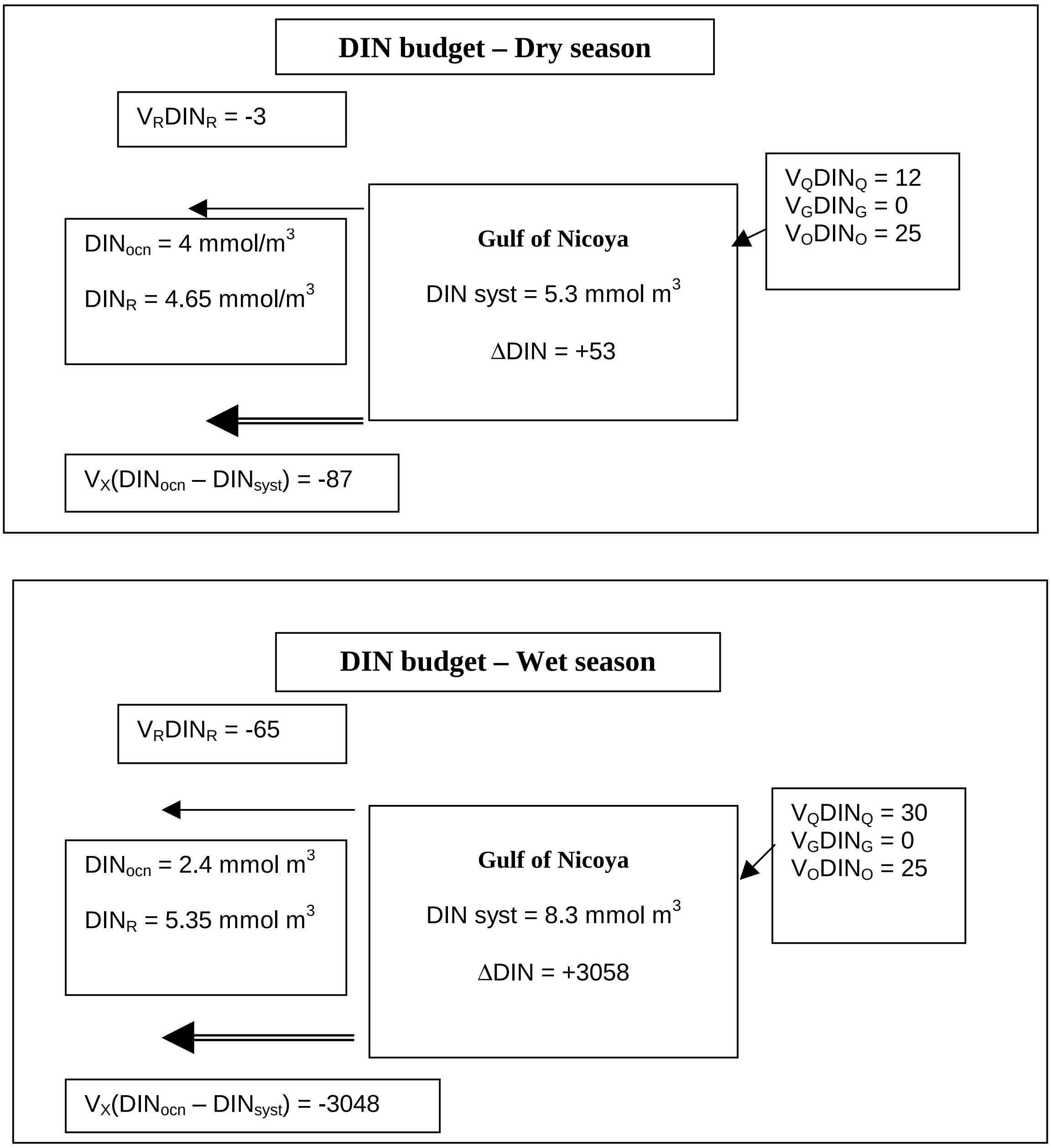


Figure 5.8. DIN budgets for Gulf of Nicoya during dry and wet seasons. Fluxes in 10^3 mol day^{-1}.

Stoichiometric calculations

The seasonal input of organic materials from the Rio Tempisque and the fringing mangrove systems are likely to provide significant organic materials to the estuary. These, in addition to internal cycling and other nutrient processes, will contribute to the reactions occurring within the system and can be addressed in terms of net processes by stoichiometric estimates based on the molar C:N:P ratios of the material (Gordon *et al.* 1996). For this purpose, we assume the material is plankton with a C:N:P ratio of 106:16:1.

Nitrogen fixation minus denitrification *(nfix-denit)* provides an estimate of net nitrogen flux for the system and can be established as the difference between observed and expected ΔDIN, where ΔDIN is 16xΔDIP. For the dry season, *(nfix-denit)* = -0.7 mmol m^{-2} day^{-1} and for the wet season, (*nfix-denit)* = -0.66 mmol m^{-2} day^{-1}. The net annual rate for (*nfix-denit)* therefore is estimated as -0.24 mol m^{-2} $year^{-1}$. Thus, the system denitrifies at a relative constant and moderate rate throughout the year.

Net ecosystem metabolism (NEM = (*p-r*) or production minus respiration) is derived from *(p-r)* = 106 x ΔDIP. Thus, for the dry season (*p–r)* = -5.1 mmol C m^{-2} day^{-1} and for the wet season [*p–r*] = -42.6 mmol C m^{-2} day^{-1}. The annual net ecosystem metabolism is therefore estimated as [*p–r*] = -9.845 moles C m^{-2} $year^{-1}$. According to these assumptions, the estuary performs as a net heterotrophic system and even more so in the wet season which probably reflects the higher particulate loading from the land.

