1. OVERVIEW OF WORKSHOP AND BUDGETS RESULTS

The 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 to 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 is 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 scientific networks to integrate expertise and information at these levels in order to deliver science knowledge that addresses LOICZ's regional and global goals.

The United Nations Environment Programme (UNEP) and Global Environment Facility (GEF) have similar interests, through the sub-programme: "Sustainable Management and Use of Natural Resources". LOICZ and UNEP, with GEF funding support, have established a project: "The Role of the Coastal Ocean in the Disturbed and Undisturbed Nutrient and Carbon Cycles" to address these mutual interests; this Workshop is the fourth of a series of regional activities within the project.

The coastal regions of East Asia extend over about 30 degrees of latitude, from tropical to subpolar climatic conditions. Physiographically, the mainland comprises extensive coastal plains and dynamic deltaic systems, mountains and steep inclines often close to the coast, and major river systems (especially in China) commonly discharging large volumes of water, sediment, nutrients and chemicals into the coastal seas. Large islands, including Taiwan and the Japanese group, share a similar topography. In addition to major rivers, many relatively short-course river systems drain into bays and estuarine systems. Seasonal patterns of discharge range from monsoonal systems in the south to ephemeral flow systems in the north that become frozen in winter. The coastal interface contains many estuaries and embayments, especially below 38 degrees North e.g., along the coast of China. Large sea systems (e.g., Yellow and East China Seas, Sea of Japan) characterise the relatively wide continental shelf and have complex circulation and mixing patterns. The Kuroshio Current has a major influence along the southern continental shelf margin. The region supports a large population that continues to greatly modify the terrestrial environment through changing and increasingly intensive land uses, *inter alia* agriculture, urban conurbations (including a number of coastal megacities) and industries. As a consequence, the human dimensions of change are marked and various, as is their pressure on the coastal zone. To the north of the 38ºN latitude, population densities are relatively small and frequently sparse. The region, thus, has a wide spectrum of natural and human conditions interacting in the coastal zone.

The Workshop was held at the Hong Kong Baptist University, Kowloon, Hong Kong on 13-15 June 2000. The terms of reference for the Workshop (Appendix VI) and a summary of activities (Appendices III and V) are contained in this report. The resource persons worked with Workshop participants from five countries (China, Japan, Korea, Russia, Taiwan) to develop and assess biogeochemical budgets for twelve coastal systems in the region, ranging from estuarine environments

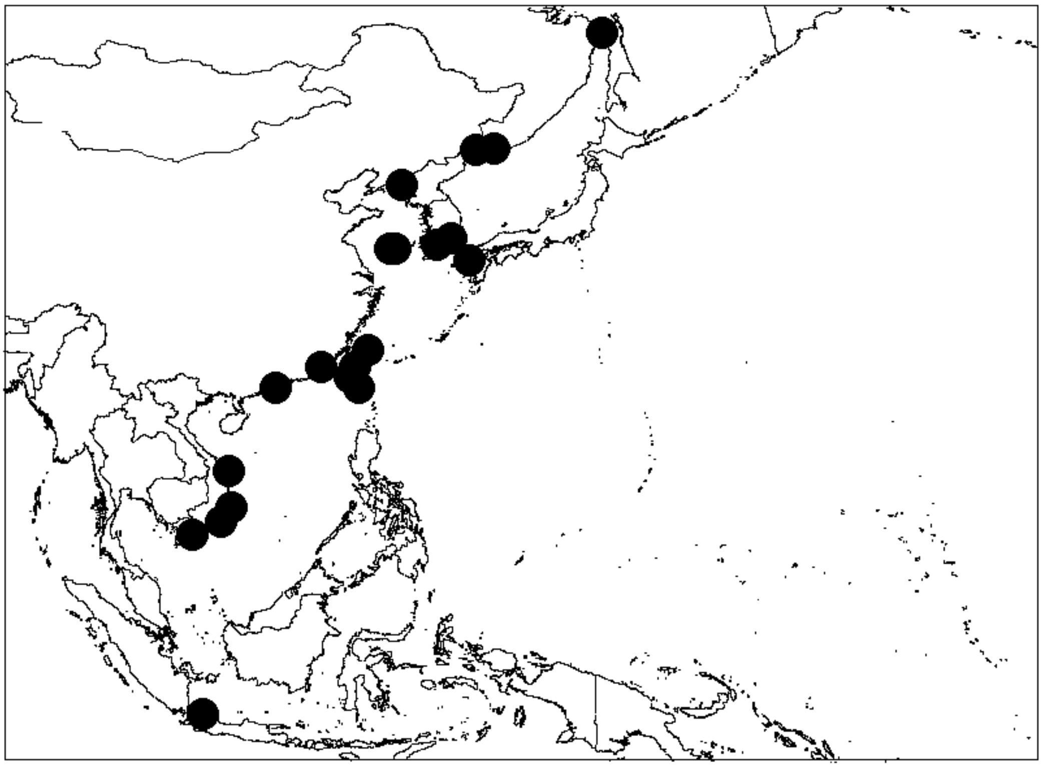


Figure 1.1 Map of budget sites developed during the East Asia regional workshop.

associated with large and small river catchments to large bays and a regional sea. Further site budgets are being developed at home institutions; two from Russia (Amur River, Ussuriysky Bay) are included here.

Biogeochemical budget models for four Vietnam estuaries and one from Indonesia are also reported here, reflecting work following on from an earlier workshop in the South China Sea region. These continuing activities from the regional biogeochemical workshop series are a vital part of the Project, in part reflecting the success of the awareness and training components of the formal workshops. Additional training opportunities are coordinated and supported by the project-funded Asia Regional Mentors (Drs Laura David and Malou McGlone). Dr Anatoly Mozherovsky, from the Pacific Oceanological Institute, Far East Branch Russian Academy of Sciences will take up the LOICZ/UNEP Regional Training Scholarship (East Asia) in late 2000, for additional training in budget analyses at the University of the Philippines (with the Asia Regional Mentors) and at the University of Hawaii (with Prof. Stephen Smith)

The initial plenary session of the Workshop outlined the LOICZ approach to biogeochemical budget modelling of nutrient fluxes in estuaries, and described tools which have been developed for site assessment and budget derivations. The final version of the CABARET software programme (for calculation of sites budget and models), presented by Dr Laura David, provides an extra dimension to the tools and training elements. The pivotal role of the Budgets and Modelling electronic website was emphasised, along with its use by scientists globally in making budget contributions to the LOICZ purpose. It was noted that in the website publication, the authorship of contributed budgets is clearly indicated, and that there is provision to update and provide additional assessment of budgets.

Twelve budgets were developed during the Workshop (Figure 1.1, Table 1.1), with additional sites identified for future work. The budgets under consideration were refined and discussed within small working groups and during plenary sessions. A method was developed (Appendix I; Prof. Tetsuo Yanagi) for calculation of exchange in systems for which there is no salinity difference between the system and the ocean; the Indonesian system (Teluk Banten) is used as a test case for this method. As well, a preliminary approach was made to development of a method for calculating both advection and mixing in stratified systems (Appendix II), as the current LOICZ salt-water budget approach does not include an estimate of horizontal mixing but assumes all of the horizontal exchange of salt is due to advection.

The common element in the budget descriptions is the use of the LOICZ approach to budget development, which allows for global comparisons and application of the typology approach. The differences in the descriptive presentations reflect the variability in richness of site data, the complexity of the sites and processes, and the extent of general knowledge and detailed understanding of processes for each site. Background information for the various estuarine locations (describing the physical environmental conditions and related forcing functions, history and potential anthropogenic pressure) is an important part of the budget information for each site. These budgets, associated data and wider availability in electronic form (CD-ROM, LOICZ website) will provide opportunities for further assessment, comparisons and the potential for use with 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 nonconservative fluxes are reported per unit area (Tables 1.1 and 1.2).

Key outcomes and findings from the Workshop include:

1. The Net Ecosystem Metabolism (NEM; [*p-r*]) and [*nfix-denit*] values calculated for the systems changed seasonally in value (and sometimes in sign). Commonly, the wet or flood season rates were greater than the dry season rates by several-fold. While this may reflect a response to nutrient loads, companion changes were observed in water exchange rates and the relative dominance of freshwater and coastal ocean waters in the systems.

2. Loads of DIN and DIP from riverine sources seasonally increased with wet or flood conditions yielding nutrient loads up to an order of magnitude higher than the dry season. Nitrogen load (as DIN) showed a greater increase than for DIP, probably reflecting increased drainage and leaching from agricultural lands as well as from sources due to other human activities. Nutrient loading from precipitation is sometimes a significant input factor.

3. Understandably, water exchange rates for the systems were less during the wet or flood seasons, in some cases down to less than one day. In these circumstances, system budget estimates were not made, as the signal for assessment of biological activity in the system is uncertain and materials are probably functioning conservatively with regard to the system. Indeed, there are cases described in which wet season river input effectively "jets" through the system, apparently flushing materials from the catchment to the coastal shelf.

4. An assessment was made for a large delta system and its component estuaries (the Pearl River) and for a regional sea (Yellow Sea). The Pearl River estuaries show differing net metabolic activities reflecting both their inherent characteristics and catchment inputs. The Yellow Sea net metabolic performance is of interest in its apparently low rates per unit area. Recognising the highly reactive system metabolism in adjacent river estuaries (several of which are described here), we infer that much of the metabolic transformation of land-derived nutrients to the Yellow Sea is occurring within the near coastal sublittoral and tidal areas.

LOICZ is grateful for the support and efforts of Professor Ming Wong and his Institute staff in hosting the workshop, and to the resource scientists for their contributions to the success of the workshop. LOICZ particularly 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.

Table 1.1 Budgeted East Asian and South China Sea region sites, locations, sizes and water exchange times.

System Name	**Long.** (°E)	**Lat.** (°N)	**Area** (km^2)	**Depth** (m)	**Exchange Time** (days)
East Asia region					
Russia					
Amursky Bay	131.8	43.2	400	15	250
Amur River estuary	141.3	53.0	20000	30	30
Ussuriysky Bay	131.8	43.3	75	3	6
Korea					
Nakdong River estuary	128.9	35.1	96	5	7
Sumjin River estuary	127.8	34.9	55	21	156
China					
Jiulong River	118.0	24.4	85	6	2
Pearl River estuary (total system)	113.6	22.6	1180	7	<3
Aimen estuary	113.1	22.0	440	4	15
Modaomen estuary	113.4	22.2	350	5	10
Yalujiang River estuary	124.3	39.8	170	6	5
Yellow Sea system	124.0	36.0	420000	44	7 years
Japan					
Dokai Bay	130.8	33.9	11	8	21
Taiwan					
Chiku Lagoon	120.1	23.1	10	2	6
Tapong Bay	120.2	22.7	5	2	11
Tsengwen River estuary	120.1	23.0	3	2	184 (dry), 6 (wet)
Tanshui River estuary	121.4	25.2	17	4	4
South China Sea region					
Vietnam					
PhanThiet Bay	108.1	10.8	370	15	30
VanPhong Bay	109.5	12.6	410	17	52
Tien River estuary	106.5	9.8	230	6	5
ThuBon River estuary	108.8	15.8	12	7	4
Indonesia					
Teluk Banten	106.2	-6.0	150	7	3

Table 1.2 Budgeted East Asia and South China Sea region sites, loads and estimated *[nfix-denit]* and *[p-r]*.

System Name	DIP load	DIN load	ΔDIP	ΔDIN	*[nfix-denit]*	*[p-r]*
	mmol m^{-2} yr^{-1}					
East Asia region						
Russia						
Amursky Bay	5	144	18	-154	-440	-1800
Amur River estuary	35	1240	36	-730	-1820	-4750
Ussuriysky Bay	10	38	27	110	-1850	-2700
Korea						
Nakdong River estuary	350	58000	-186	-49500	-37000	18000
Sumjin River estuary	40	2820	-25	-1700	-1460	3000
China						
Jiulong River	35	8800	-160	-930	1700	18000
Pearl River estuary (total system)	680	23100	7000	-2000	-8000	-43000
Aimen estuary[A]	95	4630	-70	-3760	-2750	7300
Modaomen estuary[A]	260	13000	-190	-3600	-550	20200
Yalujiang River estuary	70	78000	70	31000	-32000	-7700
Yellow Sea system	1	110	<1	-100	-100	-21
Japan						
Dokai Bay	270	11	-4	-232	-220	365
Taiwan						
Chiku Lagoon	400	3400	-100	-2300	-1500	10600
Tapong Bay	300	1200	-60	140	2200	6200
Tsengwen River estuary[B]	35	1650	-10	-300	-300	100
Tanshui River estuary	1120	51000	-200	-13000	-26000	6000
South China Sea region						
Vietnam						
PhanThiet Bay	13	320	44	-1860	-2550	-4750
VanPhong Bay	0	0	0	800	800	4
Tien River estuary[C]	800	13600	18	220	-90	-1800
ThuBon River estuary[C]	9800	26600	-4700	-12000	62000	50000
Indonesia						
Teluk Banten	2	7	-11	-220	-44	1170

A – The Aimen and Modaomen estuaries are elements of the greater Pearl River estuary; the Pearl River estuary results are the sum of those two estuaries plus the Pearl River element (see Dupra *et al*. 2000) of the total system.
B – Includes dry and wet season estimates but not flood periods when nutrients are considered to behave conservatively.
C – ΔDIP, ΔDIN and stoichiometric values are calculated from dry season data only; nutrients are considered to behave conservatively during the wet season.

2. BUDGETS FOR ESTUARIES IN RUSSIA

2.1 Amursky Bay

Anatoly V. Mozherovsky, S.V. Smith and V. Dupra

<u>Study area description</u>

Amursky Bay is a 400 km^2 embayment (~ 15 m deep; volume ~ 6x10^9 m^3) adjacent to the city of Vladivostok, Russia (Figure 2.1). The bay receives freshwater input primarily from the Tavrichanka Estuary, a short (2 km), narrow (2 km), shallow (0.3-5 m) lagoon located at the end of the bay, and exchanges water with Piter Great Gulf, Japan Sea (43.2°N, 131.5°E). Communication with the gulf is through three mouths in the southern zone, 150, 50 and 50 m wide. In addition to river flow (averaging about 4x10^6 m^3 d^{-1} since 1936) (Gidrometeoizdat, Prymorye Hydrometeorological Administration 1998), the budgeted portion of the bay receives waste load from Vladivostok, Artem and Nadezhdinsky districts. The phosphorus content (DIP) of the waste load averages about 14 µM, and the nitrogen (DIN) averages about 390 µM. For the budgeted part of Amursky Bay, waste load was about 0.2x10^6 m^3 d^{-1} in 1998 (Gidrometeoizdat, Prymorye Hydrometeorological Administration 1999).

The weather in the region is cold and humid. Annual mean temperature is 5°C, varying from -15°C in January to 20°C in July. The annual mean rainfall is 600 mm and evaporation is 450 mm. In this zone, two main seasons are recognized: the dry season with low rainfall (October-April, 0-60 mm), and the rainy season (May-September; >500 mm). The annual rainfall minus evaporation balance is positive but is negligible in the water budget (Gidrometeoizdat, Prymorye Hydrometeorological Administration 1996, 1997, 1998).

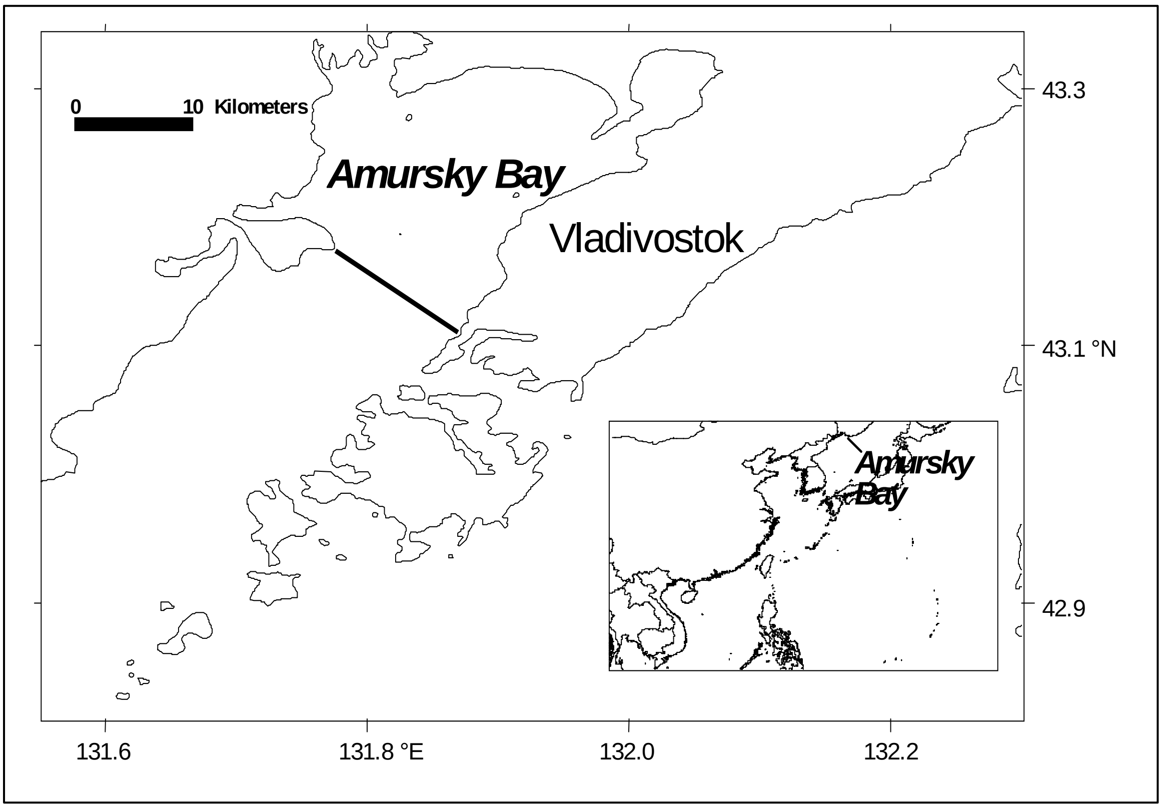


Figure 2.1. Map and location of Amursky Bay, Russia, with the budgeted area indicated.

The budgets undertaken here were based on hydrographic data collected on two dates in 1997 (10 and 28 September) (Cruise Report, R/V "Professor Gagarinsky" 1997, Gramm-Osipova 1997). River discharge at that time was about 2 x 10^6 m^3 d^{-1} (Gidrometeoizdat, Prymorye Hydrometeorological Administration 1996, 1997, 1998). Nutrient concentration data for the river were not obtained during the hydrographic survey but are interpolated (mean value for 1996-1998) from the data in Figures 2.2 and 2.3 to be 1 µM DIP and 40 µM DIN (Gidrometeoizdat, Prymorye Hydrometeorological Administration 1999).

Water and salt budgets

Water and salt budgets for Amursky Bay (Figure 2.4) were calculated with the "CABARET" program. The water exchange time averages about 250 days.

Budgets of nonconservative materials

DIP balance

The system appears to be a net DIP source (ΔDIP = +20x10^3 mol d^{-1}, or +0.05 mmol m^{-2} d^{-1}). There is apparently very low net flux in surface waters and some release in the deep water (Figure 5).

DIN balance

The system appears to be a net DIN sink (ΔDIN = -169x10^3 mol d^{-1}, or -0.4 mmol m^{-2} d^{-1}), with high net uptake in the surface waters and slight release in the deep water (Figure 6).

Stoichiometric calculations of aspects of net system metabolism

If it is assumed that the reacting material has a Redfield C:N:P composition of 106:16:1, then the slight net DIP release indicates an oxidation of approximately 5 mmol C m^{-2} d^{-1}. Similarly, the release of DIP and uptake of DIN suggests a net denitrification rate of approximately 1.2 mmol m^{-2} d^{-1}.