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APPENDICES

Appendix I Groundwater Issues and Biogeochemical Budgets: Yucatan Region

R.W. Buddemeier

The interactions between coastal groundwater and the marine and estuarine systems adjacent to the shoreline are increasingly recognised as important. Coastal groundwater extraction has led to saltwater intrusion into coastal aquifers in many locations, decreasing the resource base available for support of populations, agriculture, and industry (Smith *et al*. 1997). In other areas, groundwater discharge may provide a pathway for the transport of contaminants or nutrients originating on land into coastal waters that are increasingly threatened by pollution and eutrophication. Even in the absence of anthropogenic interference, some coastal regions may have enough submarine groundwater discharge (SGD) to influence coastal budgets of water, salt, and nutrients. These influences need to be quantified in support of the overall LOICZ approach to characterising the biogeochemical functioning of the world coastal zone, which is based on understanding the functioning of type localities that can then be globalised using a coastal typology system.

LOICZ, in cooperation with the Russian Academy of Sciences, convened an international symposium on the subject in 1996 (Buddemeier 1996). Subsequently, the Scientific Committee on Oceanic Research (SCOR), in partnership with LOICZ, has formed an international scientific working group to address the questions associated with SGD (SCOR WG-112: Magnitude of submarine groundwater discharge and its influence on coastal oceanographic processes).

In a more applied context, questions of SGD have been considered in developing the LOICZ typology approach, and especially in the Biogeochemical Budgeting effort (http://www.nioz.nl/loicz). Budgeting issues relating to groundwater are discussed at http://data.ecology.su.se/mnode/methods/gw.htm. Most of the early coastal budgeting exercises focused on systems where groundwater input was either actually or probably a negligible effect. However, the present workshop addresses a number of coastal systems in which groundwater is not only significant, but is the dominant or sole soure of terrestrial input.

The Yucatan Peninsula of Mexico (Figure 1.1) is a classic example of a carbonate landscape with extensive karst development. The relatively porous surface material and the extensive network of solution cavities, caves, conduits and fractures means that any surface water that is not lost to evapotransiration rapidly infiltrates to the groundwater, and is quickly lost to the ocean through the highly permeable carbonate platform. Studies of the water balance of the Peninsula have suggested that the annual outflow of groundwater along the coasts of the northern half of the Peninsula amounts to an average of about 9 million cubic metres per kilometre of coastline (Hanshaw and Back 1980). The spatial patterns of this outflow may be strongly influenced by the geology of the Peninsula (Perry and Velasquez-Oliman 1996).

Reactive nitrogen and silica concentrations in the groundwater are very high compared with the surrounding waters of the Gulf of Mexico and the Caribbean Sea (Hanshaw and Back 1970, Herrera-Silveira *et al.* 1998). Discharge of large quantities of nutrient-rich freshwater into the narrow lagoons and restricted bays that characterise much of the Yucatan coast results in distinctive budgets that require adaptation of standard budgeting approaches.

In particular, the high groundwater fluxes are temporally variable, responding not only to seasonal changes in rainfall, but also to shorter-term variations. Even more significant, however, is the spatial variation in discharge, which in many areas is dominated by submarine springs or cave mouths at or below sea level. These 'point source' discharges may or may not be accompanied by adjacent diffuse discharge or smaller groundwater outflows. They are more difficult to measure than are surface streams, and are less amenable to modelling than porous medium groundwater flow. The budgeting process therefore is improved by a substantial level of local familiarity and judgment in incorporating often poorly-measured variables. In this context it is encouraging that there are suggestions that dissolved silica may prove to be an effective groundwater tracer in carbonate system discharges (see Appendix II)

The experience and information gained during the workshop has resulted in both advances in the understanding of groundwater-dominated coastal systems, and further extension of both budgeting techniques and the inventory of LOICZ coastal budgets.

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Appendix II. Quantifying Groundwater Flow Using Water Budgets and Multiple Conservative Tracers

S.V. Smith, V. Camacho-Ibar, J. Herrera-Silveira, D. Valdes, L. David, M. Merino and R.W. Buddemeier

Introduction

One of the most difficult estimates for C, N and P biogeochemical budgeting in many systems is the input of groundwater (V_G) and its dissolved constituents into coastal ecosystems. In regions such as the Yucatán Peninsula of south-eastern México, where groundwater flows are known to be significant and surface runoff is near 0, this determination becomes critical (see, for example, Perry and Velasquez-Oliman 1996; Back and Hanshaw 1970; Hanshaw and Back 1980). In this particular environment, Hanshaw and Back estimated that the 1,100 km northern portion of the peninsula has an average groundwater outflow to the ocean of approximately 8.6 x 10^6 m^3 km^{-1} yr^{-1}. Those authors report some evidence for spatially heterogeneous distribution of this outflow, as would be anticipated from the very heterogeneous distribution of sinkholes, or *cenotes* (e.g., Perry and Velasquez-Oliman 1996).

A geochemical approach to the estimation of groundwater flow is the use of alternative geochemical tracers. Examples include radium (Moore 1996a and b), radon (Burnett *et al.* 1996), and methane (Chanton *et al.* 1996). Data provided by several participants to this workshop provided hints that silicate might be used as a quasi-conservative tracer of groundwater inputs to some coastal lagoons around the Yucatán Peninsula. D.R. Corbett (personal communication) has noted that groundwater silicate appears to be nearly conservative in the carbonate terrain of Florida Bay. In the case of Yucatán, silicate levels are elevated and not highly variable in groundwater and surface waters across much of the peninsula (Herrera-Silveira *et al.* 1998; Herrera Silveira 1999), and several of the coastal lagoons discussed in this report show elevated Si concentrations (e.g., Celestún; Herrera *et al.* this report). Celestún Lagoon provides particular insight. Mixing diagrams suggest that the silicate distribution in this system with known groundwater discharge may be distributed approximately conservatively with respect to salinity (Herrera-Silveira 1995; Herrera-Silveira and Ramírez-Ramírez 1998). Because the atmospheric term (precipitation minus evaporation) in many of the Yucatán lagoons is significant relative to groundwater flow, mixing diagrams of silicate versus salinity will not in general be linear; there are three end-member water masses, not two (see Boyle *et al.* 1974).

Chelem Lagoon and Ria Lagartos are of interest in this context, because these systems have elevated silicate (hence, the suggestion of groundwater input) even though they are hypersaline systems (Valdés and Real 1998; Valdés this report). There is, moreover, precedent for using Si as a hydrological tracer (Kennedy *et al.* 1986; Wels *et al.* 1991).

The Nichupté Lagoonal System also provides insight. Systems such as this one appear to receive significant freshwater inflow from local runoff which occurs during rainfall events (Merino *et al.* 1990), and this complication must be considered.

Theoretical analysis

With this background in mind, we have expanded the calculations laid out in Gordon *et al.* (1996), to the case where groundwater might have a unique signature which would distinguish it from rainwater. Conservation of water in the system is described as follows:

$$\frac{dV_{syst}}{dt} = V_Q + V_P + V_E + V_G + V_O + V_R \tag{1}$$

where dV_{syst}/dt is the change of volume in the system over time; the *V*'s denote volume fluxes, with the subscripts *Q, P, E, G,* and *O* representing river discharge, precipitation, evaporation, groundwater, and other freshwater sources (e.g., sewage), respectively. The subscript *R* is the ‘residual flow’ necessary to conserve mass and is treated as the unknown. It is convenient, for the discussion to follow, to consider that V_{PE} represents the net of precipitation minus evaporation. Moreover, it is convenient (although by no means necessary) to treat the system as at steady state, that is $dV_{syst}/dt = 0$. With these simplifications and assumptions, the equation can be solved for V_R:

$$V_R = -V_Q - V_{PE} - V_G - V_O \tag{1a}$$

If salt is conserved, then a similar equation can be written for the conservation of salt (*S*). The equation will have an additional term (V_X), to describe the mixing of water between the system of interest and the ocean (*ocn*):

$$\frac{V_{syst} dS_{syt}}{dt} = V_Q S_Q + V_{PE} S_{PE} + V_G S_G + V_O S_O + V_R S_R + V_X (S_{ocn} - S_{syst}) \tag{2}$$

In this equation, S_{syst} and S_{ocn} are the salinity values for the system and oceanic boxes; S_R, the ‘residual salinity’, is taken to be the salinity at the boundary between the system and the ocean (i.e., the average of S_{ocn} and S_{syst}). Some of the terms (e.g., salinity of the precipitation - evaporation and the term for other flow) can usually be treated as near 0 and are dropped out of the analysis here in order to simplify the equations; they can be re-inserted in systems where they might be quantitatively significant. One clear test of ‘significance’ is to evaluate both these simple versions of the equations and the more complete equations - even if with hypothetical data. A change of less than 25% in the estimate of unknowns probably lies within the range of uncertainty in the known quantities. We can consider this equation at steady state (that is, VdS/dt = 0), combine it with (1a), and solve for V_X:

$$V_X = \frac{V_Q (S_R - S_Q) + V_{PE} (S_R) + V_G (S_R - S_G)}{(S_{ocn} - S_{syst})} \tag{3}$$

If all the terms on the right side of the equation are known, then obviously an estimate for V_X can be derived; this is the ‘standard LOICZ procedure’. Consider the case where one term (V_G) is not known, but for which a second conservative tracer (let us assume that tracer is silicate, *Si*) is known. An equation exactly analogous to (3) can be written:

$$V_X = \frac{V_Q (Si_R - Si_Q) + V_{PE} (Si_R) + V_G (Si_R - Si_G)}{(Si_{ocn} - Si_{syst})} \tag{4}$$

Equations (3) and (4) can be combined to give an estimate of V_G:

$$V_G = \frac{(S_{ocn} - S_{syst})\lfloor V_Q (Si_R - Si_Q) + V_{PE} Si_R \rfloor - (Si_{ocn} - Si_{syst})\lfloor V_Q (S_R - S_Q) + V_{PE} S_R \rfloor}{(Si_{ocn} - Si_{syst})(S_R - S_G) - (S_{ocn} - S_{syst})(Si_R - Si_G)} \tag{5}$$

Results and Discussion

There are several caveats to the use of equation (5). The most obvious ones are that the salinity and silicate content of the groundwater are known, and that the silicate concentration is conservative with respect to salinity. Slight nonconservative behavior of the silicate would ordinarily be expected to introduce a relatively small error in the calculations. Because these systems receive little or no surface-water discharge, which might have high concentrations of diatoms (with relatively soluble SiO_2 frustules), reactive forms of particulate silicate are not being supplied to these systems. Indeed, the classical paper by Boyle *et al.* (1974) reviewing the use of mixing diagrams to assess the chemical mass-balance of estuaries concluded (p. 1724): “...in no case has it been proved unambiguously that silica exhibits non-conservative behavior in estuarine mixing.” Moreover, because groundwater and lagoonal silicate concentrations are very high compared to concentrations of dissolved inorganic N and P, large deviations from conservative behavior are not expected in these systems.