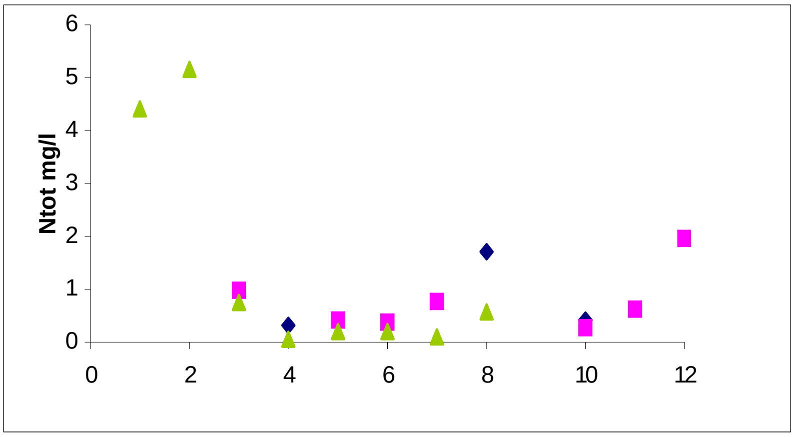


Figure 2.2. Plot diagram for nitrate in Razdol'naya River water for 1996-1998 .

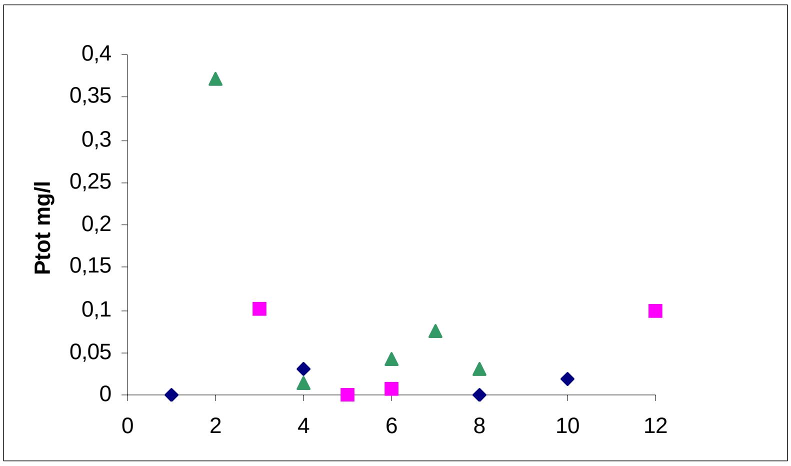


Figure 2.3. Plot diagram for phosphorus concentration in Razdol'naya River water for 1996-1997.

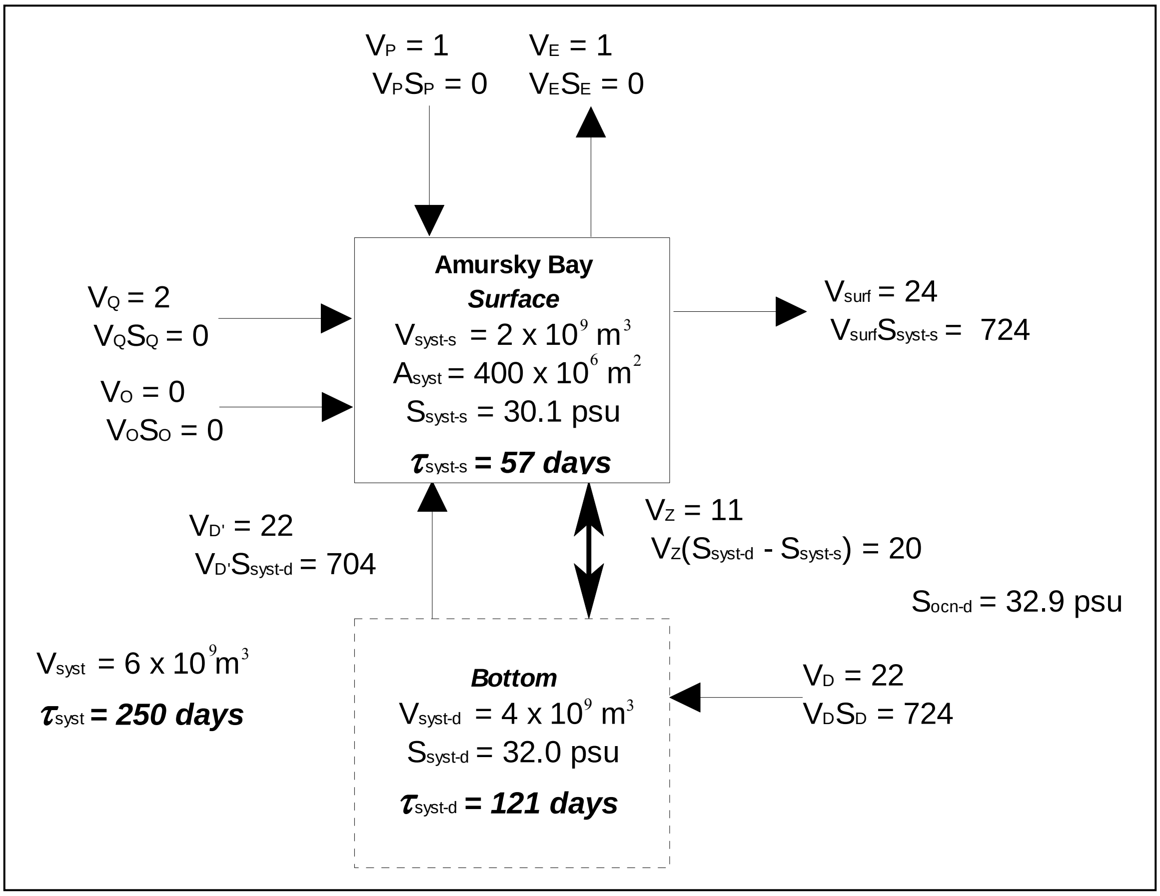


Figure 2.4. Water and salt budgets for two-layer model for Amursky Bay in September 1997. Water flux in 10^6 m^3 d^{-1} and salt flux in 10^6 psu-m^3 d^{-1}.

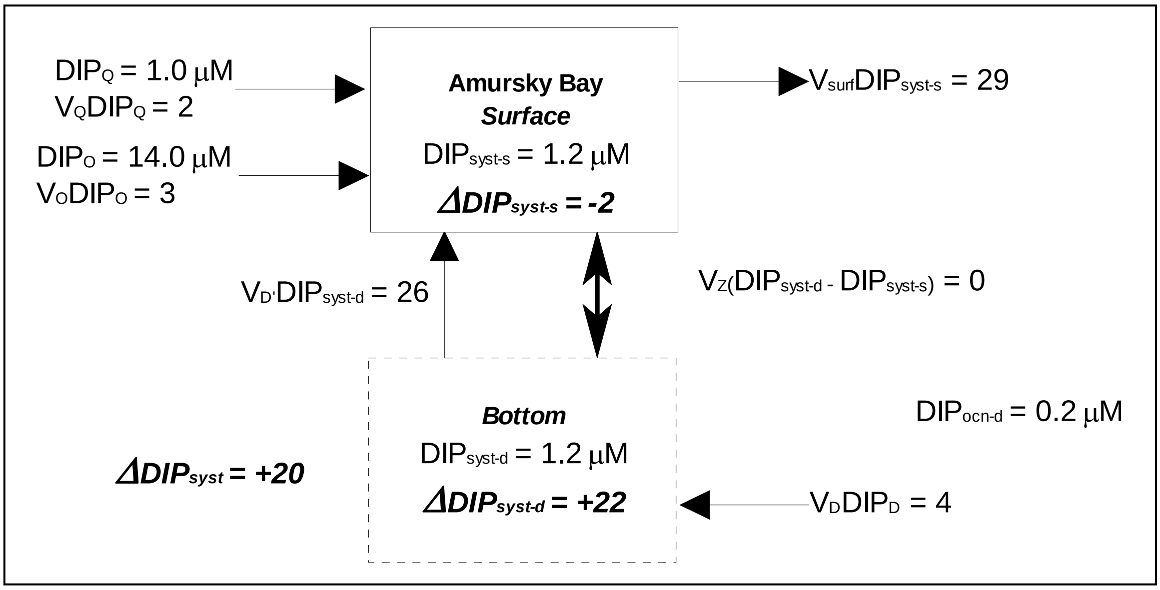


Figure 2.5. DIP budget for two-layer model for Amursky Bay in September 1997. Flux in 10^3 mol d^{-1}.

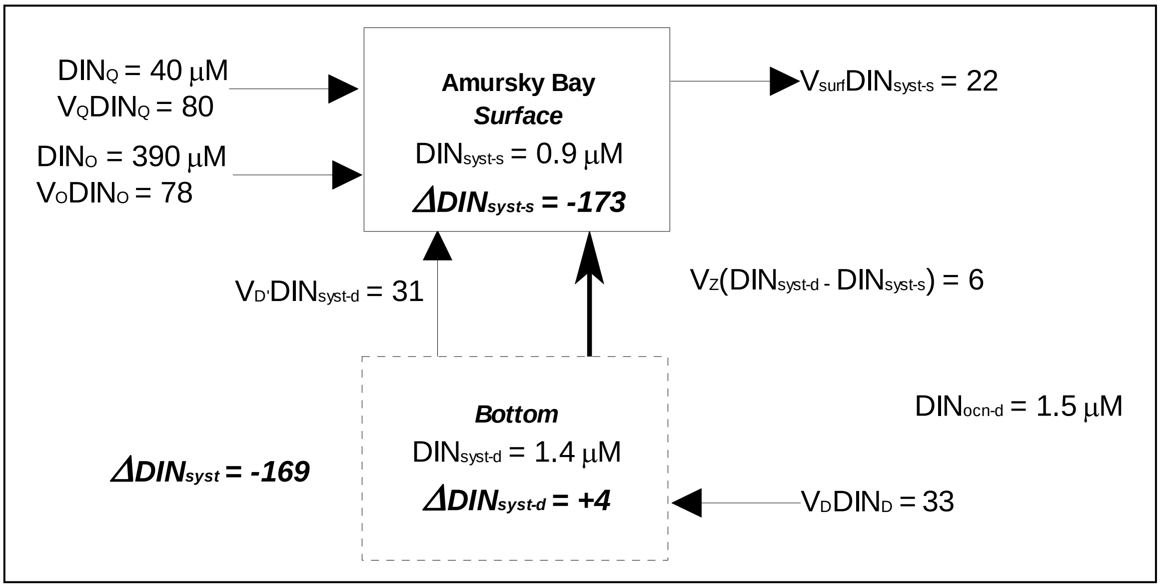


Figure 2.6. DIN budget for two-layer model for Amursky Bay in September 1997. Flux in 10^3 mol d^{-1}.

2.2 Amur River estuary

Anatoly V. Mozherovsky

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

The Amur River (141.33 °E, 53.00 °N) is one of the largest rivers in the Far East region (Figure 2.7). The length is 4,400 km with an area of about 1,900 x 10^3 km^2. The annual river discharge is about 3,600 x 10^9 m^3. The fresh water discharge can be observed for more than 200 km out to sea from the mouth of the river.

The main sources of the river flow are the Sikhote-Alin Mountain Ridge and the southern part of Siberia. The area is characterized by high precipitation in the winter, which contributes about 18-22% of the annual river discharge. The spring flood during April and May supplies about 25-30% of the annual water discharge. Brief floods are common in the summer and autumn up until October or November. In the winter, the river discharge is relatively low, about 3-5% of the annual discharge. Complete ice cover usually starts in mid-November and continues until early May. Mean temperature ranges from -26°C in the winter to +18°C in the summer. Mean rainfall is 600-700 mm yr^{-1} and evaporation is 450-550 mm yr^{-1}.

Human population in this area is small. Agricultural and industrial activities are low. Main pollution sources are large towns (population 100,000-600,000), shipbuilding, pulp and paper, mining and timber industries.

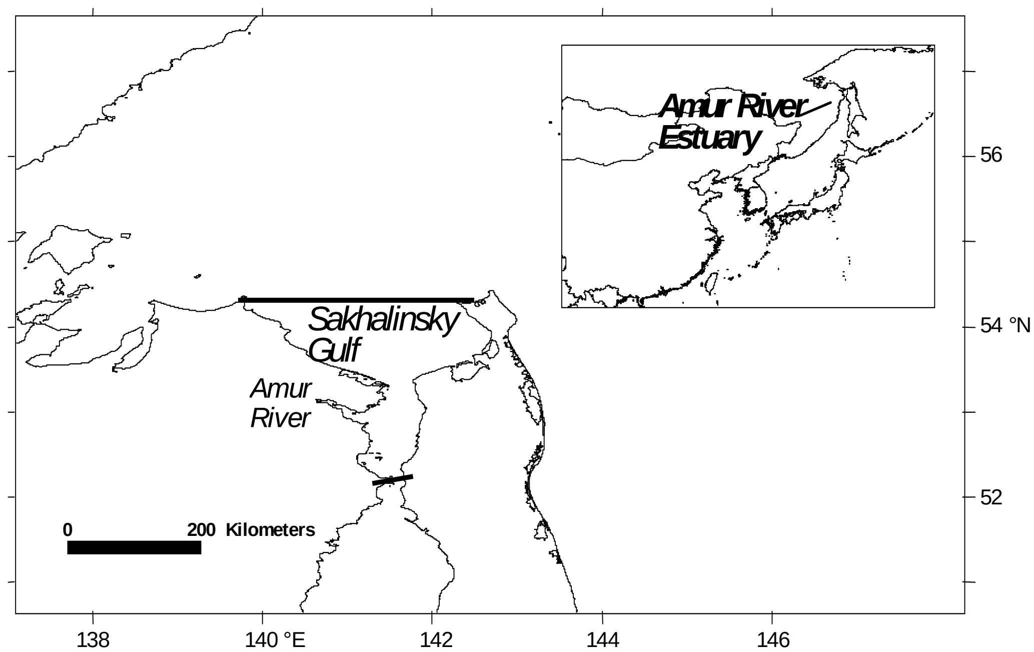


Figure 2.7. Map of the Amur River estuary. Solid bars show the boundary of the budgeted system.

For budgeting purposes, the Amur River estuary and Sakhalinsky Gulf were considered as one box. The Amur River estuary has an area of about 4,400 km^2 with a length of 130 km and width of 46 km. The average depth of the estuary is 30 m. Sakhalinsky Gulf has an area of 15,600 km^2 and depth range of 15-40 m.

Hydrology of the area was studied during five cruises held between 1986 and 1994 by Pacific Oceanological Institute (POI FEB RAS). Data was provided by I.D.Rostov (http://poi.febras.ru/stuff/rostov.htm). See Table 2.1.

Table 2.1. Hydrological data for the Amur River and Sakhalinsky Gulf

		Salinity psu		DIN µM		DIP µM	
		system	ocean	system	ocean	system	ocean
Amur River				34		0.8	
Sakhalinsky Gulf							
Cruise Jul 1992	0-5 m	31	32	5.0	0.7	0.5	0.3
	5-15 m	32	33	7.0	1.6	1.0	0.8
Cruise Aug 93	0-5 m	28	30	1.5	0.4	0.4	0.5
	5-15 m	31	32	4.0	0.7	0.7	0.8
Cruise Oct 94	0-5 m	20	30	1.7	0.1	0.9	0.6
	5-15 m	29	31	2.6	0.3	1.6	0.9
Average	0-5 m	24	30	3.0	0.2	0.6	0.2
	5-15 m	31	32	5.0	0.4	1.1	0.7

Water discharge for the wet season was calculated based on the river discharge data from 1963 to 1998 (Figure 2.8). Water discharge for the wet season is equal to $21x10^3$ m^3 sec^{-1} or $2x10^9$ m^3 d^{-1}. Nutrient concentrations in the river water discharge were calculated from data measured in 1996 (Figures 2.9 and 2.10). A one-box, two-layer model was used to budget for the wet season.

Water and salt balance

Water and salt budgets for the system (Figure 2.11) were calculated following LOICZ procedure (Gordon *et al*. 1996). Water exchange time was about 30 days.

Budgets of nonconservative materials

DIP and DIN balance

Figures 2.12 and 2.13 summarize the two-layer DIP and DIN budgets for the system. The net nonconservative nutrient fluxes for the whole system were calculated as ΔDIP = $+2x10^6$ mol P d^{-1}, or +0.1 mmol P m^{-2} d^{-1} and ΔDIN = $-45x10^6$ mol N d^{-1} or -2 mmol N m^{-2} d^{-1}.

Stoichiometric calculations of aspects of net system metabolism

If it is assumed that the reacting material has a Redfield C:N:P composition of 106:16:1, then the upper layer is autotrophic: *(p-r)* = +33 mmol m^{-2} d^{-1} and net nitrogen fixing: *(nfix-denit)* = + 0.3 mmol m^{-2} d^{-1}. The lower layer is heterotrophic: *(p-r)* = -46 mmol m^{-2} d^{-1} and net denitrifiying: *(nfix-denit)* = -5 mmol m^{-2} d^{-1}. This implies that whatever organic material is fixed in the upper layer is broken down at lower depths. Some organic material in the sediments may also contribute to heterotrophy and denitrification in the lower box. The whole system is heterotrophic: *(p-r)* = -13 mmol m^{-2} d^{-1} and net denitrifying: *(nfix-denit)* = -5.0 mmol m^{-2} d^{-1}.

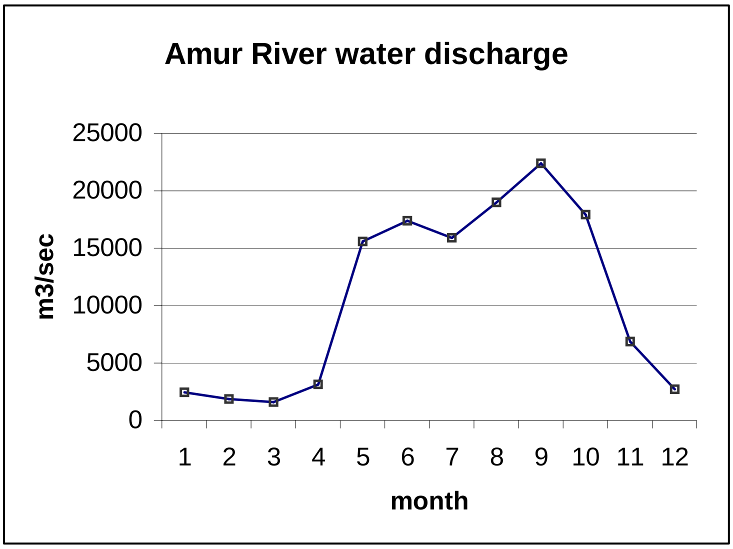


Figure 2.8. Plot diagram of average monthly discharge for Amur River.

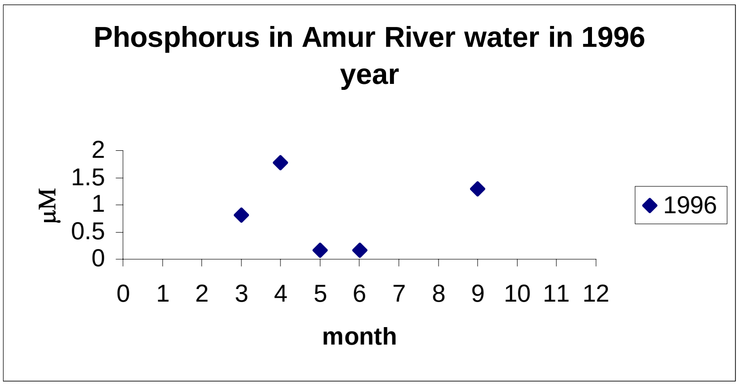


Figure 2.9. Plot diagram of dissolved inorganic phosphorus concentrations for the Amur River water discharge in 1996.