A second set of considerations may actually be more important. Not surprisingly, V_G is calculated as a volume flux scaled to the other freshwater input terms - V_Q, and V_P (i.e., the net of V_P and V_E) as the equation has been simplified and formulated. The value for V_G is therefore only as good as the estimates of these other flux terms. Moreover, the calculation of V_G as formulated is actually a calculation of the flux of water with high silicate (and usually low salinity). V_Q, as well as V_G, is likely to fit that profile. Therefore, if V_Q is either poorly constrained or large relative to V_G, then the calculation will not be robust. Of course some other tracer might differ between river-water and groundwater and could be substituted for silicate. In the case of the northern Yucatán Peninsula, with virtually no river flow and high groundwater flow, the equation generally appears robust.

A third caveat, which we have learned by application of this equation to examples in this report, is that the estimate of V_G is quite variably sensitive to the estimated values of salinity and silicate in the groundwater. In some instances, the calculation is sensitive to one of these variables, sometimes to the other, sometimes to both, and sometimes to neither. The sensitivity is largely reflecting regions where the denominator of equation (5) is close to 0 and responsive to slight variations in these two variables. We have found it convenient to create a spreadsheet matrix with a range of salinity and silicate values (for most cases in the Yucatán systems, salinity ranging from 0 to 12 psu in steps of 1 psu, and silicate ranging from 100 to 500 μM, in steps of 50 μM, appears appropriate). In effect, for the observed characteristics of salinity and silicate concentrations in the lagoon, this matrix is a ‘sensitivity map’ in salinity-silicate space. We can then look in the matrix to see where the estimated value falls with respect to sensitivity to these two variables. In cases with the denominator near 0, slight variations can make the estimated value for V_G become either very large or negative or both.

An abbreviated version of this matrix is shown as Table 1 and graphically as Figure 1, for Celestún Lagoon. In this example, estimated groundwater flux is in a region of the matrix that is moderately sensitive to uncertainty in salinity higher than the estimated value and very sensitive to higher silicate concentrations. Lower values of either salinity or silicate do not dramatically alter the calculations.

Versions of equation (5) are used in several of the case studies given in this report: Celestún Lagoon and Dzilam Lagoon (both budgets by Herrera-Silveira *et al.*), and Chelem Lagoon and Ria Lagartos (Valdez) (Table 2). All of these systems are located in the state of Yucatán, along the north and north-west portion of the Yucatán Peninsula. None of these systems has significant river inflow; all have evaporation in excess of precipitation; Celestún and Dzilam both have salinity below oceanic, even though evaporation exceeds rainfall in the region. Chelem and Ria Lagartos are both hypersaline throughout most of their extent, although salinity at the mouths of these systems is slightly lower than coastal seawater (Table 3). The presence of depressed salinity at the mouths of these systems, even though they are in net evaporative regions with no significant river flow, is proof that a low-salinity source (groundwater) must be important in the water budgets. All four of these systems show elevated silicate levels in the lagoon waters. The range of estimated V_G for these systems taken as whole units is about 1 to 4×10^6 m^3 km^{-1} yr^{-1} (Table 4), with portions of the systems showing locally much higher rates (see individual nutrient budgets in main body of this report).

A system for which the calculations did not initially seem to work was the Nichupté Lagoonal System, Quintana Roo (Merino). There, the initially calculated groundwater fluxes were negative (Table 5A). We recognise that negative groundwater flux (i.e., saline intrusion into the aquifer) does occur in some locations. Indeed, that is a significant problem in many areas of México where groundwater exploitation exceeds recharge. This is not the case in most of Yucatán, because of the large volume of recharge and relatively low utilisation rates. Moreover, there are known springs in Nichupté.

After examination of the salinity-silicate sensitivity matrix, we think that the problem lies with local surface flow which is not adequately accounted for in the water budget. For this system, V_P - V_E for the analyzed period was -21×10^6 m^3 yr^{-1}. A positive flux for non-groundwater freshwater inflow would reverse the sign of the estimated groundwater flux. This interpretation is consistent with the analysis by Merino *et al.* (1990). Those authors observed that the wetlands immediately adjacent to Nichupté cover an area approximately equal in size to the lagoon, and that runoff from a significant fraction of this wetland area is apparently important. Those authors estimated that local runoff during rainfall events might deliver between two-thirds and all of that rainfall directly to Nichupté. It can be assumed that this local runoff would be low in salinity and probably would have had inadequate time to have elevated silicate concentrations. For the period in question, adding 67% of the rainfall as local runoff would be equivalent to adding 44×10^6 m^3 yr^{-1} of additional fresh water. When this local runoff is added (Table 5B), the resultant estimates of groundwater flux become positive.

We also tried the use of the equation for Terminos Lagoon, Campeche (David), on the southwest portion of the Yucatán Peninsula, without success. Calculated groundwater flow was clearly far too large to be physically reasonable, although it was still a small quantity in comparison to river flow. In that instance, the dominance of freshwater inflow by rivers (also high in silicate and low in salinity) precludes the ready use of this equation.

Conclusions

We conclude that the use of silicate as a second ‘conservative tracer’ seems to work as an estimator of groundwater flow for much of the northern Yucatan Peninsula. Undoubtedly this technique might be further adjusted, especially with site-specific data on groundwater composition. Moreover, it is clear that specific considerations such as local runoff should be taken into account in the water budget. Finally, domination of the water budget by river flow, which is likely to have a silicate concentration similar to that of groundwater, will compromise this approach.

The water fluxes associated with groundwater in the northern Yucatan Peninsula are significant to both the water and nutrient (especially nitrogen) budgets of the lagoons (main body of report). The work by Corbett *et al.* (in press) in Florida Bay underscores the potential importance of groundwater in the nutrient budgets of such carbonate terraines with high groundwater flow and low surface flow.

Although the mean flow rates at the scale of the individual systems in the Yucatan Peninsula appear to be well below the regional estimate of Hanshaw and Back (1980), we believe that the general pattern is consistent with their analysis; it seems likely that much of the Peninsula does, indeed, have low groundwater flow rates, and that small regions account for a significant proportion of the total flow for the entire region.

Table 1. Salinity--silicate sensitivity matrix for Celestún Lagoon. Rainfall minus evaporation for this system is -17x10^6 m^3 yr^{-1}; lagoon mouth and oceanic salinity and silicate values are given in Table 3. As summarised in Table 4, the estimated groundwater flow (at groundwater salinity and silicate concentrations of 9 psu and 244 µM, respectively) is 51x10^6 m^3 yr^{-1}. Figure 1 illustrates this same matrix graphically.

	Groundwater salinity (psu)						
Groundwater silicate (µM)	**0**	**2**	**4**	**6**	**8**	**10**	**12**
	Estimated groundwater flux (10^6 m^3 yr^{-1})						
100	21	23	24	26	29	32	36
200	27	30	33	37	43	50	60
300	39	45	53	64	81	111	175
400	69	89	126	218	786	-488	-186
500	287	6,024	-317	-154	-102	-76	-61

Table 2. Physical dimensions and estimated rainfall minus evaporation data for four Yucatán coastal lagoons.

SYSTEM	**AREA (km^2)**	**LENGTH (km)**	**P-E (mm yr^{-1})**	**V_P -V_E (10^6 m^3 yr^{-1})**
Celestún	28	21	-600	-17
Chelem	15	20	-1,600	-24
Dzilam	9	15	-600	-7
Lagartos	94	80	-1,400	-132

Table 3. Estimated water composition for groundwater, water at the mouth, and open coastal seawater, for the four lagoons listed in Table 2. In the case of Celestún, annual average data are reported here; the text in the main body of the report uses seasonal data. For Chelem and Lagartos, groundwater salinity and silicate data are estimated from Herrera-Silveira *et al.* (1998).

SYSTEM	**GW Salinity (psu)**	**Mouth salinity (psu)**	**Ocean Salinity (psu)**	**GW silicate (µM)**	**Mouth silicate (µM)**	**Ocean silicate (µM)**
Celestún	7.3	32.9	35.3	244	38	9
Chelem	2	36.6	37.3	200	46	5
Dzilam	8	35.6	36.8	150	61	16
Lagartos	2	37.0	35.6	200	26	12

Table 4. Estimated groundwater fluxes for the four lagoon systems listed in Table 2, based on data in Tables 2 and 3, and solution of Equation 5. Rounding differences and seasonal *versus* annual data result in slight discrepancies between the data reported here and that in the main body of the report.

SYSTEM	V_G (10^6 m^3 yr^{-1})	V_G (10^6 m^3 km^{-1} yr^{-1})
Celestún	51	2.4
Chelem	23	1.2
Dzilam	10	0.7
Lagartos	311	3.9

Table 5. Salinity--silicate sensitivity matrices for Nichupté Lagoonal System. Part A is calculated with V_P-V_E = -17x10^6 m^3 yr^{-1} and without local runoff. Lagoon salinity and silicate values are 27.7 psu and 7 µM, respectively; oceanic values are 31.7 and 2. Note that over this apparently reasonable range of groundwater salinity and silicate values, the estimated groundwater flux is consistently negative. Part B repeats the calculation but adds 44 x 10^6 m^3 yr^{-1} of local runoff, as adapted from Merino *et al.* (1990).

Part A. Without local runoff							
	Groundwater salinity (psu)						
Groundwater silicate (µM)	**0**	**2**	**4**	**6**	**8**	**10**	**12**
	Estimated groundwater flux (10^6 m^3 yr^{-1})						
100	-15	-14	-14	-13	-13	-12	-12
200	-6	-5	-5	-5	-5	-5	-5
300	-3	-3	-3	-3	-3	-3	-3
400	-2	-2	-2	-2	-2	-2	-2
500	-2	-2	-2	-2	-2	-2	-2

Part B. With local runoff							
	Groundwater salinity (psu)						
Groundwater silicate (µM)	**0**	**2**	**4**	**6**	**8**	**10**	**12**
	Estimated groundwater flux (10^6 m^3 yr^{-1})						
100	16	16	15	15	14	14	13
200	6	6	6	6	6	6	6
300	4	4	4	4	4	4	4
400	3	3	3	3	3	3	3
500	2	2	2	2	2	2	2