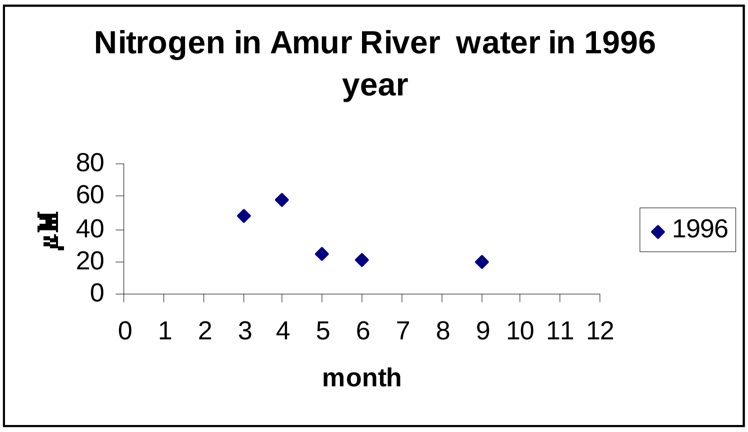


Figure 2.10. Plot diagram of dissolved inorganic nitrogen concentrations for the Amur River water discharge in 1996.

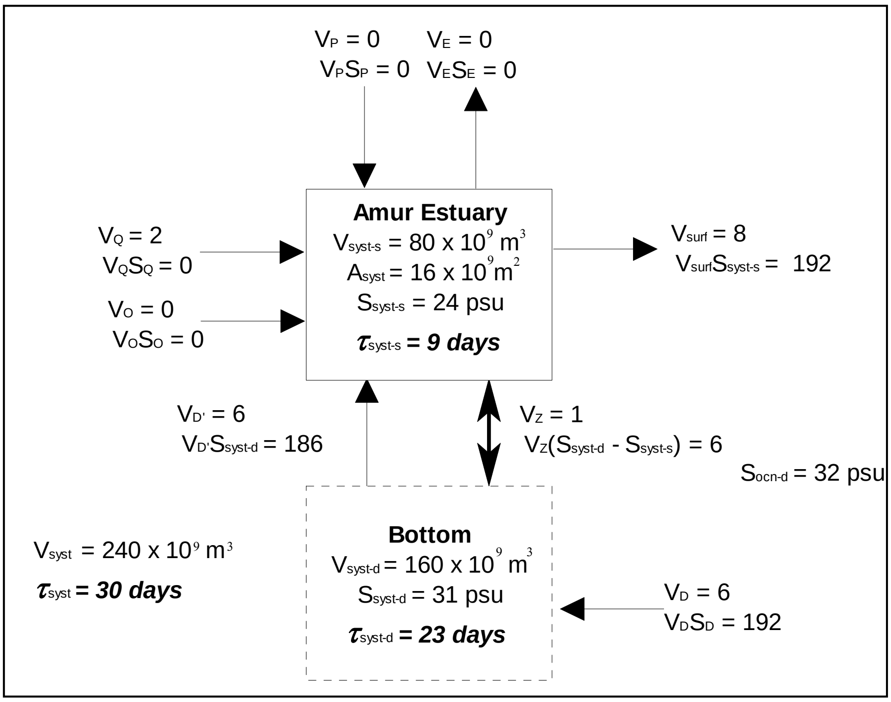


Figure 2.11. Water and salt balance for the Amur River estuary in the wet season. Water flux in 10^9 m^3 d^{-1} and salt flux in10^9 psu-m^3 d^{-1}.

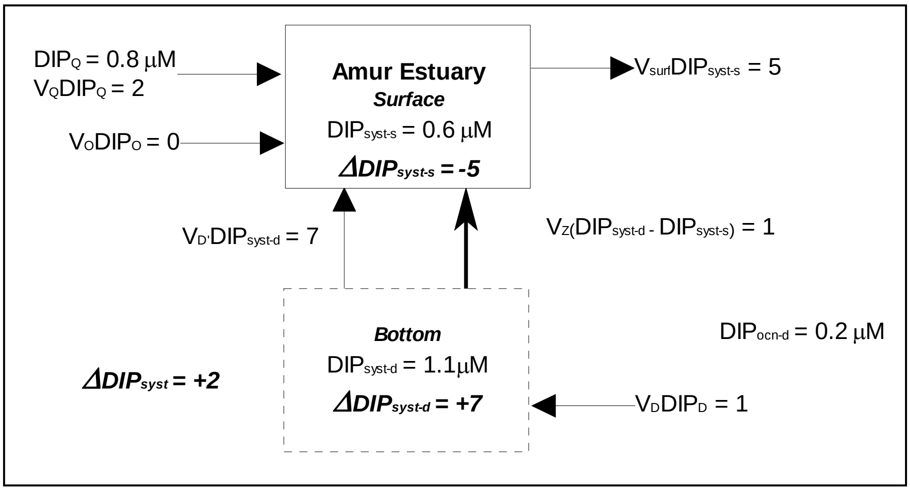


Figure 2.12. Dissolved inorganic phosphorus balance for the Amur River estuary in the wet season. Flux in 10^6 mol d^{-1}.

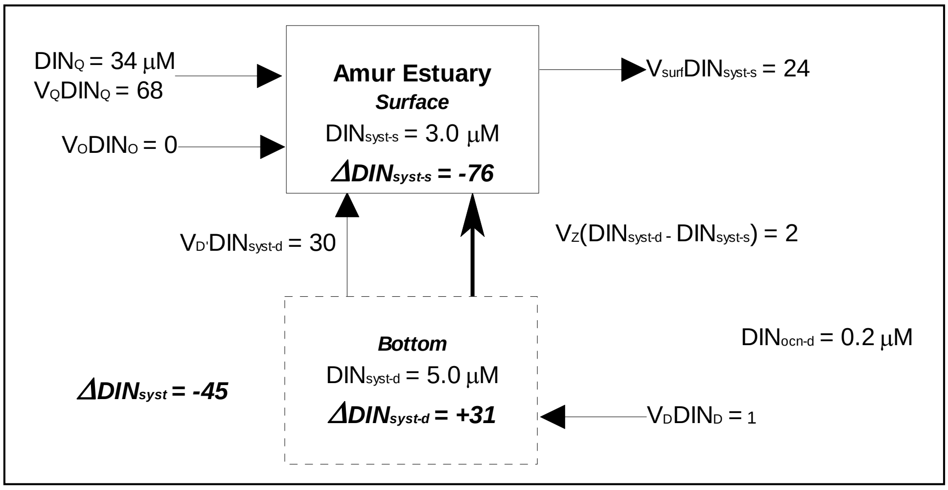


Figure 2.13. Dissolved inorganic nitrogen balance for the Amur River estuary in the wet season. Flux in 10^6 mol d^{-1}.

2.3 Ussuriyskiy Bay

Anatoly V. Mozherovsky

Study area description

Ussuriyskiy Bay (43.27°N, 131.82°E) is a relatively large embayment with an area of about 750 km^2. The average depth of the bay is ~ 40 m with a volume of ~ $30x10^9$ m^3. The bay is adjacent to the city of Vladivostok, Russia (Figure 2.14). Ussuriyskiy Bay exchanges water with Peter the Great Gulf, Japan Sea.

The weather in the region is cold and humid. The annual mean temperature is 5°C, varying from -15°C in January to +20°C in July. The annual mean rainfall is 600 mm and evaporation is 450 mm. In this zone, two main seasons are recognized: the dry season with low rainfall (October-April, 0-60 mm), and the rainy season (May-September; >500 mm).

The estuarine part of Ussuriyskiy Bay ranges from 5-10 km long, 3-5 km wide and 0.3-5 m deep. The estuary is located at the landward end of the bay. Freshwater inputs come primarily from the Artyomovka River (70 km long; watershed area of 1,500 km^2) and the Shkotovka River (60 km long; watershed area of 700 km^2). Measurements for river discharge and nutrient concentrations are not available for the Shkotovka River. Data for Shkotovka River discharge used in this paper were calculated based on the ratio and proportion of watershed and river discharge of Artyomovka River and Shkotovka River. Shkotovka River discharge is half of that of the Artyomovka River. Nutrient concentrations for the Shkotovka River discharge were assumed the same as Artyomovka River. Waste load and other sources both for water and nutrients are considered low in the area.

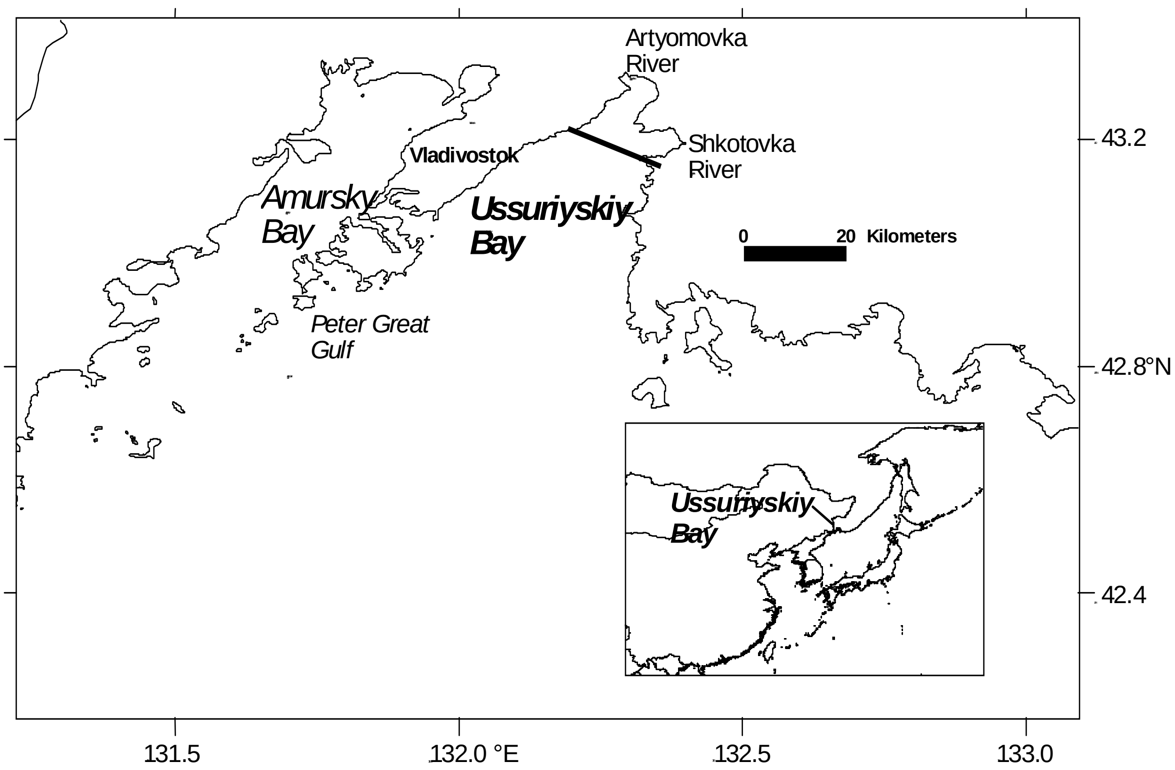


Figure 2.14. Map of Ussuriyskiy Bay. Solid bar shows the boundary of the budgeted system.

The budgets were based on hydrographic data collected between 1999 and 2000 (November and December 1999, and March 2000) by the Pacific Oceanological Institute (POI FEB RAS). The data were provided by G. I. Yurasov. An area of 75 km^2 with an average depth of 3 m was considered in this budget.

Water and salt balance

Water and salt budgets for wet and dry seasons for Ussuriyskiy Bay were calculated following the LOICZ biogeochemical modelling guidelines (Gordon *et al*. 1996). Total flow from the two rivers was estimated as 4 m^3 sec^{-1} or $350x10^3$ m^3 d^{-1} in the dry season and 11 m^3 sec^{-1} or $1,000x10^3$ m^3 d^{-1} in wet season. The net balance of rainfall minus evaporation is positive but is negligible in the water budget. Results are very similar for both seasons (Figure 2.16). The water exchange times averaged about 9 and 3 days for dry and wet seasons, respectively.

Budgets of nonconservative materials

DIP and DIN balance

The dissolved inorganic phosphorus and nitrogen (DIP and DIN) were averages from measurements taken in 1996 to 1998 and interpolated as 1.3 μM (DIP) and 12 μM (DIN) for dry season, and 1.8 μM (DIP) and 13 μM (DIN) for the wet season (Figures 2.14 and 2.15).

Figures 2.17 and 2.18 illustrate the DIP and DIN budgets for Ussuriyskiy Bay both for the dry and wet seasons. Assuming that nutrient loads into the bay were delivered via rivers and the other sources were insignificant, the budgets show: ΔDIP = $+5x10^3$ mol P d^{-1} (+0.07 mmol P m^{-2} d^{-1}) and ΔDIN = $+22x10^3$ mol N d^{-1}(+0.3 mmol N m^{-2} d^{-1}) for the dry season; and ΔDIP = $+6x10^3$ mol P d^{-1} (+0.08 mmol P m^{-2} d^{-1}) and ΔDIN = $+25x10^3$ mol N d^{-1}(+0.3 mmol N m^{-2} d^{-1}) for the wet season

Table 2.2. Hydrographic data for Ussuriyskiy Bay.

	Salinity (psu)	**DIN** (μM)	**DIP** (μM)
Dry season			
System	33.5	4.9	0.8
Ocean	34.0	3.9	0.6
Wet season			
System	33.0	5.0	0.8
Ocean	33.5	4.5	0.7

Stoichiometric calculations of aspects of net system metabolism

If it is assumed that the reacting material has a Redfield C:N:P composition of 106:16:1, then the system is net heterotrophic: (*p-r*) = -7 mmol m^{-2} d^{-1} and net denitrifying: (*nfix-denit*) = -0.8 mmol m^{-2} d^{-1} for dry season; and (*p-r*) = -8 mmol m^{-2} d^{-1} and (*nfix-denit*) = -1 mmol m^{-2} d^{-1} for wet season.

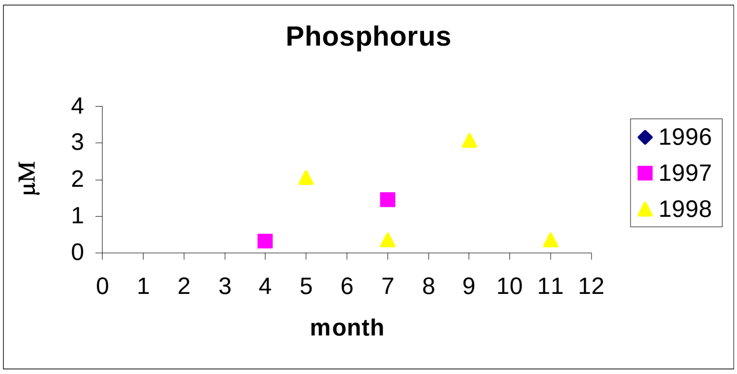


Figure 2.14. Plot diagram for dissolved inorganic phosphorus for the Artyomovka river water discharge in 1996-1998.

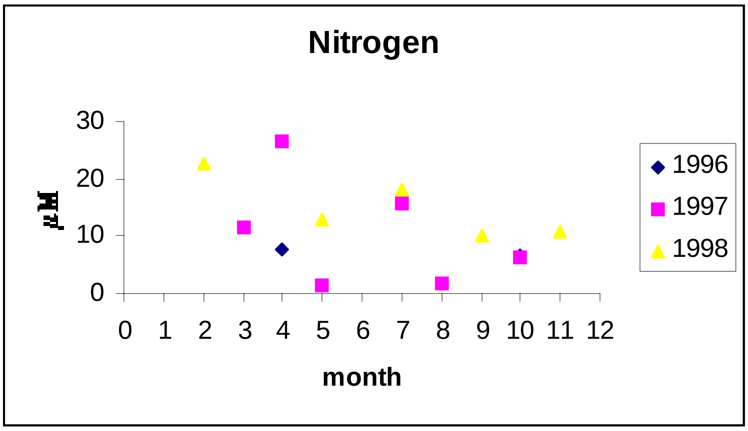


Figure 2.15. Plot diagram for dissolved inorganic nitrogen concentrations for the Artyomovka river water discharge in 1996-1998.

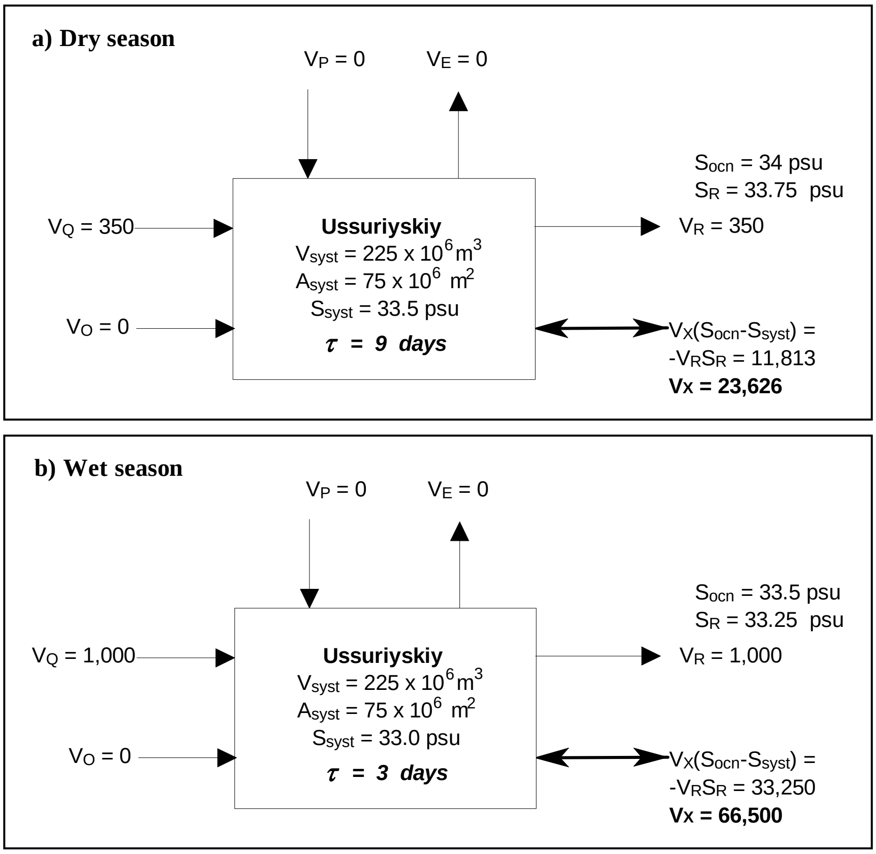


Figure 2.16. Water and salt balance for Ussuriyskiy Bay in dry (a) and wet (b) seasons. Water flux in 10^3 m^3 d^{-1} and salt flux in10^3 psu-m^3 d^{-1}.