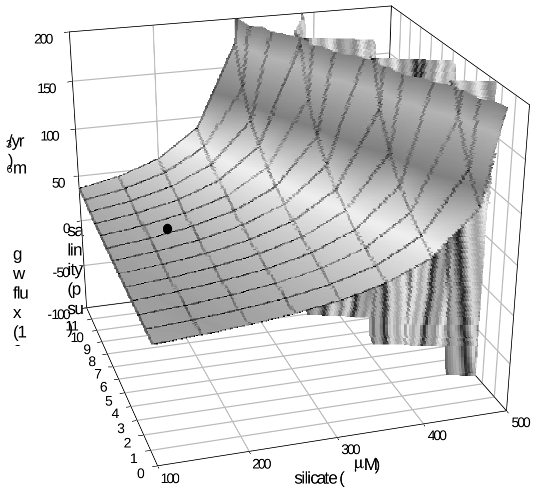

Figure AII.1. Graphic representation of estimated groundwater flux in Celestún Lagoon as a function of varying groundwater salinity and silicate (graph based on Table 1). The black dot represents the estimated composition of Celestún groundwater. It can be seen that the estimated flux is more sensitive to varying silicate than to salinity, and that at silicate or salinity values elevated above the estimated composition, the calculated flux becomes very high (>200) and then collapses to negative values.

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Appendix III Workshop Report

1. Welcome and Opening

Participants were welcomed to the Centro de Investigacion y de Estudios Avanzados IPN Unidad Merida (CINVESTAV) facilities by the Director, Dr Gerardo Gold Bouchot. In wishing the group every success in their work, Dr Gold invited participants to visit the various facilities and researchers of the Institute during the Workshop.

Dr David Valdes Lozano briefed participants on the Workshop arrangements. Resource persons were identified, including Land-Ocean Interactions in the Coastal Zone (LOICZ) Scientific Steering Committee members (Prof. Steve Smith, Dr Bob Buddemeier, Dr Silvia Ibarra Obando, Prof. Fred Wulf) and Dr Victor Camacho-Ibar. Dr Chris Crossland, LOICZ IPO Executive Officer, was identified as providing support for the Workshop. Participants were introduced and working documents were distributed.

2. Introduction and Background

2.1 LOICZ Core Project

An outline of LOICZ goals and approaches was presented by Dr Chris Crossland, who stressed the importance of the Workshop outcomes (see Terms of Reference, Appendix VI) to the continuing development of understanding of global change in the coastal zone within the International Geosphere-Biosphere Programme (IGBP). Key elements of the Project place emphasis on determining horizontal material fluxes at localities and sites, scaling site information to the regional and global dimensions by typological methods, and linking flux information to the human dimension. The pivotal nature of derived biogeochemical budgets within LOICZ was highlighted, and the links to other elements of the Project (river catchments, typology, human dimension) was briefly described.

2.2 Mexico and LOICZ

The contribution of Mexican science to LOICZ was summarised by Dr Silvia Ibarra Obando, who noted particularly the scientific workshops and studies over the last two years. The continuity of effort and contribution from an earlier biogeochemical budgets workshop in Mexico (Smith et al. 1997) provided a context for the current Workshop. The outcomes from the 1998 San Quintin study (Regional Environmental Change, in press), which brought together research on the material flux and human dimension, are an example of the utility of the budgetary approach. A natural extension to these activities is to an evaluation of the Caribbean seaboard and wider Central American, within the context of LOICZ regional assessments. Companion work by LOICZ in other regions of the world, especially in the development of estuarine biochemical budgets for the Australian, South-East Asia (and planned or in progress for Africa, South Asia and Europe), give a further context for the Workshop.

2.3 Biogeochemical Budgets Web-Site

The dependence of LOICZ on contribution and participation of the ‘community of science’ for the building and assembling of budgets describing global coastal systems was emphasised by Prof Fred Wulff, in introducing the “Budgets” web-site. The LOICZ Biogeochemical Models web-site is a vital presentation tool and information collection site for the developing information. The site (http://data.ecology.su.se/MNODE/) can be accessed directly or through the LOICZ home pages (http://www.nioz.nl/loicz/). This and other Workshop models, and contributions from individual scientists, continue to be added and displayed on the site. Guidelines for the LOICZ modelling approach, tutorials and budget information are listed (including literature pointing to as yet un-budgeted sites). The web-site, its structure and opportunities were demonstrated. Participants were encouraged to contribute beyond this Workshop and to utilise the information.

2.4 Budgets and Global Comparisons

The Workshop leader, Prof Steve Smith, described the purpose of the Workshop and the approach and progress of LOICZ in developing biogeochemical budgets. The development of a global statement by end 2002 depends on LOICZ accessing and using available data for the budgets and, by use of a series of typologies, extrapolating regional sites information to a picture of the world's coastal zone. In addition, several relatively data-rich regions will be explored in detail to extend the overall first-order assessment to areas of second- and third-order budgets which allow further assessment of forcing functions and system responses.

Global assessment will require more than 100 site budgets. Already intra- and inter-regional comparisons are providing some insights into apparent trends in patterns, for example, in DIP relationships with latitude and perhaps signatures of responses by coastal systems in response to anthropogenic pressures. New tools for assessment of system function also are emerging, such as relationships between salt and tidal exchange times.

The program of the Workshop and for report preparation was outlined for guidance of participants.

3. San Quintin Bay - A Case Study

The San Quintin Bay study was presented by Dr Victor Camacho-Ibar as a teaching example, including further refinements of estimates from existing data and using a multiple box model approach. Discussion covered issues of choosing box boundaries from inspection and analysis of data, development of stoichiometric assessments and the rigour introduced by use of additive seasonal data rather than average data values. Outcomes of the more detailed model confirm the earlier whole-system, single-box analysis that aquaculture in the Bay is having little effect on the system. The use of a multiple-box model representing sectional regions of a system, has positive ramification for use of the budgetary approach coastal zone management.

4. Presentation of Biogeochemical Budgets

The budgets contributed to the Workshop covered a range of regional areas and climatic conditions. A key element was the introduction of a suite of budgeted sites on the Yucatan Peninsula - an area well-known for its groundwater-dominated rather than surface flow hydrology. This provided a unique opportunity to evaluate the implication of groundwater processes and quality on material fluxes in the coastal systems.

The contributed budgets for the systems were briefly considered by participants, including an overview of the system settings, data availability, approaches being taken to build the biogeochemical budgets, and the status and problems in the development of estimates. The Yucatan Peninsula sites have been conveniently grouped into those with an obvious river or surface flow input, and those which have an apparent groundwater input; groundwater contributions are likely also to the "surface flow" systems. Systems under evaluation included:

a) Gulf of California

Estuario el Sargento, Sonora	Cesar Almeda (presented by Prof Steve Smith)
Rio Colorado, Baha California	Francisco Munoz Arriola

b) Central America (other than Mexico)

Laguna de la Restinga, Venezuela	Luis Troccoli and Jorge Herrera-Silveira
Golfo de Nicoyo, Costa Rica	Prof. Steve Smith

c) Yucatan Peninsula

i) *Surface Flow Systems*

Laguna de Terminos, Campeche	Dr Laura David
Bahia de Chetumal, Quintana Roo	Teresa Alvarez Legorreta

ii) *Groundwater-Influenced Systems*

Laguna Celestun, Yucatan	Dr Jorge Herrera-Silveira
Laguna Chelem, Yucatan	Dr David Valdes Lozano
Ria Lagartos, Yucatan	Dr David Valdes Lozano
Laguna Nichupte, Quintana Roo	Dr Martin Merino Ibarra

5. Budgets Development

Participants worked interactively in the development of their site budgets, supplemented with methodological and site/issues-based tutorials and discussions. Estimates for sites and additional evolution of assessment approaches were made, often incorporating more detailed spatial and temporal boxes into the models. Budget refinements were made in light of outcomes from individual and group discussions of issues emerging from additional plenary sessions.

Groundwater processes and assessment provided a basis for evaluating the G_W term in budget development. Work was done on evaluating silicate relationships with respect to groundwater signals and estimates for biogeochemical budgets.

6. Additional Plenary Sessions and Presentations

Further plenary sessions and group discussions included:

- Budgets and Groundwater Issues (Dr Bob Buddemeier)
- Typology and scaling-up of budget site information in the context of meeting LOICZ goals for evaluating global changes in the coastal zone (Dr Bob Buddemeier)
- Silicate and groundwater (Dr Victor Camacho-Ibar and Prof. Steve Smith)

Regional descriptions of coastal and management issues provided a wider context of the use and opportunity for application of scientific information relevant to the Workshop. Presentations from CINVESTAV staff included:

- A review of issues and research approaches being taken and planned to evaluate the key problem of eutrophication in coastal waters (Dr Jorge Herrera-Silveira), and
- An overview of coastal problems and initiatives being taken through CINVESTAV to develop effective management approaches for the regional coastal zone (Jorge Euan and Luis Capurro).

7. Outcomes and Wrap up

Budgets for all systems were in final stage of completion, some requiring some additions to text descriptions and a check on data before contribution. Participants provided (or will have provided by 1 February 1999) copies of their complete estimates for inclusion in the Workshop Report and for lodgement on the LOICZ web-site.

Additional sites were identified for which data is available and which may potentially yield budgets: for the Yucatan Peninsula (6 sites) and for the other regions of Mexico adjacent to the Gulf of Mexico (2 sites). Participants committed themselves to making contact with other researchers for data and either to carry out or to encourage further site evaluations for contribution to LOICZ.

The timetable for delivery of final budgets and publication of the Workshop Report was established: all contributions for the Report is to be provided by 1 February 1999 with additional budgets to be contributed by mid-March 1999. All will be included in a CD ROM containing the full regional information from this and the earlier workshop in Mexico.

The participants joined with LOICZ in expressing thanks to the local organisers and gratefully acknowledged the strong support provided by CINVESTAV in hosting the Workshop. In particular, the participants noted the contribution and efforts of Drs David Valdes Lozano, Jorge Herrera-Silveira and Luis Troccoli for local organisation, and Dr Silvia Ibarra Obando for regional organisation.

A field trip to local Yucatan lagoon sites, on Saturday 16 January, provided valuable on-ground appreciation of the coastal zone management issues and the ecosystems.