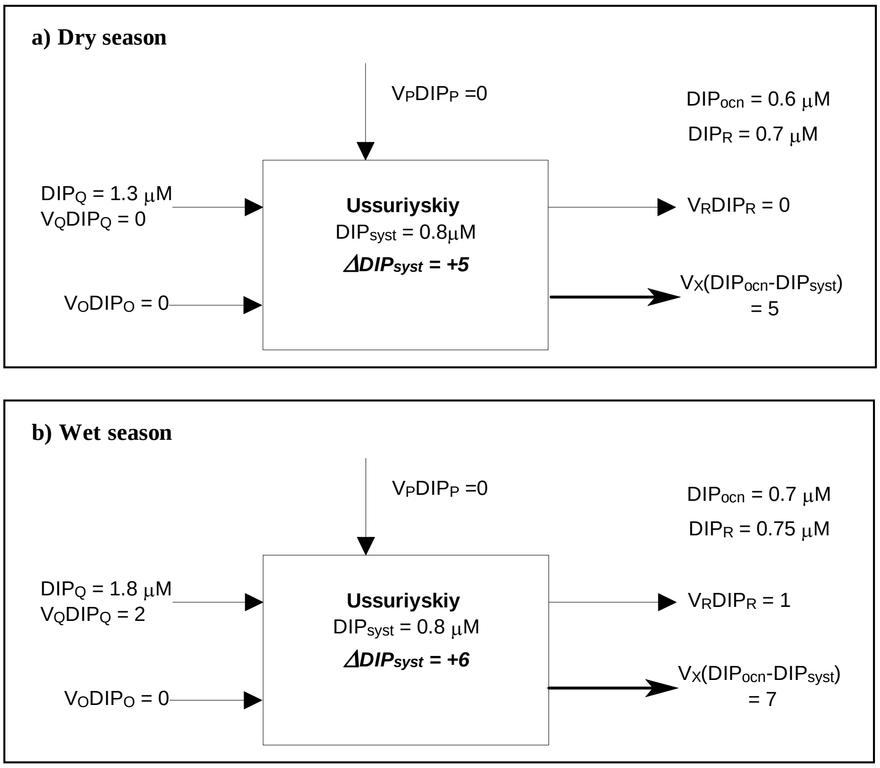


Figure 2.17. Dissolved inorganic phosphorus budgets for Ussuriyskiy Bay in dry (a) and wet (b) seasons. Flux in 10^3 mol d^{-1}.

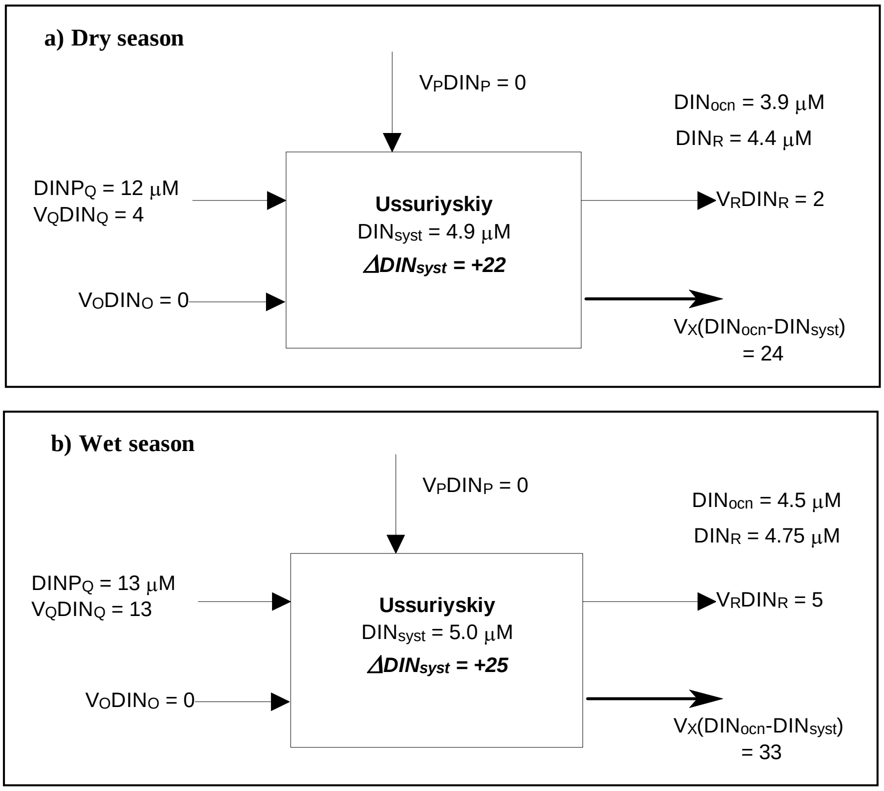


Figure 2.18. Dissolved inorganic nitrogen budgets for Ussuriyskiy Bay in dry (a) and wet (b) seasons. Flux in 10^3 mol d^{-1}.

3. BUDGETS FOR ESTUARIES IN JAPAN

3.1 Dokai Bay

Tetsuo Yanagi

Study area description

Dokai Bay is a hyper-eutrophicated semi-enclosed bay, located in the northern part of Kyushu, the main western island of Japan (Figure 3.1). Its volume is 88×10^6 m^3, surface area 11 km^2, average depth 8 m, width 1 km and bay length 11 km.

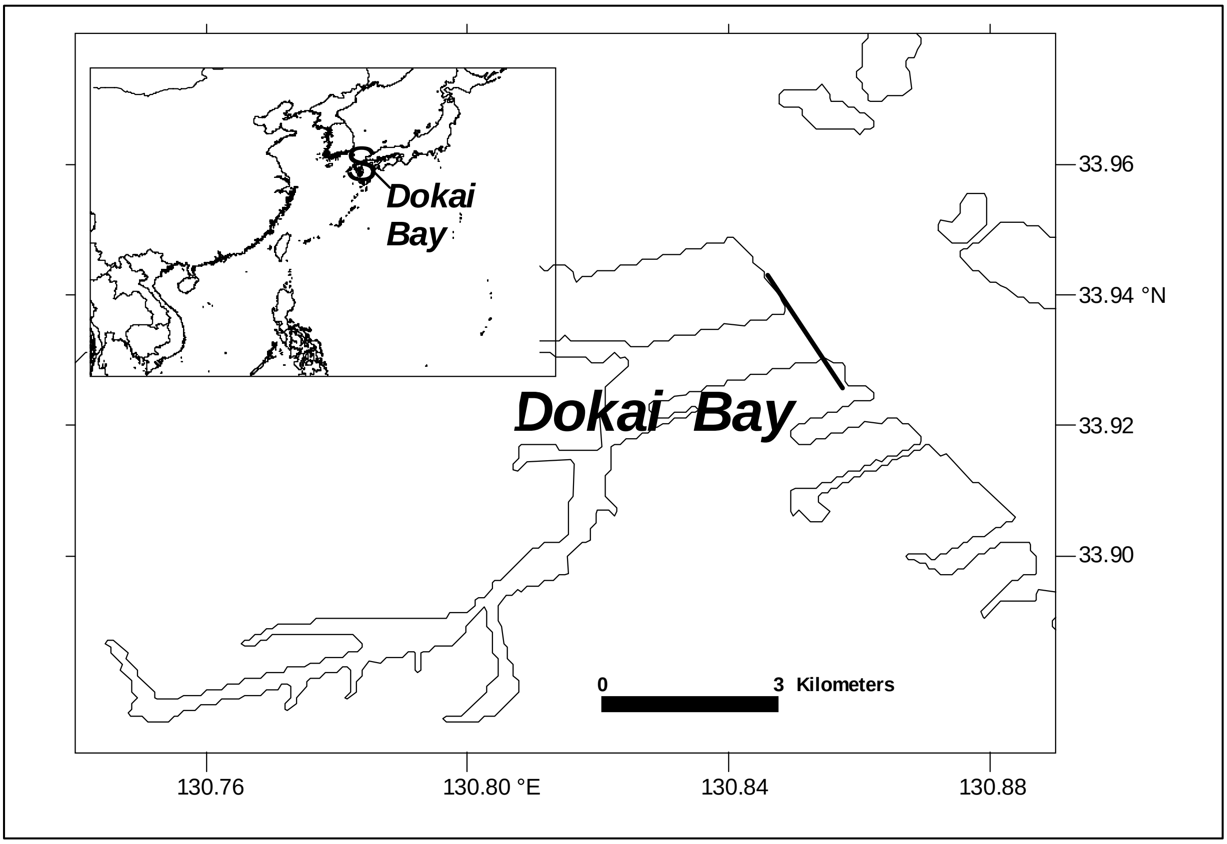


Figure 3.1. Map and location of Dokai Bay, Japan. The limit of the budgeted area. is marked.

Intensive field observations of water temperature, salinity, nitrogen and phosphorus were conducted at 1-meter depth intervals at seven stations on 20 August 1998. Results are shown in Figure 3.2. Water mass with low salinity, small density and high concentrations of TP and TN flows into the head of the bay. Such distributions of salinity and nutrients are considered to be quasi-steady state because their temporal variations are much smaller than their spatial variations (Yanagi and Yamada 2000).

Water and salt balance

Figure 3.3 shows the water and salt budgets. Here 30.7 psu is the average salinity from Station 2 to Station 7 and 31.3 psu at Station 1. The residual volume transport from Dokai Bay V_R is 81×10^3 m^3 d^{-1} and the mixing volume across the open boundary V_X is estimated to be $4{,}185 \times 10^3$ m^3 d^{-1} which is about 50 times that of V_R.

Budgets of nonconservative materials

DIP and DOP budgets

DIP and DOP budgets are shown in Figure 3.4(a) and (b). Concentrations of DIP and DOP in the bay are 2.1 μM and 0.7 μM, respectively. DIP of 115 mol d^{-1} is transformed to organic form and DOP of 7 mol d^{-1} is transformed to DIP or POP.

DIN and DON budgets

DIN and DON budgets are shown in Figure 3.5(a) and (b). Concentrations of DIN and DON in the bay are 95 μM and 37 μM, respectively. DIN of 9×10^3 mol d^{-1} is transformed to organic form and DON of 2×10^3 mol d^{-1} is generated from DIN or PON.

POP and PON budgets

POP and PON budgets are shown in Figure 3.6(a) and (b). POP of 2×10^3 mol d^{-1} and PON of 13×10^3 mol d^{-1} are decomposed in Dokai Bay.

Stoichiometric calculations of aspects of net system metabolism

When we assume that the main primary producer in Dokai Bay is phytoplankton and the Redfield ratio, C:P = 106:1, is applied, the net primary production in Dokai Bay is estimated to be $(p\text{-}r) = 12\times10^3$ mol d^{-1} (1 mmol C m^{-2} d^{-1}).

Nitrogen fixation minus denitrification (*nfix-denit*) flux is estimated by the following formula:

$$(nfix\text{-}denit) = (\Delta DIN) - (\Delta DIP)(N{:}P)_{part} \quad (1)$$

$$(nfix\text{-}denit) = (\Delta DIN + \Delta DON) - (\Delta DIP + \Delta DOP)(N{:}P)_{part} \quad (2)$$

Here $(N{:}P)_{part}$ denotes the mol ratio of PON and POP in Dokai Bay which is shown in Figure 3.6. Denitrification calculated using Equation (1) is 7×10^3 mol d^{-1} (0.6 mmol m^{-2} d^{-1}) while 5×10^3 mol d^{-1} (0.5 mmol m^{-2} d^{-1}) using Equation (2).

Comparison of the results of nitrogen budget in narrow and deep Dokai Bay and wide and shallow Hakata Bay (Yanagi 1999) is shown in Table 3.1.

Table 3.1. Comparison between Hakata Bay and Dokai Bay.

System	**Volume** (10^8 m^3)	**Depth** (m)	**TN load from land** (10^5 mol d^{-1})	**TN load by release** (10^5 mol d^{-1})	**TN load** (mmol m^{-3} d^{-1})	**TN** (μM)
Hakata Bay	4	7	9	4	3	35 (14)
Dokai Bay	1	8	5	1	1	143 (33)

System	**TN** (days)	**PP** (gC m^{-2} day^{-1})	**PON** (μM)	**DIN:DON:PON**
Hakata Bay	9.5	0.33	8	2.1:1.1:1.0
Dokai Bay	16.7	0.01	11	8.6:3.4:1.0

Ratio of TN load per unit volume in Dokai Bay to that in Hakata Bay is 2.1 but that of TN concentration is 4.1. This means that Dokai Bay becomes eutrophicated easily compared with Hakata Bay. Such difference may result from the longer residence time of TN in Dokai Bay, where the trapping effect of nitrogen is dominant in a narrow and deep semi-enclosed bay with dominant estuarine circulation as schematically shown in Figure 3.7.

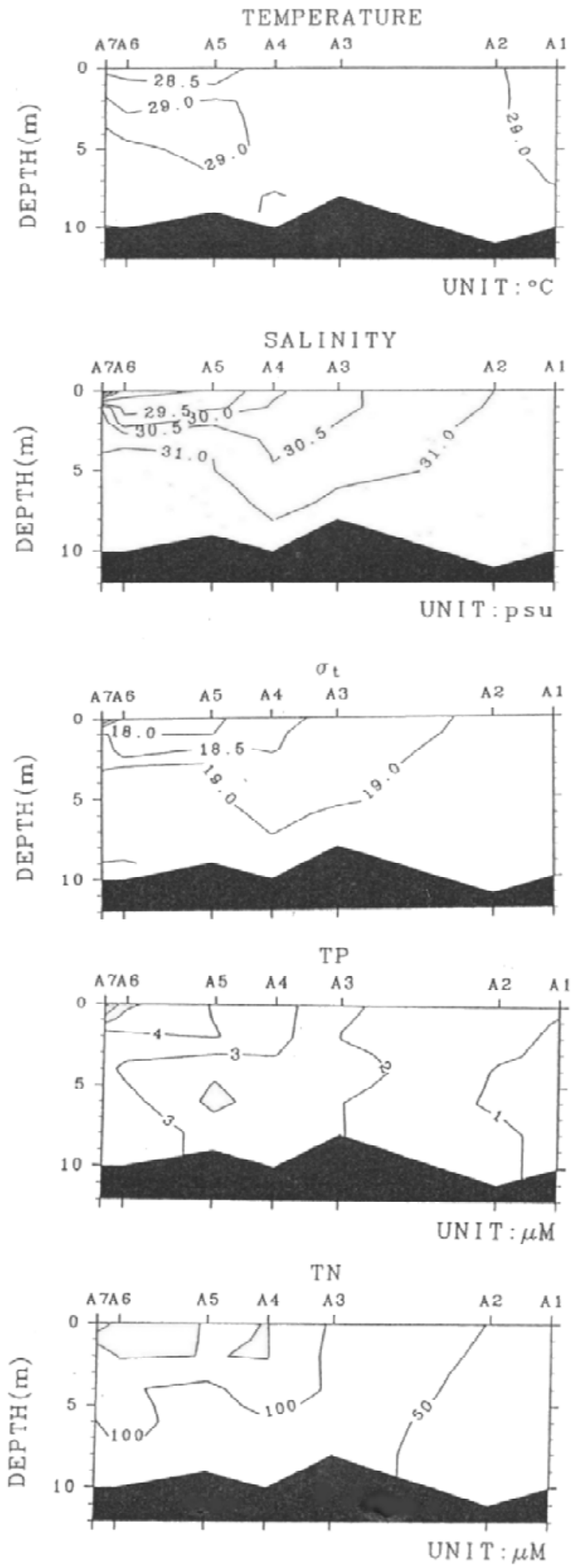


Figure 3.2. Vertical distributions of water temperature, salinity, density, total phosphorus and total nitrogen on 20 August 1998.

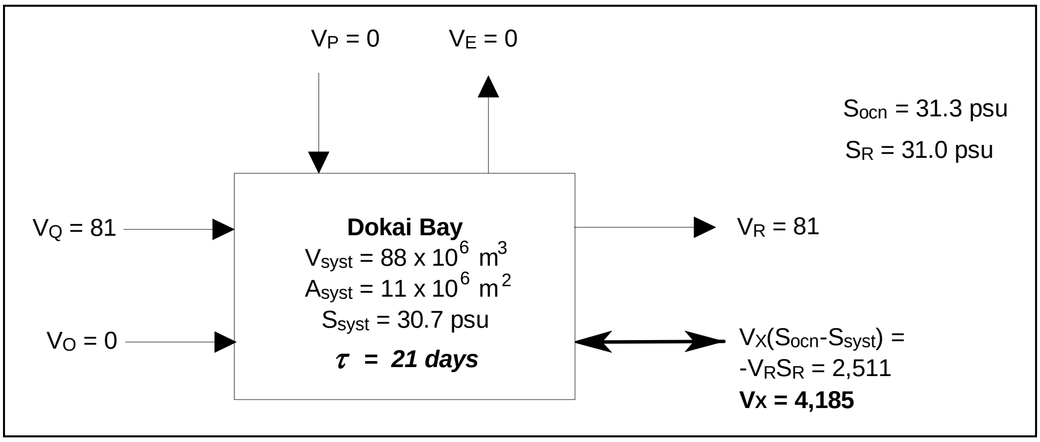
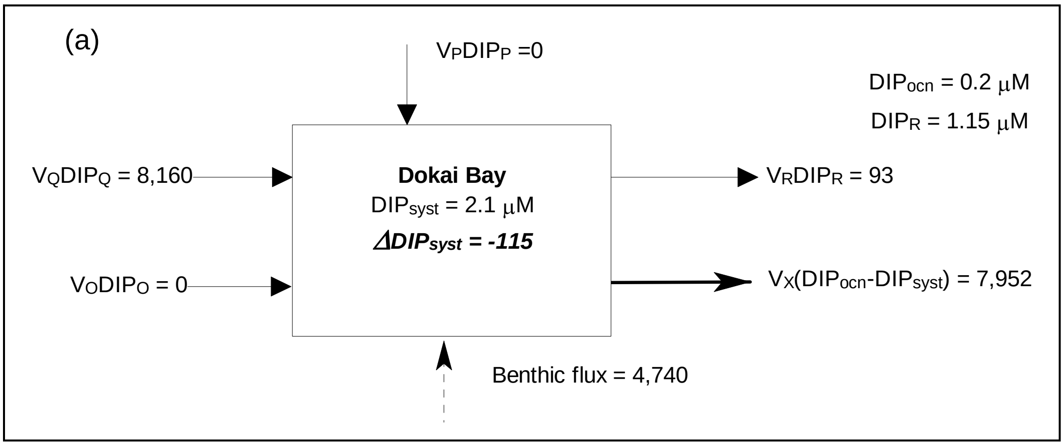


Figure 3.3. Water and salt budgets for Dokai Bay. Water flux in 10^3 m^3 d^{-1} and salt flux in 10^3 psu-m^3 d^{-1}.



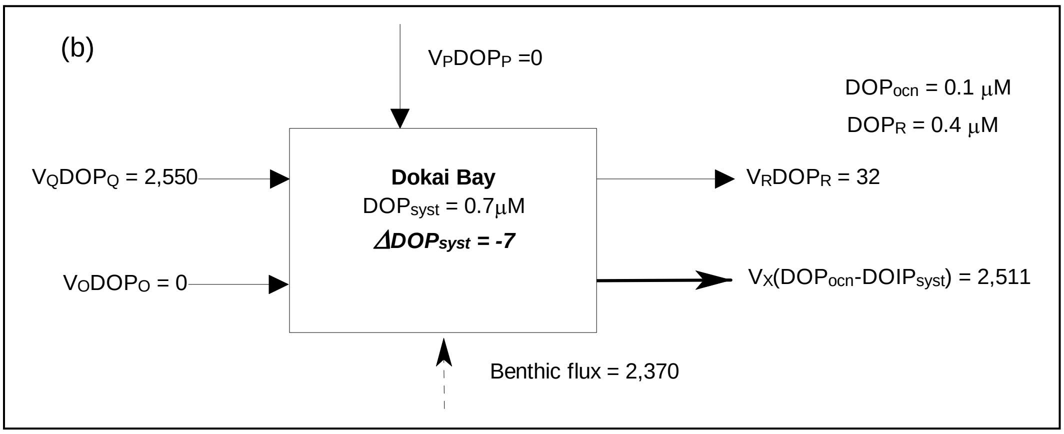


Figure 3.4. DIP (a) and DOP (b) budgets for Dokai Bay. Flux in 10^3 mol d^{-1}.

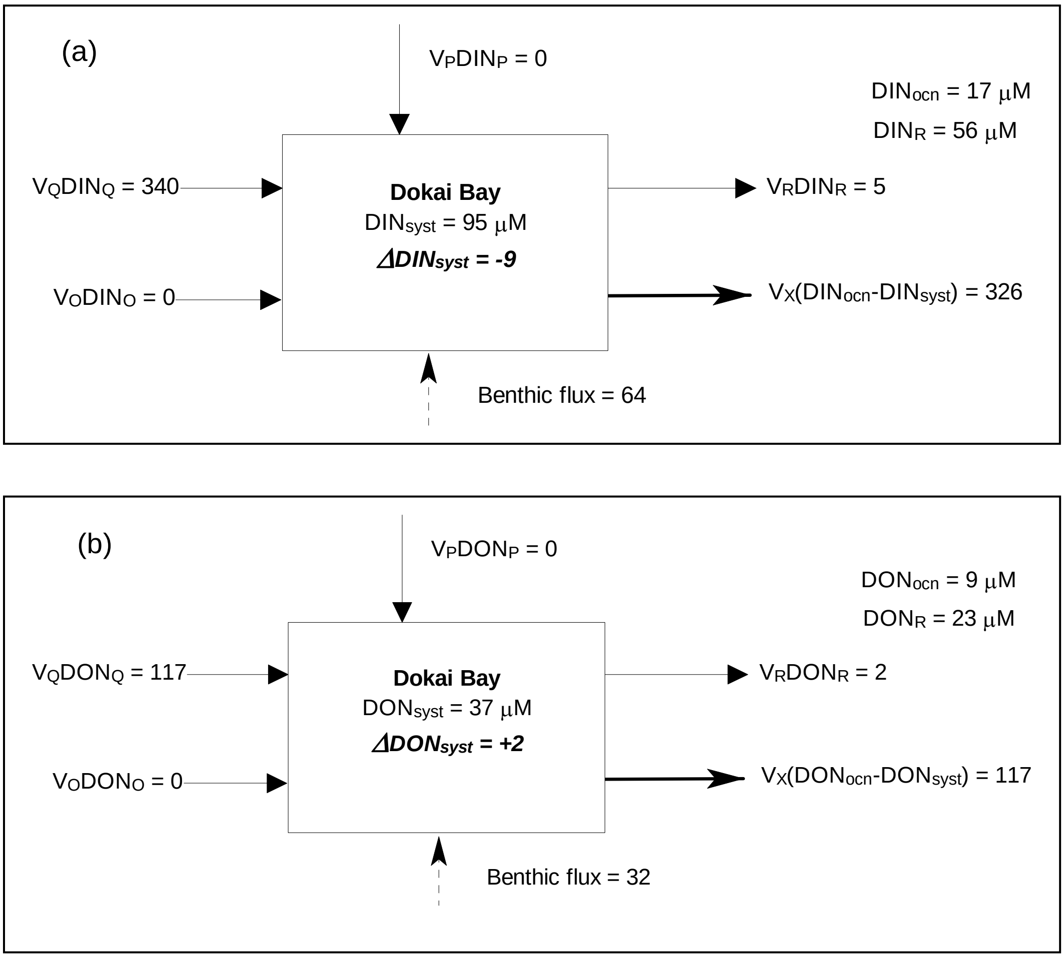


Figure 3.5. DIN (a) and DON (b) budgets for Dokai Bay. Flux in 10^3 mol d^{-1}.

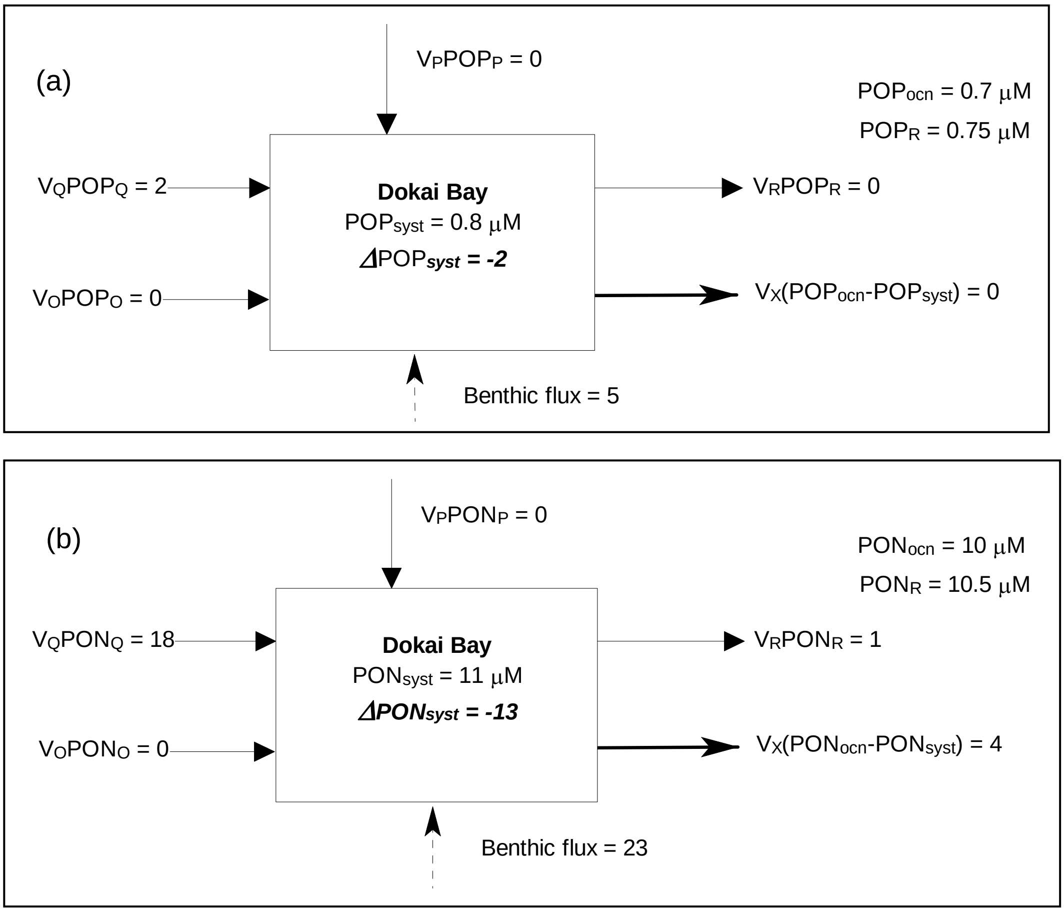


Figure 3.6. POP (a) and PON (b) budgets for Dokai Bay. Flux in 10^3 mol d^{-1}.

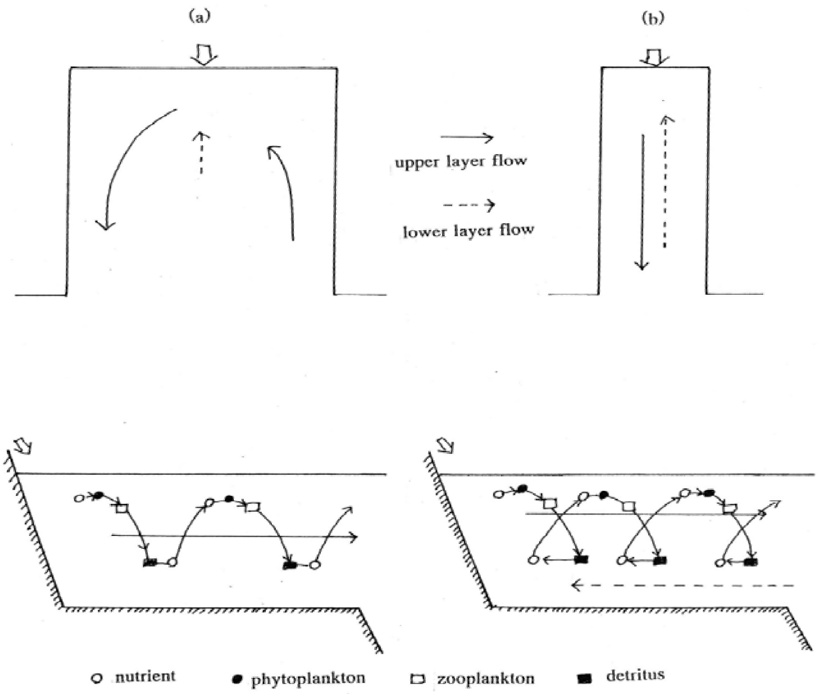


Figure 3.7. Schematic representation of transport of nitrogen in (a) a wide and shallow estuary

and (b) a narrow and deep estuary.

4. BUDGETS FOR ESTUARIES IN KOREA

4.1 Nakdong River estuary

Sung Ryull Yang and Hwan Seok Song

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

The Nakdong River, located to the south-eastern part of the Korean Peninsula (Figure 4.1), is the second largest river in South Korea (second to the Han River, which flows through Seoul), with a total length of 530 km, and a drainage area of 24,000 km^2 (approximately 2,400×10^3 ha). The estuary of the Nakdong River is located between 35.03° and 35.13°N, and 128.48° and 129.00°E. The estuarine area acts as a buffer between fresh and salt water, and contains the largest nesting grounds for migratory birds in eastern countries due to the abundance of phytoplankton and zooplankton, mollusks, seaweeds and aquatic plants (Lee *et al.* 1993; Park *et al.* 1986)). Average annual temperature is between 12°C and 14°C, and annual precipitation is 1,160 mm. The variation of annual precipitation is very high. About two thirds of annual precipitation is concentrated in three months, between July and September.

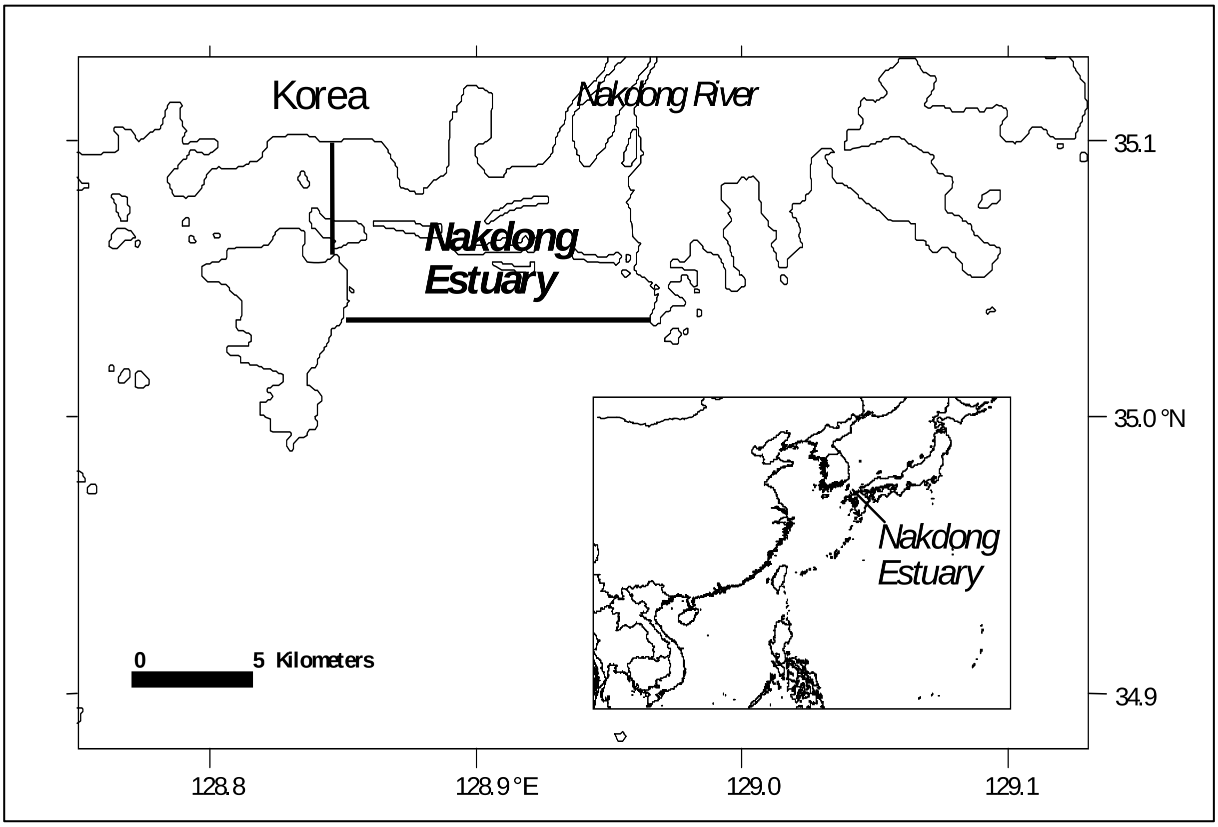


Figure 3.1. Map and location of the Nakdong River estuary. The boundaries of the budgeted area are indicated.

The average flow rate is 470 m^3 sec^{-1}or about 41,000×10^3 m^3 d^{-1}. The Nakdong River estuary is heavily polluted and also eutrophicated due to the discharge of sewage from domestic and industrial sources (Pusan Institute of Health and Environmental Research 1993). Sewage from domestic sources is 2,000×10^3 m^3 d^{-1} comprising 74% of the total; the other 26%, 700×10^3 m^3 d^{-1}, comes from industrial sources. An estuarine dike system 2 km in length was constructed in 1989 to conserve freshwater for drinking, agricultural and industrial usage. However, this dike construction prevents the free exchange of water in the estuary and leads to reduction in the water quality of both the freshwater lake upstream and the coastal environment downstream.

Water and salt balance

The LOICZ Biogeochemical Modelling Guidelines (Gordon *et al*. 1996) were used to calculate the stoichiometrically linked water-salt-nutrient budgets. A mean pan evaporation of 3 mm d^{-1} (for the estuary; V_E = -300×10^3 m^3 d^{-1}) for both wet season (June to September) and dry season (October to May) was obtained from the local weather office in Pusan. This rate was multiplied with the area (96 km^2) to get V_E. The average depth of the estuary used in this calculation is 5 m. No pan correction factors were used. Precipitations were 13 mm d^{-1} (for the estuary; V_P = 1,300×10^3 m^3 d^{-1}) for the wet season (June to September) and 3 mm d^{-1} (for the estuary V_P = 300×10^3 m^3 d^{-1}) for the dry season (October to May), based on 1988-1998 data from weather office stations in Pusan.

During the wet season, salinity values used for the budget calculation are 28.9 psu for the ocean and 3.7 psu for the estuarine system. During the dry season, these values were 33.2 psu and 31.7 psu for the ocean and estuary, respectively.

The difference between the precipitation and evaporation was very great. The volume of groundwater and wastewater input is 170×10^3 m^3 d^{-1} for the rainy season and 30×10^3 m^3 d^{-1} for the dry season. Water exchange time for the estuary was calculated to be 12 days in the wet season and 5 days in the dry season. Table 1 summarizes the water budget and water exchange time for the bay for both seasons. Figure 2 represents the water and salt budgets for the wet and dry seasons.

Table 4.1. Water budget and exchange time for Nakdong River estuary system.

Processes	**Wet Season June-September** (4 months) (10^6 m^3 d^{-1})	**Dry Season October-May** (8 months) (10^6 m^3 d^{-1})	**Annual Average** (10^6 m^3 d^{-1})
V_P	1.3	0.3	0.6
V_E	-0.3	-0.3	-0.3
V_Q	23	4	10
V_G	0.17	0.03	0.08
V_O	0.006	0.001	0.003
V_R	-24	4	11
V_X	16	87	63
τ (days)	12	5	7

V_{syst} = 480×10^6 m^3

Budgets of nonconservative materials

DIP balance

Table 4.2 summarizes the nutrient concentrations for wet and dry seasons in the Nakdong River. The average DIP concentrations inside the boxes were taken from the same data set as DIN. The average DIP concentration of runoff is 1.3 μM for the wet season, and 1.9 μM for the dry season. The oceanic

DIP concentration is 0.7 µM for the wet season, and 0.1 µM for the dry season. Groundwater DIP concentration is 0.4 µM for the wet season, and 0.6 µM for the dry season.

Figure 4.3 illustrates the DIP budgets for the wet and dry seasons. The waste load of DIP in each season was calculated from the riverine flux and from the industrial sources. The riverine flux accounted for most of the DIP load in this region.

DIN balance
DIN is defined as $NO_3^- + NO_2^- + NH_4^+$. The average DIN concentrations inside the boxes were taken from the data set of various sources including several cruises conducted by the project supported by Korean Ministry of Education (Moon and Kwon 1994; Moon and Choi 1991; Song 1998). The average DIN concentration of runoff is 163 µM for the wet season, and 245 µM for the dry season. The oceanic DIN concentration is 29 µM for the wet season, and 35 µM for the dry season. Groundwater DIN concentration is 51 µM for the wet season, and 77 µM for the dry season.

Table 4.2. Salinity and dissolved inorganic nutrient concentrations for the Nakdong River estuary system.

Variable	Wet	Dry
Salinity (psu)		
S_{syst}	3.7	31.7
S_{ocn}	28.9	33.2
Dissolved inorganic phosphorus (µM)		
DIP_P	0.01	0.01
DIP_Q	1.3	1.9
DIP_G	0.4	0.6
DIP_O	13.7	20.5
DIP_{syst}	3.3	0.3
DIP_{ocn}	0.7	0.1
Dissolved inorganic nitrogen (µM)		
DIN_P	1.2	1.8
DIN_Q	163	245
DIN_G	51	77
DIN_O	1,760	2,630
DIN_{syst}	58	69
DIN_{ocn}	29	35

Figure 4.4 represents the DIN budget for the wet and dry seasons. The waste load of DIN in each season was calculated from the riverine flux and from the industrial sources. As for the phosphate budget, the riverine flux accounted for most of the DIN load in this region. The DIN balance is strongly dominated by waste discharge in all of the budget boxes.

Stoichiometric calculations of aspects of net system metabolism
The carbon equivalent of net P flux (*p-r*) is $+10\times10^6$ mol C d^{-1} or +0.1 mol C m^{-2} d^{-1} in the wet season and $+3\times10^6$ mol C d^{-1} or +0.03 mol C m^{-2} d^{-1} in the dry season, indicating a net autotrophic system. Estimated (*nfix-denit*) was -22×10^6 mol N d^{-1} or about -0.2 mol m^{-2} d^{-1} in the wet season and -8×10^6 mol N d^{-1} or about -0.1 mol m^{-2} d^{-1} in the dry season, indicating a net denitrifying system.

Table 4.3. Dissolved inorganic nutrient fluxes and derived apparent net system metabolism for the Nakdong River estuary system.