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Appendix V Workshop Agenda

Tuesday, 12 January

Participants arrive in Merida

Wednesday, 13 January

0900 Welcome Dr Gerardo Gold Bouchot, Director CINVESTAV
0910 Announcements – David Valdes Lozano
0920 Comments on LOICZ and IGBP – Chris Crossland
0930 Mexico and LOICZ – Silvia Ibarra Obando
0940 Budgets and LOICZ Web site – Fred Wulff
1010 Budgets and global comparisons – Steve Smith
1030 COFFEE
1010 San Quintin, a case example – Victor Camacho Ibar
1100 Estero el Sargento, Sonora – Cesar Almeda (per Steve Smith)
Rio Colorado, Baha California – Francisco Munoz Arriola
1145 Guatemala site – Norma Gil Rodas
Laguna de la Restinga, Venezuela – Luis Troccoli and Jorge Herrera-Silveira
Golfo de Nicoya, Costa Rica – Steve Smith
1215 Budgets and groundwater issues – Bob Buddemeier
1300 LUNCH
1400 Laguna de Terminos, Campeche – Laura David
Bahia de Chetumal, Quintana Roo – Teresa Alvarez Legorreta
1430 Celestun, Yucatan – Jorge Herrera-Silveira
Laguna Chelem, Yucatan – David Valdes Lozano
1500 Ria Lagartos, Yucatan – David Valdes Lozano
Laguna Nichupte, Yucatan – Martin Merino
1530 COFFEE
1600 Discussion
1700 Presentation: – "Eutrophication in Yucatan Coasts: A primary producer perspective" – Jorge Herrera-Silveira

Thursday, 14 January

0900 Comments and Announcements – Steve Smith
0910 Plenary discussions: Where from here?
1000 Break out/Tutorial discussions and writing groups
1030 COFFEE
1100 Break out/Tutorial discussions and writing groups
1240 Plenary discussion
1300 LUNCH
1400 Break out discussion and writing groups
1500 COFFEE
1530 Continue discussion and writing groups
1630 Plenary discussion
1700 Presentation: – "Management of the Coastal Zone in Mexico" – Luis Capurro and Jorge Euan

Friday, 15 January

0900 Comments and announcements – Steve Smith
0910 Continue discussion and writing groups
1030 COFFEE
1100 Continue discussion and writing groups
1200 Plenary discussion: – Status of Budgets
1300 LUNCH
1400 Plenary discussion: Wrap up – Comparisons and Future Work
1630 Adjourn

Saturday, 16 January

Field trip
Participants depart Merida

Appendix VI Terms of Reference for Workshop

LOICZ WORKSHOP II ON MEXICAN AND CENTRAL AMERICAN COASTAL LAGOONS

CINVESTAV, Merida, Mexico

12-16 January 1999

Primary Goal:

To work with researchers dealing with Mexican and Central American coastal lagoons, in order to extract budgetary information from as many systems as feasible from existing data. The Mexican and Central American lagoons span a climatic regime ranging from cool (arid) temperate to both wet and dry tropics; they vary from relatively little to a high degree of perturbation from human activities; and many of the lagoons are relatively to very well studied. Much (but not all) information to budget many of these systems is available, and there is a small but active scientific community of researchers working on these lagoons. The workshop is therefore seen as an opportunity to give several of these researchers relatively detailed instructions in the use of the LOICZ Biogeochemical Modelling Guidelines, and to scope out both how many of these lagoonal systems seem amenable to budgeting and what further information is required to budget the systems. This workshop will complement the earlier, very successful workshop held in Ensenada in June 1997, by adding important (and under-represented) sites on the Gulf of Mexico coast and by extending site representation further south into Central America.

Anticipated Products:

1. Development of at least preliminary budgets for as many systems as feasible during the workshop.
2. Examination of other additional data, brought by the Mexican researchers or provided in advance, to scope out how many additional systems can be budgeted over the next year.
3. Contribution of these additional sites to two or three papers to be published in the refereed scientific literature: (a) In combination with expected output from the Australasian estuaries report, a paper comparing the biogeochemical functioning of estuaries in arid regions. (b) In combination with expected output from the South American Estuaries workshop and available data from the U.S. and perhaps Canada, a paper on latitudinal gradients in estuarine biogeochemical functioning. (c) A regional paper on comparison of lagoonal biogeochemical function over the hydrological and climatic gradients of Mexico.

Participation:

The number of participants will be limited to less than 20 persons, to allow the active involvement of all participants.

Workplan:

Participants will be expected to come prepared to participate in discussions on coastal budgets. Preparation should include reading the LOICZ Biogeochemical Modelling Guidelines (Gordon *et al.* 1996), the Mexican Lagoons Workshop Report (Smith *et al.* 1997), examination of the tutorials presented on the LOICZ Modelling web page (http://data.ecology.su.se/MNODE/) and arriving with spreadsheets containing available budgeting information from ‘their sites.’

Each participant should arrive with a draft of at least one water/salt and nutrient budget set, generally following the LOICZ procedures. It would be helpful if participants also brought a draft writeup (1-3 text pages + site map), in electronic form plus 'budget boxes' (hand-drawn for the boxes is okay; these will be drafted according to a common format). Examples can be found in the 'Mexican Lagoons' workshop report. For the sake of consistency, please express rates as annual and in molar (rather than mass) units.

Background Documents (for reference, to meet LOICZ initiatives):

Gordon, D.C.Jr, Boudreau, P.R., Mann, K.H., Ong J.-E., Silvert, W.L., Smith, S.V., Wattayakom, G., Wulff, F. and Yanagi, T. 1996 LOICZ Biogeochemical Modelling Guidelines. *LOICZ Reports & Studies*, No.**5**. LOICZ, Texel, The Netherlands, 96 pages.

Smith, S.V., Ibarra-Obando, S., Boudreau, P.R. and Camacho-Ibar, V.F. 1997 Comparison of carbon, nitrogen and phosphorus fluxes in Mexican coastal lagoons. *LOICZ Reports and Studies* .**10**, LOICZ, Texel, The Netherlands, 84 pages.

LOICZ Modelling web page, for everyone with www access:
(http://data.ecology.su.se/MNODE/)