Process	**Wet Season** (10^3 mol d^{-1})	**Dry Season** (10^3 mol d^{-1})	**Annual average** (10^3 mol d^{-1})
V_PDIP_P	0	0	0
V_QDIP_Q	30	8	15
V_GDIP_G	68	18	35
V_ODIP_O	82	21	41
V_RDIP_R	48	1	17
$V_X(DIP_{OCN}-DIP_{SYST})$	42	17	25
ΔDIP	-90	-29	-49
V_PDIN_P	0	0	0
V_QDIN_Q	4,000	6,000	5,000
V_GDIN_G	9,000	2,000	4,000
V_ODIN_O	11,000	3,000	6,000
V_RDIN_R	1,000	0	300
$V_X(DIN_{OCN}-DIN_{SYST})$	0	3,000	2,000
ΔDIN	-23,000	-8,000	-13,000
(*p-r*) (10^3 mol C d^{-1})	+10,000	+3,000	+5,000
(*nfix-denit*) (10^3 mol N d^{-1})	-22,000	-8,000	-13,000
(*p-r*) (mol C m^{-2} d^{-1})	+0.1	+0.03	+0.05
(*nfix-denit*) (mol N m^{-2} d^{-1})	-0.2	-0.1	-0.1

Budgeted area = 96 km^2

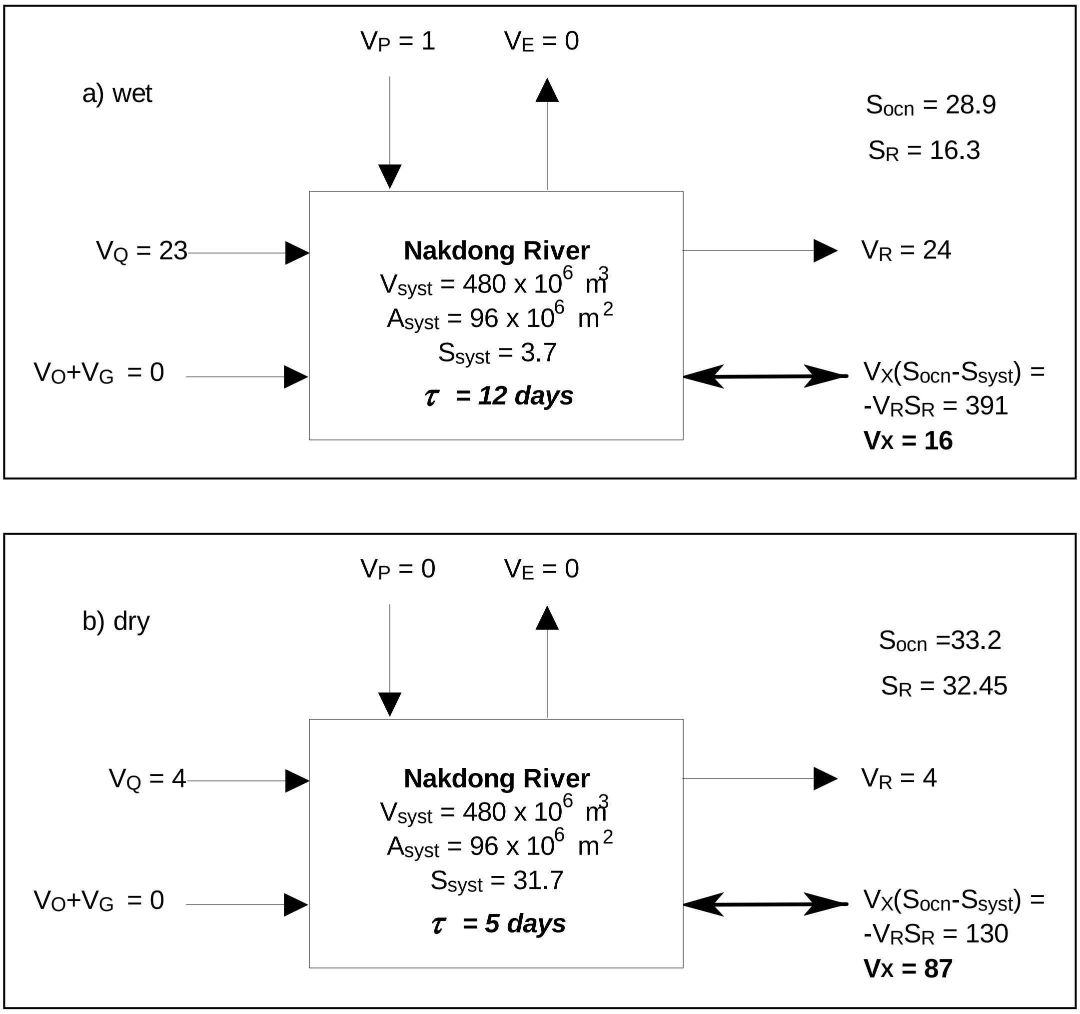


Figure 4.2. Salt and water budgets for the Nakdong River estuary in the wet (a) and dry (b) seasons. Water in 10^6 m^3 d^{-1} and salt flux in 10^6 psu-m^3 d^{-1}.

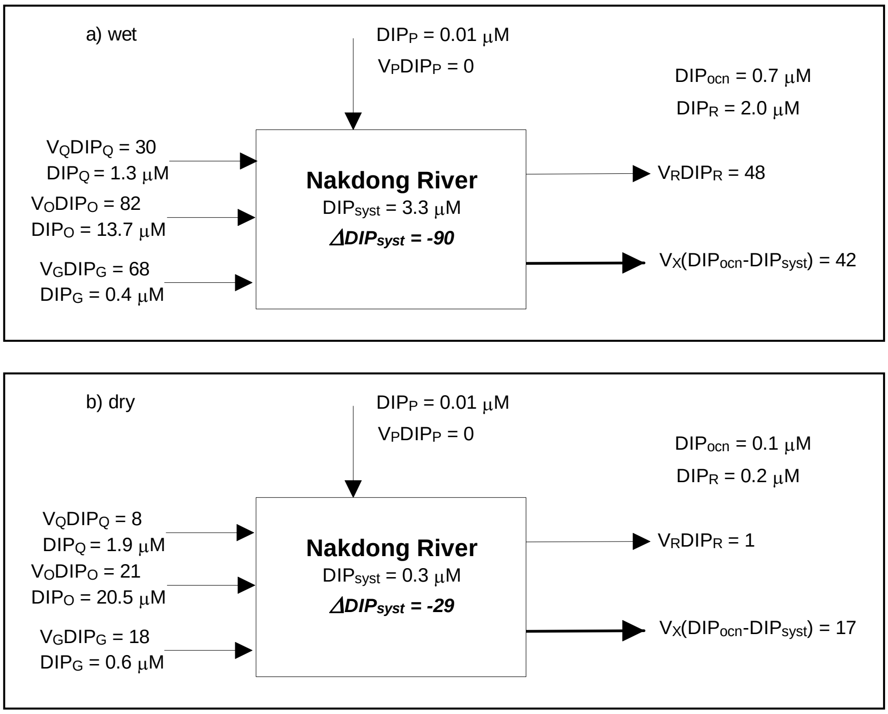


Figure 4.3. Dissolved inorganic phosphorus budget for the Nakdong River estuary in the wet (a) and dry (b) seasons. Flux in 10^3 mol d^{-1}.

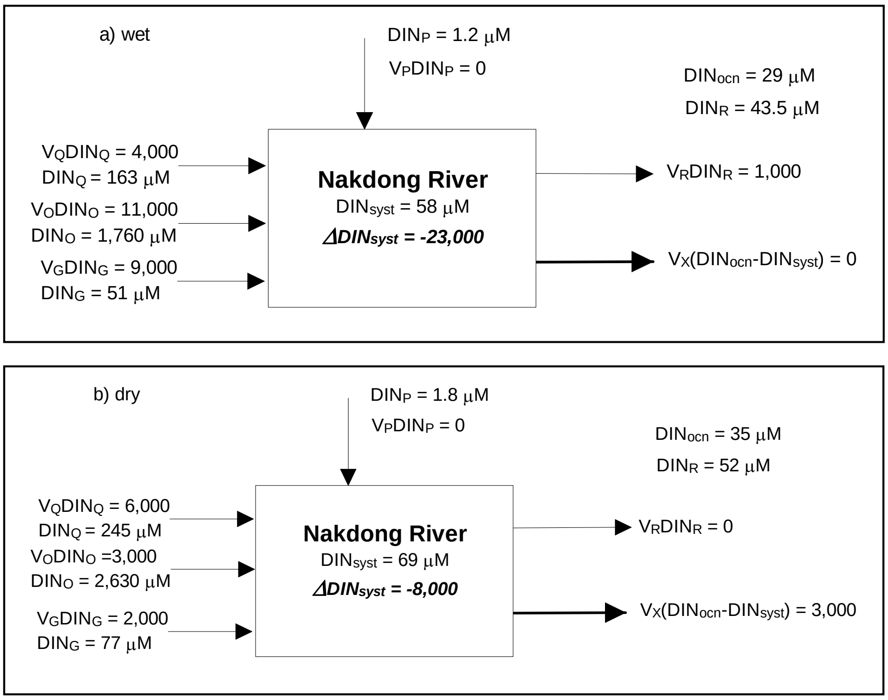


Figure 4.4. Dissolved inorganic nitrogen budgets for the Nakdong River estuary in the wet (a) and dry (b) seasons. Flux in 10^3 mol d^{-1}.

4.2 Sumjin River Estuary

Sung Ryull Yang, Jong Ki Kim and Hwan Seok Song

Study area description

The Sumjin River (34.91°N, 127.76°E) (Figure 4.5) is the fourth largest river in South Korea, with a drainage area of 5,000 km^2; the length of the main stream is 200 km. The lower reach is 35 km long, with a drainage area of 55 km^2. The budgeted area of the system is about 55 km^2, and the average depth is 21 m. The flow rate is 20 $m^3\ sec^{-1}$ or about $2\times10^6\ m^3\ d^{-1}$. The northern boundary of the Sumjin River is 35.83°N, and the southern boundary is 34.67°N. The tidal cycle is semi-diurnal. The historical long-term average annual air temperature of this region is 17.3°C, and the average annual precipitation is 1,530 mm. The lower reaches of the Sumjin River are amongst the highest precipitation areas in Korea (Shim *et al.* 1984). There are frequent floods during the summer season (between July and September).

The Sumjin River estuary is the only major river system in South Korea that is not hindered by the construction of dikes (Kim 2000). The upper reaches of the Sumjin River maintain relatively pristine conditions. On the seaward side of the estuarine area, however, there are major industrial installations, including the Kwangyang steel company and Yochun petrochemical complex. The volumes of waste discharges are: $58\times10^3\ m^3\ d^{-1}$ from domestic sewage, $100\times10^3\ m^3\ d^{-1}$ from industrial wastes, and $9\times10^3\ m^3\ d^{-1}$ from domestic animals.

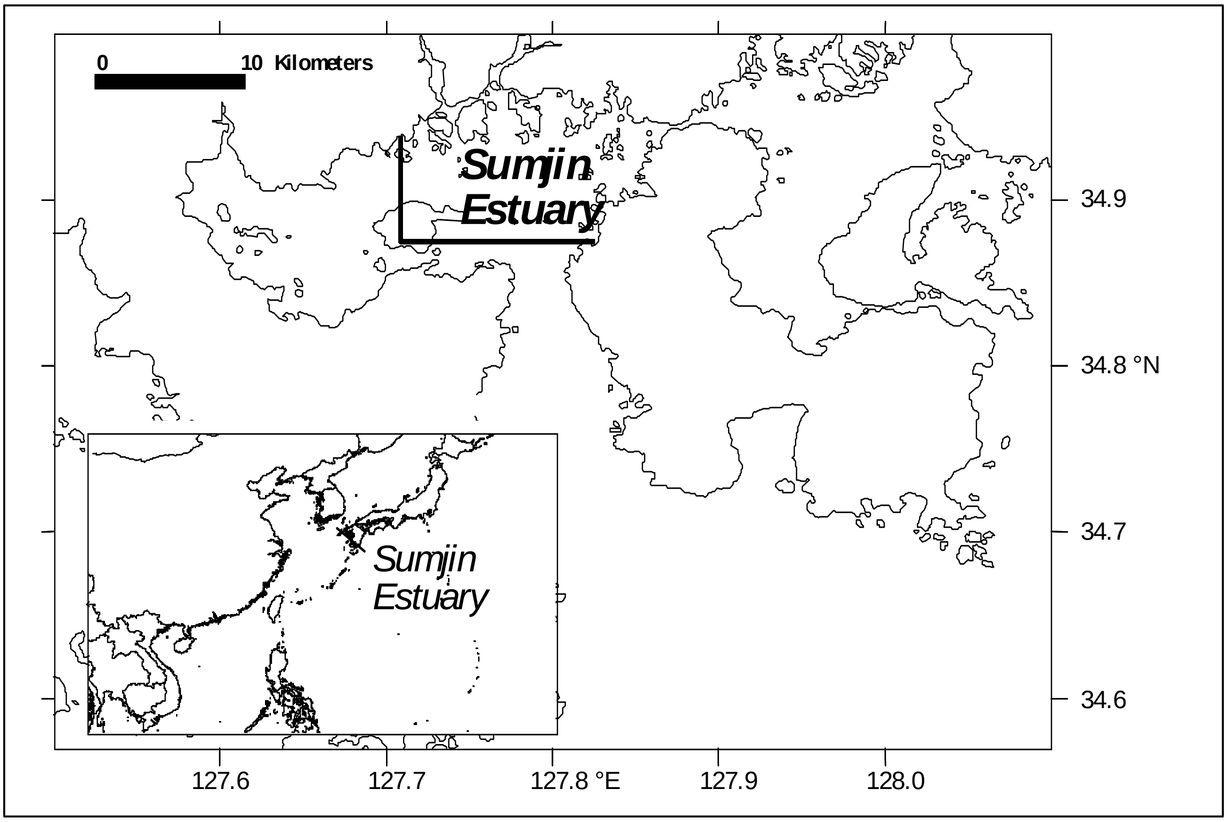


Figure 4.5. Map and location of the Sumjin River estuary.

Water and salt balance

The LOICZ Biogeochemical Modelling Guidelines (Gordon *et al*. 1996) were used to calculate the stoichiometrically linked water-salt-nutrient budgets. Table 4.4 summarizes the water and salt budgets for the estuary for the wet and dry seasons. Figure 4.6 represents the water and salt budgets for both seasons. Mean pan evaporations of 3 mm d^{-1} (V_E = -165×10^3 m^3 d^{-1}) for the wet season (July to September) and 4 mm d^{-1} (V_E = -220×10^3 m^3 d^{-1}) for the dry season (October to June) were used for the budget calculations. No pan correction factors were used. Mean precipitation rates were 15 mm d^{-1} (V_P = 825×10^3 m^3 d^{-1}) for the wet season and 4 mm d^{-1} (V_P = 220×10^3 m^3 d^{-1}) for the dry season based on 1988-1998 data.

Table 4.4. Water budget and exchange time for Sumjin River estuary system.

Processes	**Wet Season July-September (3 months)** (10^6 m^3 d^{-1})	**Dry Season October-June (9 months)** (10^6 m^3 d^{-1})	**Annual Average** (10^6 m^3 d^{-1})
V_P	0.8	0.2	0.4
V_E	-0.2	-0.2	-0.2
V_Q	1.9	1.6	1.7
V_G	0	0	0
V_O	0.2	0.2	0.2
V_R	3	2	2
V_X	8	5	6
τ (day)	109	171	156

V_{syst} = $1,100\text{x}10^6$ m^3

During the wet season, salinity values used for the budget calculation are 33.4 psu for the ocean and 23.0 psu for the estuarine system. During the dry season, these values were 34.4 psu and 23.8 psu for the ocean and estuary, respectively.

The water exchange time for the estuary was calculated to be 109 days in the wet season and 171 days in the dry season.

Budgets of nonconservative materials

DIP balance

Table 4.5 presents nutrient concentrations for both seasons. The average DIP concentration of runoff is 1.0 µM for the wet season, and 0.6 µM for the dry season. The oceanic DIP concentration is 1.5 µM for the wet season, and 1.2 µM for the dry season. Groundwater DIP concentration is negligible for both seasons. The waste load of DIP in each season was calculated from the riverine flux and from the industrial sources. The riverine flux accounted for most of the PO_4 load in this region. Figure 4.7 shows the DIP budgets for the wet and dry seasons.

DIN balance

DIN is defined as NO_3^- + NO_2^- + NH_4^+. The average DIN concentration of runoff is 82 µM for the wet season and 39 µM for the dry season. The oceanic DIN concentration is 30 µM for the wet season, and 41 µM for the dry season. Groundwater DIN concentration is assumed to be 0 µM both for the wet and dry seasons. In any case, this flux is small. The waste load of DIN in each season was calculated from the riverine flux and from the industrial sources. As with the PO_4 budget, the riverine flux accounted for most of the DIN load in this region. The balance for DIN is strongly dominated by waste discharge in all of the budget boxes. Figure 4.8 represents the DIN budgets for the wet and dry seasons.

Table 4.5. Salinity and dissolved inorganic nutrient concentrations for Sumjin River estuary system.

Variable	Wet	Dry
	Salinity (psu)	
S_{syst}	23.0	23.8
S_{ocn}	33.4	34.4
	Dissolved inorganic phosphorus (μM)	
DIP_P	0.0	0.0
DIP_Q	1.0	0.6
DIP_G	0	0.0
DIP_O	23	23
DIP_{syst}	1.2	1.2
DIP_{ocn}	1.5	1.2
	Dissolved inorganic nitrogen (μM)	
DIN_P	0	1.4
DIN_Q	82	39
DIN_G	0	0
DIN_O	1,625	1,625
DIN_{syst}	47	51
DIN_{ocn}	30	41

Table 4.6. Dissolved inorganic nutrient fluxes and derived apparent net system metabolism for Sumjin River estuary system. Budgeted area = 55 km^2.

Process	**Wet Season** (10^3 mol d^{-1})	**Dry Season** (10^3 mol d^{-1})	**Annual average** (10^3 mol d^{-1})
$V_P DIP_P$	0	0	0
$V_Q DIP_Q$	2	1	1
$V_G DIP_G$	0	0	0
$V_O DIP_O$	5	5	5
$V_R DIP_R$	4	2	3
$V_X(DIP_{ocn} - DIP_{syst})$	2	0	0
ΔDIP	-5	-4	-4
$V_P DIN_P$	0	0	0
$V_Q DIN_Q$	164	78	100
$V_G DIN_G$	0	0	0
$V_O DIN_O$	325	325	325
$V_R DIN_R$	116	92	98
$V_X(DIN_{ocn} - DIN_{syst})$	136	50	72
ΔDIN	-237	-261	-255
(*p-r*) (10^3 mol C d^{-1})	+530	+424	+451
(*nfix-denit*) (10^3 mol N d^{-1})	-157	-197	-187
(*p-r*) (mol C m^{-2} d^{-1})	+10	+8	+8.5
(*nfix-denit*) (mol N m^{-2} d^{-1})	-3	-4	-4

Stoichiometric calculations of aspects of net system metabolism
The carbon equivalent of net P flux (*p-r*) is +530×10^3 mol C d^{-1} or +10 mmol C m^{-2} d^{-1} in the wet season and +424×10^3 mol C d^{-1} or +8 mmol C m^{-2} d^{-1} in the dry season, indicating a net autotrophic system. Estimated (*nfix-denit*) was -157×10^3 mol N d^{-1} or about -3 mmol m^{-2} d^{-1} in the wet season and -197×10^3 mol N d^{-1} or about -4 mmol m^{-2} d^{-1} in the dry season, indicating a net denitrifying system.

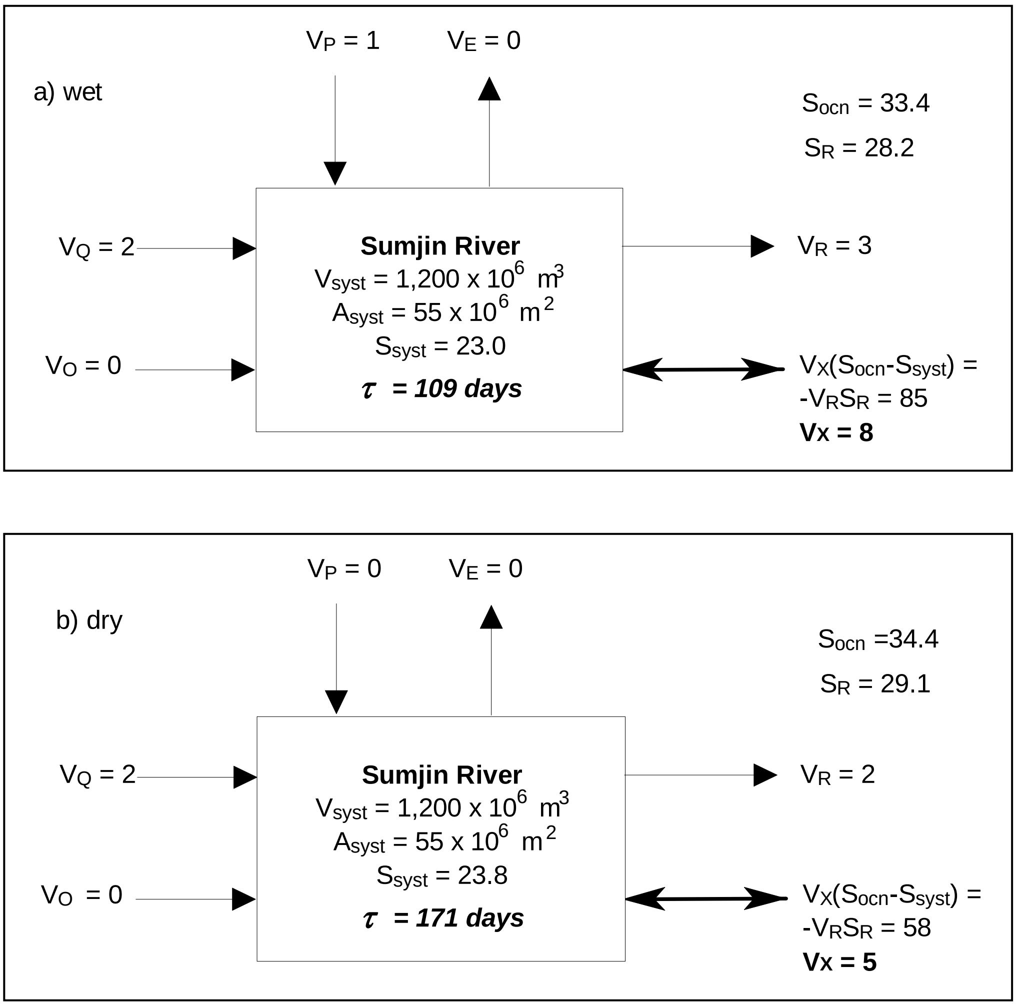


Figure 4.6. Salt and water budgets for the Sumjin River estuary in the wet (a) and dry (b) seasons. Water flux in 10^6 m^3 d^{-1} and salt flux in 10^6 psu-m^3 d^{-1}.

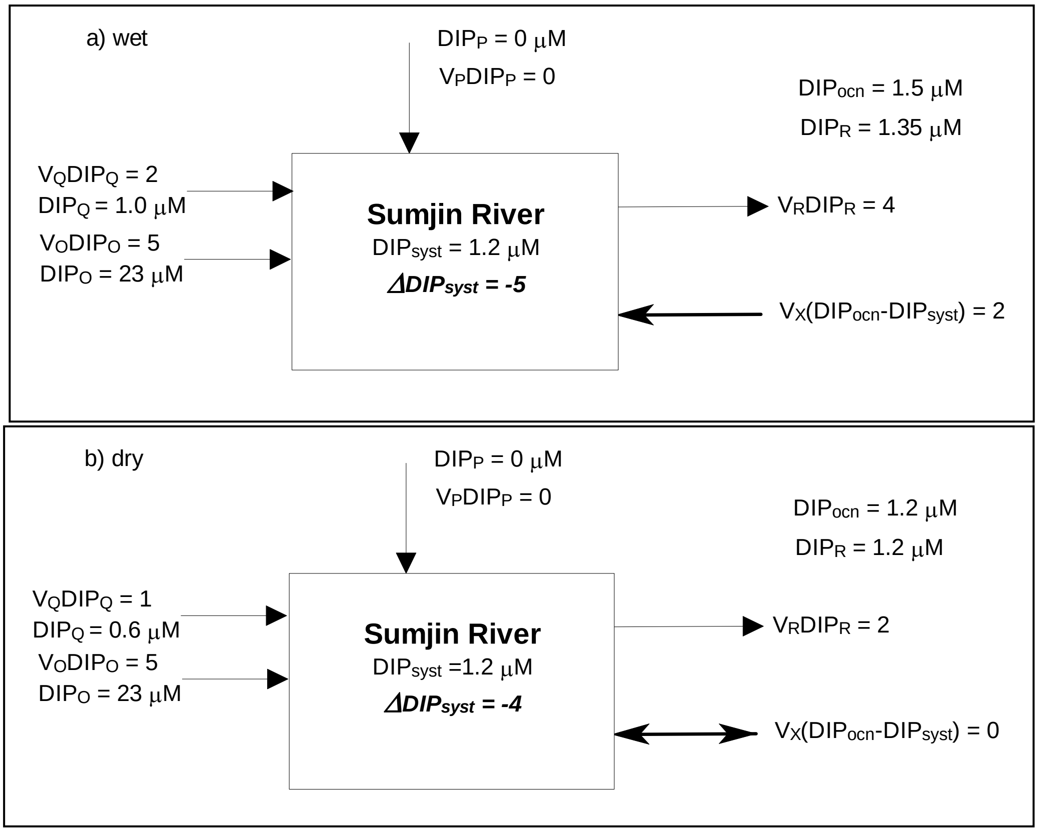


Figure 4.7. Dissolved inorganic phosphorus budget for the Sumjin River estuary in the wet (a) and dry (b) seasons. Flux in 10^3 mol d^{-1}.

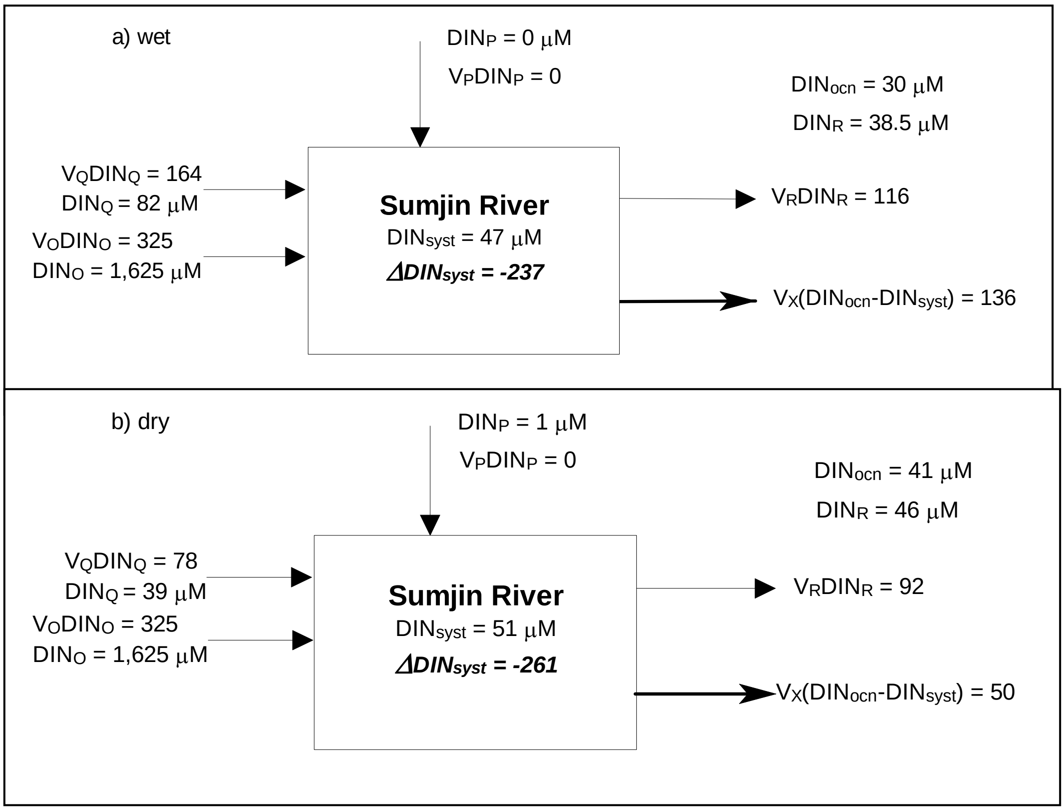


Figure 4.8. Dissolved inorganic nitrogen budgets for the Sumjin River estuary in the wet (a) and dry (b) seasons. Flux in 10^3 mol d^{-1}.

5. BUDGET FOR A REGIONAL SEA

5.1 The Yellow Sea System

C.S. Chung, G.H. Hong, S.H. Kim, J.K. Park, I.K. Bang, Y.I. Kim, D.S. Moon, J. Zhang and D.B. Yang

Study area description

The Yellow Sea is an epicontinental-shelf surrounded by the contiguous landmasses of Korea and China. The Yellow Sea, including the Bohai Sea, has a total area of 517,000 km^2 with an average water depth of 44 m with asymmetrical V-shaped bottom. The western side is much shallower than the eastern side. The area budgeted in this analysis (Figure 5.1) has an area of approximately 420,000 km^2 and a volume of approximately 17×10^{12} m^3.

A deep trough, the old Yellow River Channel, made during the last glacial period, runs longitudinally east of 125ºE. Fresh water and aeolian material therefore play a major role in Yellow Sea biogeochemistry. The Yellow Sea is under the influence of the north-east Asian monsoon. The regional monsoon may be characterized as a strong north-westerly wind during the period from autumn to early spring, with a brief wet summer (Jangma) and a relatively dry season for the rest of the year. Precipitation over the Yellow Sea is estimated as 460×10^9 m^3 yr^{-1} (Lee and Kim 1989), which is about 4 times as large as the total river discharge ca. 120×10^9 m^3 yr^{-1} (Chough and Kim 1981; Milliman and Meade 1983; Wang and Aubrey 1987). The precipitation contains a large amount of nutrients (Zhang and Liu 1994). The winter monsoon winds transports aeolian material from the contiguous Chinese continent. The summer monsoon rain transports riverine material from the contiguous land masses. The Yellow dust storm in spring is the most salient geological feature in north-east Asia (Zhang *et al*. 1993).

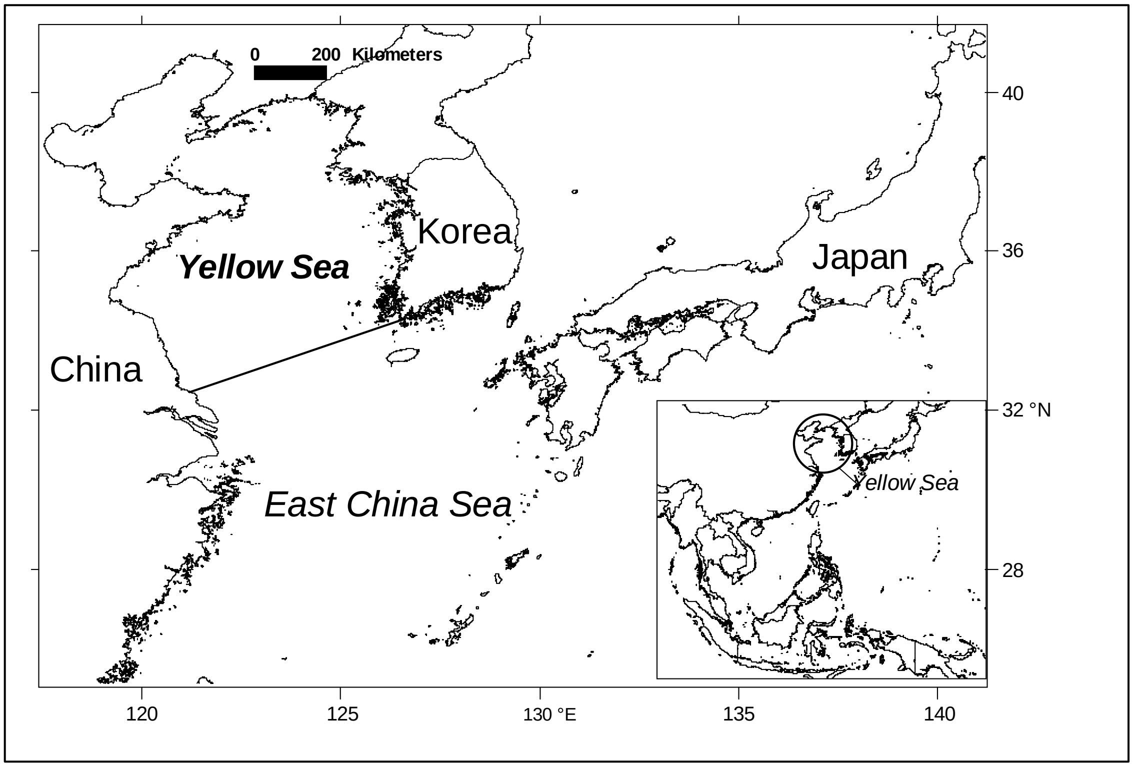


Figure 5.1. Map and location of the Yellow Sea.

Annual primary production may reach as high as 165 g C m^{-2} yr^{-1} or about 14 mol C m^{-2} yr^{-1} (Hong *et al*. 1995). However, in the central waters of the Yellow Sea, except in the coastal zone, primary productivity is limited by the lack of nutrients (Chung *et al*. 1991; Hong *et al*. 1993).

Three major potential sources of nutrient input into the Yellow Sea are river runoff (Zhang *et al*. 1995; Zhang 1996), the atmosphere (Zhang and Liu 1994; Chung *et al*. 1998) and intrusion of oceanic water from the Kuroshio Water. Recent studies have suggested that in certain parts of the Yellow Sea, biological productivity can be enhanced by the direct input of inorganic nutrients from atmospheric deposition (Zhang and Liu 1994). Among these nutrients, nitrogen and phosphorus are two of the most critical nutrients for biological growth. Therefore, information about these sources is essential in understanding and predicting the behavior of nutrients in the Yellow Sea.

Water and salt budgets were estimated, and nitrogen and phosphorus budgets were constructed, with relevant values obtained for river, atmosphere and the ocean boundary, using a simple one-box model described by Gordon *et al.* (1996).

Water and salt balance

It is difficult to set the geographical boundary of the Yellow Sea due to the continuous nature of the Yellow Sea and the East China Sea. Here, we have considered the open boundary as the straight line connecting the south-western tip of Korea to the Changjiang River mouth for convenience (Figure 5.1). Figure 5.2 presents the water and salt budgets for the Yellow Sea.

The water balance in the Yellow Sea is given by the conservation of water and salt (assuming steady state):

$$dV_{syst}/dt = 0 = V_Q + V_P + V_E + V_R$$

Groundwater is ignored, as discussed below. Salinity of river water, precipitation, and evaporation can be ignored. Therefore:

$$VdS_{syst}/dt = 0 = V_R S_R + V_x (S_{ocn} - S_{syst})$$

The freshwater flow (V_Q) is about 120×10^9 m^3 yr^{-1}. This discharge excludes the Changjiang River discharge. During the summer, Changjiang River water intrudes into the south Yellow Sea and may account for as much as a third of the total river discharge. However, this discharge is very difficult to quantify, so it is considered to be quantitatively unimportant to the overall budgets.

The precipitation (V_P) and the evaporation (V_E) are about 420×10^9 m^3 yr^{-1} and 390×10^9 m^3 yr^{-1}, respectively (Yang 1998). From the water balance, net freshwater input is approximately 150×10^9 m^3 yr^{-1} (V_R). The freshwater discharge through groundwater (V_G) was not considered because the data are not available. While there is evidence (discussed below) that this discharge may be important with respect to nutrient delivery to the coastal zone, it seems unlikely to be important at the scale of the entire system.

The average water exchange time in the Yellow Sea is estimated to be about seven years. This exchange time is similar to that derived from $^{228}Ra/^{226}Ra$ distributions (Nozaki *et al*. 1991).

<u>*Budgets of nonconservative materials*</u>

DIP balance

Figure 5.3 shows the DIP budget for the Yellow Sea. The riverine and atmospheric inputs by precipitation of dissolved inorganic phosphate (DIP) are 228×10^6 mol yr^{-1} and 168×10^6 mol yr^{-1}, respectively. Note the great importance of atmospheric inputs in this system. The average concentration of DIP is 0.4 μM in the Yellow Sea and 0.2 μM in the East China Sea (Yang 1998).

DIP mixing flux across the ocean boundary between the Yellow Sea and the East China Sea, estimated using the previous salt balance model, is an export of about 432×10^6 mol yr^{-1}, suggesting that DIP is supplied from the Yellow Sea to the East China Sea. The net internal source *(ΔDIP)* in the Yellow Sea is estimated to be about $+81\times10^6$ mol yr^{-1}.

DIN balance

The DIN budget is shown in Figure 5.4. Here, nitrate, nitrite and ammonium are lumped into DIN. Nitrogen removal (internal sink), *ΔDIN*, is estimated to be about $-43{,}000\times10^6$ mol yr^{-1}. The point to note here is that, despite the very large inputs of DIN via rivers and the atmosphere, virtually no DIN is transported from this system.

In the two steady-state DIP and DIN budgets described above, freshwater discharge through the submarine groundwater (V_G) was not considered because we do not have a quantitative data set. However, it is known that groundwater may enter coastal surface waters as dispersive seepage along shorelines. For example, in Great South Bay, New York, 10-20% of the freshwater entering the bay was from groundwater, and submarine groundwater discharge attributed up to 50% of the nitrate in the bay (Capone and Bautista 1985). Dry deposition of N and P were not considered here either, due to lack of data, although they are probably not negligible. Therefore, assessment of freshwater discharge through the submarine groundwater and dry deposition in the Yellow Sea is necessary. It seems unlikely that groundwater discharge is important at the scale of the entire system, but it may be important in inshore waters.

Stoichimetric calculations of aspects of net system metabolism

The ΔDIP of $+81\times10^{6}$ mol yr^{-1} for the Yellow Sea suggests that the system is apparently net heterotrophic; (p-r) is -9×10^{9} mol C yr^{-1} or about -21 mmol C m^{-2} yr^{-1}. This rate of net heterotrophy represents well less than 1% of the estimated primary production rate of about 14 mol C m^{-2} yr^{-1}.

System nitrogen metabolism includes both denitrification and nitrogen fixation. As DIP has no volatile phase, we can estimate the net internal sink of DIN from the net internal sink of DIP using a Redfield ratio (N:P = 16:1). The estimated net internal source of DIN (ΔDIP x 16) would be about $+1{,}300\times10^{6}$ mol yr^{-1}. Nitrogen fixation minus denitrification ($nfix$-$denit$), the difference between the internal sink and the net internal source of DIN amounts to about -42×10^{9} mol yr^{-1} or about -100 mmol N m^{-2} yr^{-1}. This is well within the range of typical coastal ocean net denitrification rates; the actual rate would be higher if dry deposition of N and groundwater were included in the budget.

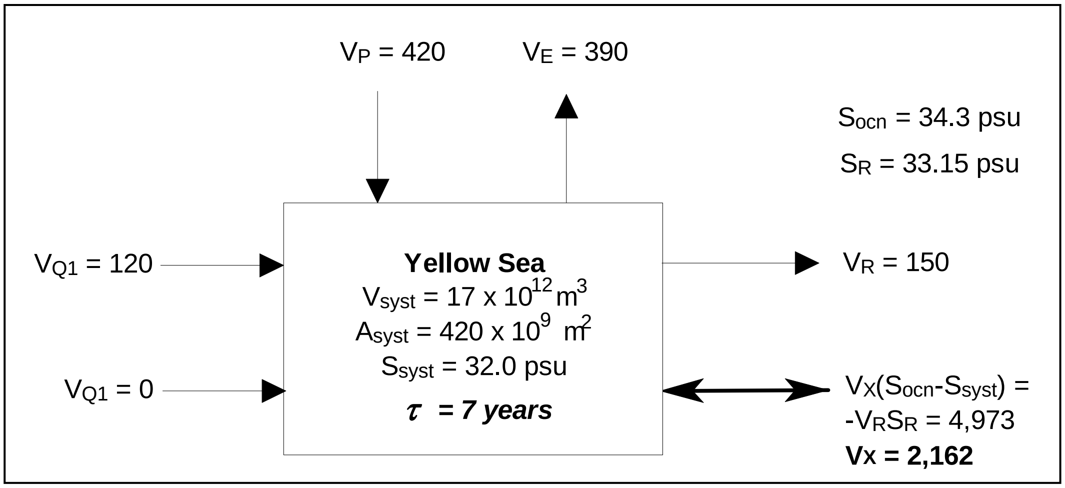


Figure 5.2. Water and salt budgets for the Yellow Sea. Water flux in 10^9 m^3 yr^{-1} and salt flux in 10^9 psu-m^3 yr^{-1} .

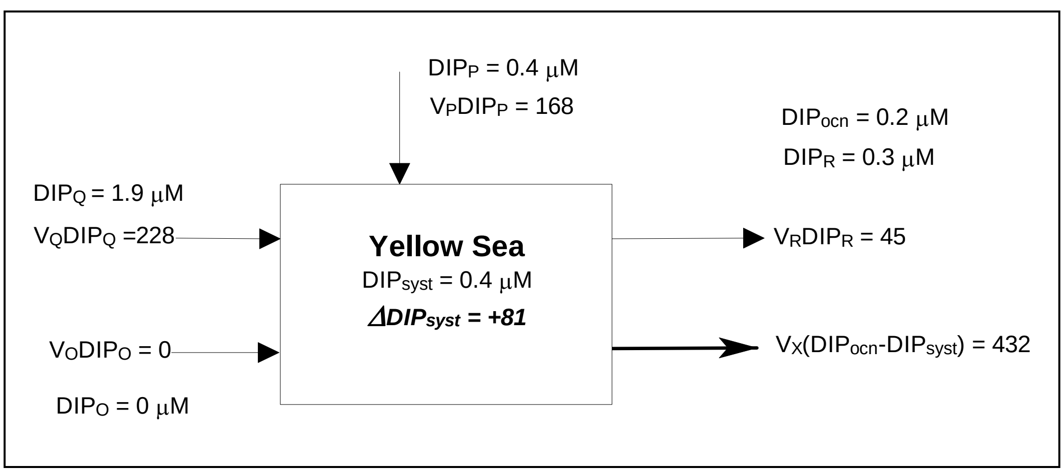


Figure 5.3. Steady-state DIP budget for the Yellow Sea. Flux in 10^6 mol yr^{-1}.

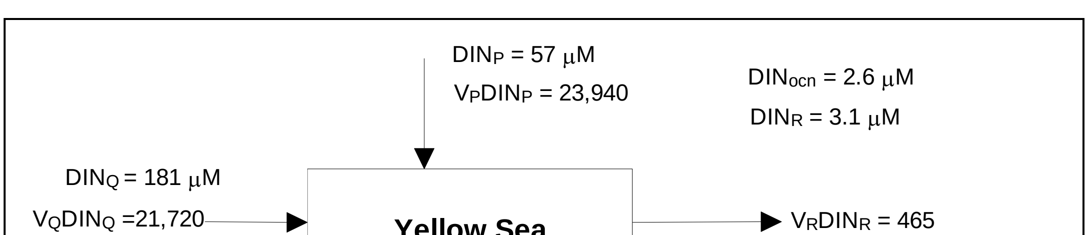


Figure 5.4. Steady-state DIN budget for the Yellow Sea. Flux in 10^6 mol yr^{-1}.

6. BUDGETS FOR ESTUARIES IN CHINA

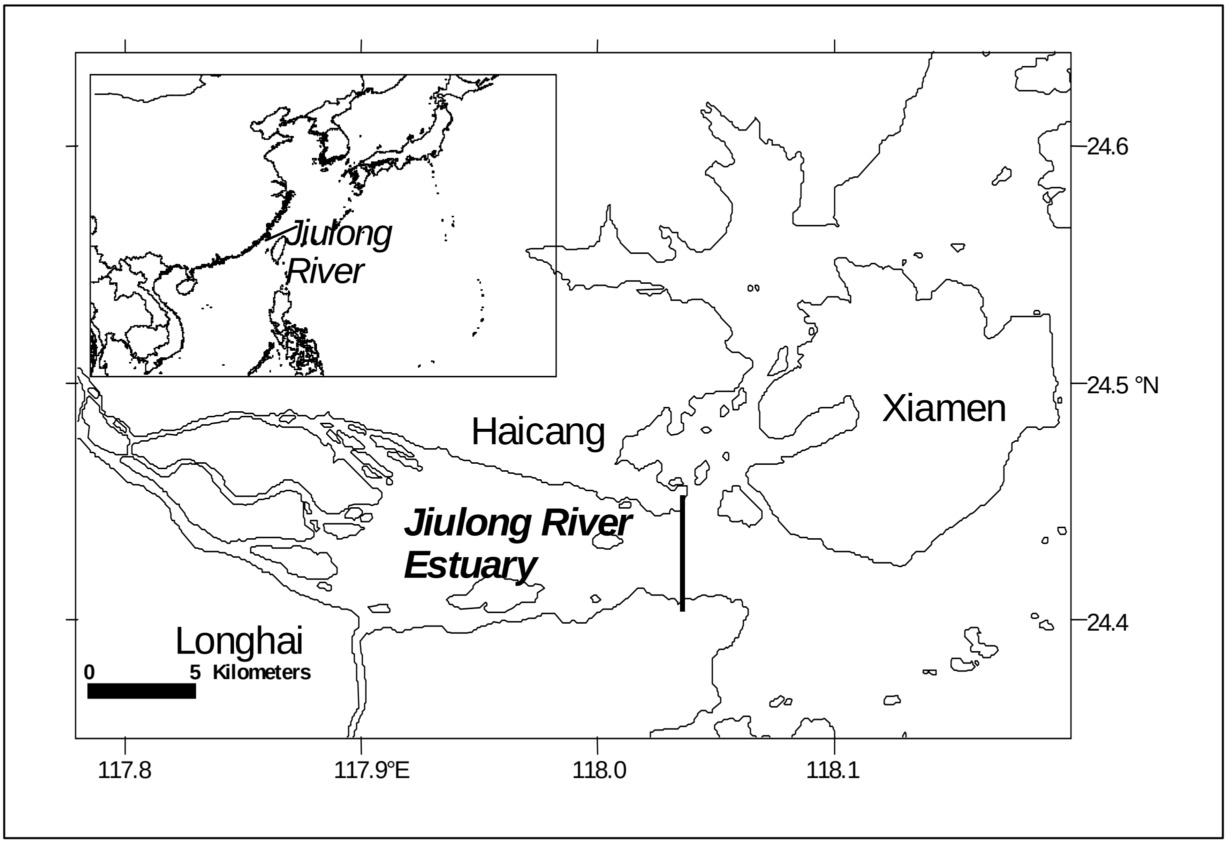
6.1 Jiulong River Estuary

Huasheng Hong and Wenzhi Cao

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

The Jiulong River (24.45°N, 118.00°E) is the second largest river in Fujian Province, China. The river has a catchment area of 14,700 km^2, and an annual average river flow discharge of $14{,}800 \times 10^6$ m^3, which flows into the coastal region of Xiamen (Figure 6.1). Physiographically, the Jiulong River estuary is a relatively enclosed system, and hence is ideal for LOICZ budgetary calculations according to the LOICZ Biogeochemical Modelling Guidelines (Gordon *et al*. 1996).

The Jiulong River inlet and estuarine system has an area of about 85 km^2, which contains a water volume of 550×10^6 m^3 estimated by bathymetry (Executive Office of the Control and Management for Marine Pollution in Xiamen Demonstrative Region 1998). Tide is a major factor affecting mixing of freshwater and seawater, along with wind and advective exchange. Phytoplankton are apparently the major primary producers in this system, dominated by *Skeletonema costatum* and *Melosira sulcata*.



The Jiulong River inlet and estuarine system is a typical subtropical system with temperate climate and high rainfall. The water temperature and pH fluctuate from 13°C to 32°C and from 7.8 to 8.5, respectively. The dissolved oxygen in the water varies from 5.6 mg l^{-1} to 10.0 mg l^{-1}, seasonally. Biological resources are rich and primary production is relatively high (Yang *et al.* 1996). The average rate for primary production is approximately 13 mol C m^{-2} yr^{-1} (Chen *et al*. 1994).

There are two municipalities and six counties along this river. The economic activities within the Jiulong River watershed contributed industrial wastewater of 1.4 billion tonnes in 1985 (Chen *et al*. 1993). The Jiulong River watershed is the most intensively agricultural region in Fujian Province. More N and P fertilizers and other agricultural chemicals are used here than in other parts of Fujian Province. Paddy field and subtropical orchards are the predominant agricultural land uses in the watershed. More than 50% of the watershed is covered by mountains. If the non-point source wastes from agricultural activities are taken into account, nutrient fluxes are significantly larger than previous estimates based on the industrial statistics. The high nutrient loading is directly responsible for degradation of water quality; some regions of the inlet and estuarine system have been affected by eutrophication and excessive growth of benthic algae since about 1985 (Chen *et al*. 1993; Hong and Shang 1998).

Water and salt balance

Results of water and salt budgets are shown in Figure 6.2. The river discharge V_Q (15×10^9 m^3 yr^{-1}) is based on the average value from long-term measurements (The Survey Office of Coastal Area and Beach Land Resources 1990). Evaporation is 1,360 mm yr^{-1} (0.1×10^9 m^3 yr^{-1} over the estuary area of 85 km^2) calculated using the Penman Equation, about 13% greater than precipitation of 1,200 mm yr^{-1}; these terms are insignificant in the water budget. No research was done on supply of groundwater to the Jiulong River inlet and estuarine system, so it is assumed to be zero ($V_G = 0$) in the water budget. "Other" water input is assumed to be zero as well ($V_O = 0$). The residual water flux to the adjacent ocean V_R is -15×10^9 m^3 yr^{-1}.

For the Jiulong River estuary system, it can be assumed that the salinity of river flow, groundwater, precipitation and evaporation (S_Q, S_G, S_P and S_E) is 0. The salt balance equation is thus simplified for determining V_X. The average salinity in this region and the adjacent ocean is based on a survey of coastal resources in Fujian Province (The Survey Office of Coastal Area and Beach Land Resources 1990). Here $(S_{syst}+S_{ocn})/2$, was assigned as S_R, which is indicated by Gordon *et al*. (1996). Mixing salt flux from the adjacent sea $V_X(S_{ocn}-S_{syst})$ has to be balanced by the residual salt flux V_RS_R. V_X is estimated to be $85\text{x}10^9$ m^3 yr^{-1}. Water exchange time (ι) is estimated to be 0.0055 yr, or approximately 2 days.

Budgets of nonconservative materials

DIP balance

The DIP balance results are shown in Figure 6.3. Compared with other inputs to the Jiulong River system, the wet DIP deposit from atmosphere is negligible (Hong and Shang 1998). Riverine input of DIP is about 3×10^6 mol yr^{-1}. Inward mixing of DIP of 17×10^6 mol yr^{-1} is significantly larger than either the DIP inflow from the river or residual outflow. The net internal sink of DIP totals -14×10^6 mol yr^{-1}. It is impressive that ΔDIP is largely determined by the mixing of DIP from the adjacent "sea" onto the system, not by river transport. The box representing the "adjacent sea" adjoins Xiamen municipality and the Xiamen Harbor area and receives wastewater from human activities. This contributes to the high concentration of phosphorus. Estimated DIP input rate from the adjacent sea was 1.5 g sec^{-1} (or about 1.5×10^6 mol yr^{-1}) according to Hong *et al*. (1998). Chen *et al*. (1994) indicated that terrigenous DIP from the Jiulong River is not the major source of DIP for primary production in this system.

As a further interesting point, the Jiulong River watershed is one of the most intensively used regions in south-eastern China. Flux of DIP from the catchment represents only about 1% of the phosphorus fertilizers used if it is assumed that 10% of the area is agricultural land. This indicates the significant potential contribution of agricultural fertilizers to the estuary system. In terms of soil erosion, if the figure of 5,000 t km^{-2} yr^{-1} for 5% of the whole watershed was applied to calculate nutrient fluxes (McGlone *et al*. 2000), the contribution of DIP to the system from soil erosion approaches 21%. Intuitively, both the adjacent sea (wastewater) and the agricultural activities are significant sources of DIP in the estuarine system.

DIN balance

The DIN balance results are shown in Figure 6.4. It is assumed that DIN deposition from atmosphere is negligible. DIN input from the river is 745×10^{6} mol yr^{-1}. This input is approximately balanced by DIN export from residual flow and mixing. The internal sink of DIN is -79×10^{6} mol yr^{-1}, or about 10% of the river input. Fluxes of DIN from the catchment represent roughly 25% of the nitrogen fertilizers used, with the same assumption used for DIP, that 10% of the area is agricultural land. Calculations based on soil erosion imply that the contribution to the system from erosion may approach 55%. The budget indicates that agricultural activities are the major source of DIN to this system, in contrast to the situation for phosphorus.

Stoichiometric calculations of aspects of net system metabolism

Phytoplankton are the dominant primary producers in this estuarine ecosystem, so it is assumed that the Redfield ratio of C:N:P of 106:16:1 can be used here to roughly estimate the relationship between nitrogen fixation processes and denitrification processes. The net ecosystem metabolism (*NEM* = primary production-respiration = [*p-r*]) is calculated as the negative of ΔDIP multiplied by the C:P ratio of the reacting organic matter. NEM in this system is calculated to be about $+1.5\times10^{9}$ mol C yr^{-1} or +18 mol C m^{-2} yr^{-1}. This indicates that the Jiulong River estuary system is apparently a net autotrophic system. This high rate may be partially attributed to uptake of DIP by sorption onto sediment particles.

The net nitrogen fixation minus denitrification (*nfix-denit*) is $+145\times10^{6}$ mol N yr^{-1} or +1.7 mol N m^{-2} yr^{-1}. This indicates that the Jiulong River estuary system is a net nitrogen-fixing system.

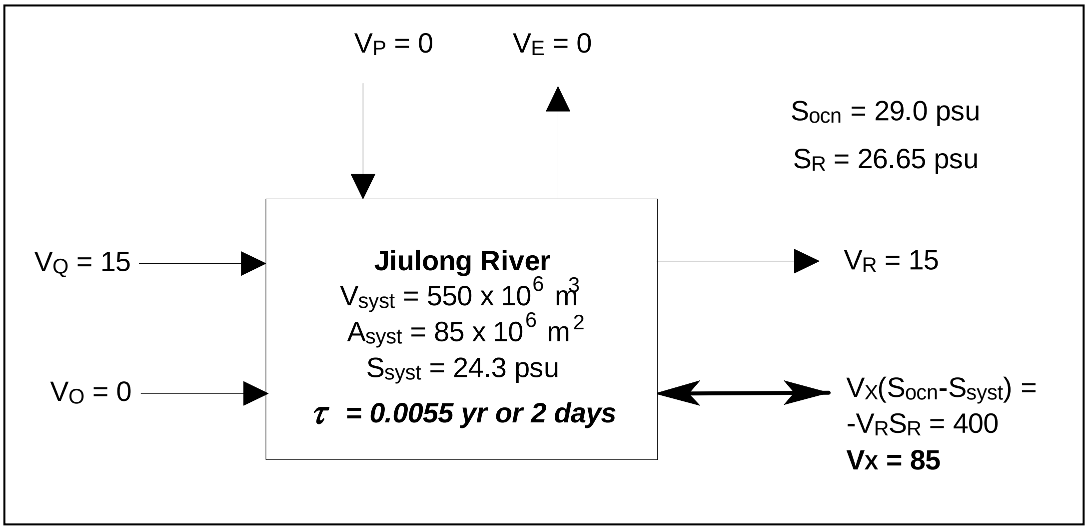


Figure 6.2. Water and salt budgets for the Jiulong River estuary system. Water flux in 10^9 m^3 yr^{-1} and salt flux 10^9 psu-m^3 yr^{-1}.

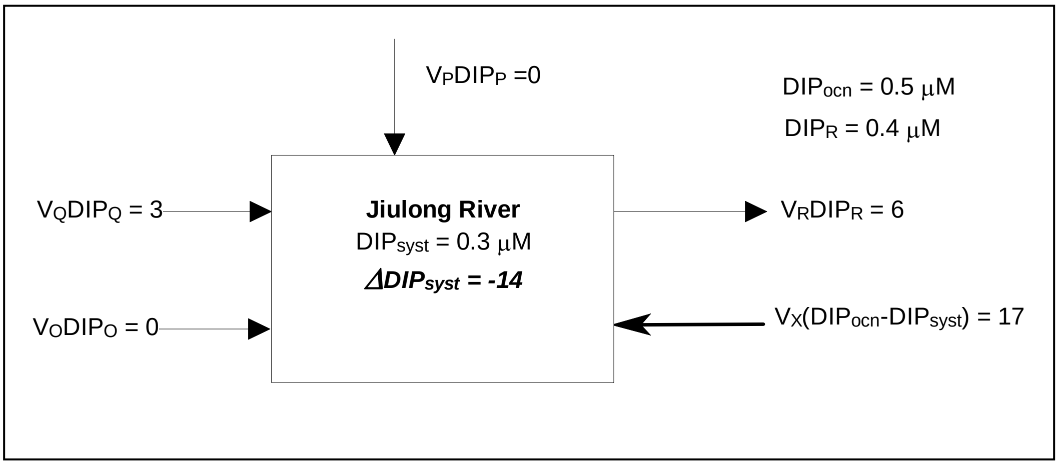


Figure 6.3. DIP budget for the Jiulong River estuary system. Flux in 10^6 mol yr^{-1}.

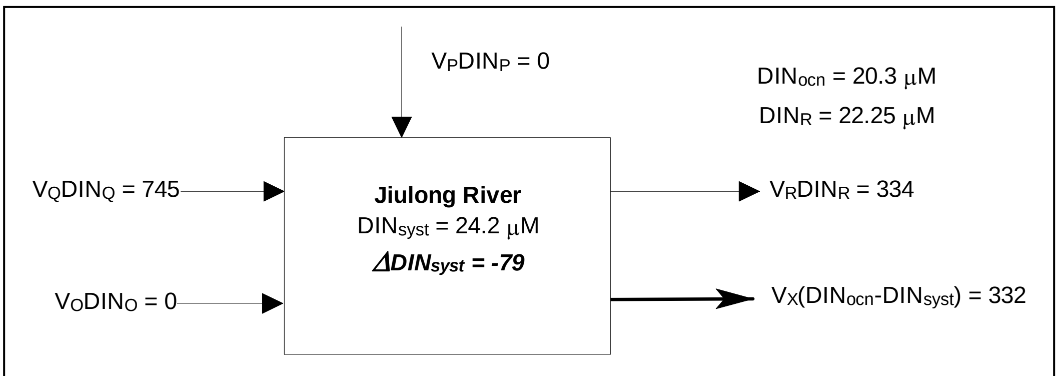


Figure 6.4. DIN budget for the Jiulong River estuary system. Flux in 10^6 mol yr^{-1}.

6.2 Aimen, Modaomen and Pearl River estuaries of the Pearl River Delta

K.C. Cheung, X.P. Nie, CY. Lan and M.H. Wong

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

The Pearl River, the largest river system in South China and the fourth largest in the country (Figure 6.5), is 2,200 km long with a catchment area of 450,000 km^2. The system consists of a dense waterway network, and has three tributaries, namely West River, North River and East River. These merge into the Pearl River delta (22.6°N, 113.6°E), which occupies an area of 4,000 km^2. The mean annual discharge of the Pearl River is 330×10^9 m^3, and the sediment load is 70×10^9 kg yr^{-1}.

The area has a sub-tropical climate, with a long summer and a short winter, average annual temperature of 21-22°C, annual rainfall of 1,600-2,000 mm, with 80% of the river's annual discharge in the wet season from April to September. Winds are usually southerly in summer; being opposite to the direction of stream flow, the wind stirs up the sand and silt of the shallow sea and brings some of the sediments back into the estuary. In winter, winds are northerly, blowing parallel to the direction of stream flow, and helping to carry away the sediments (Kot and Hu 1995).

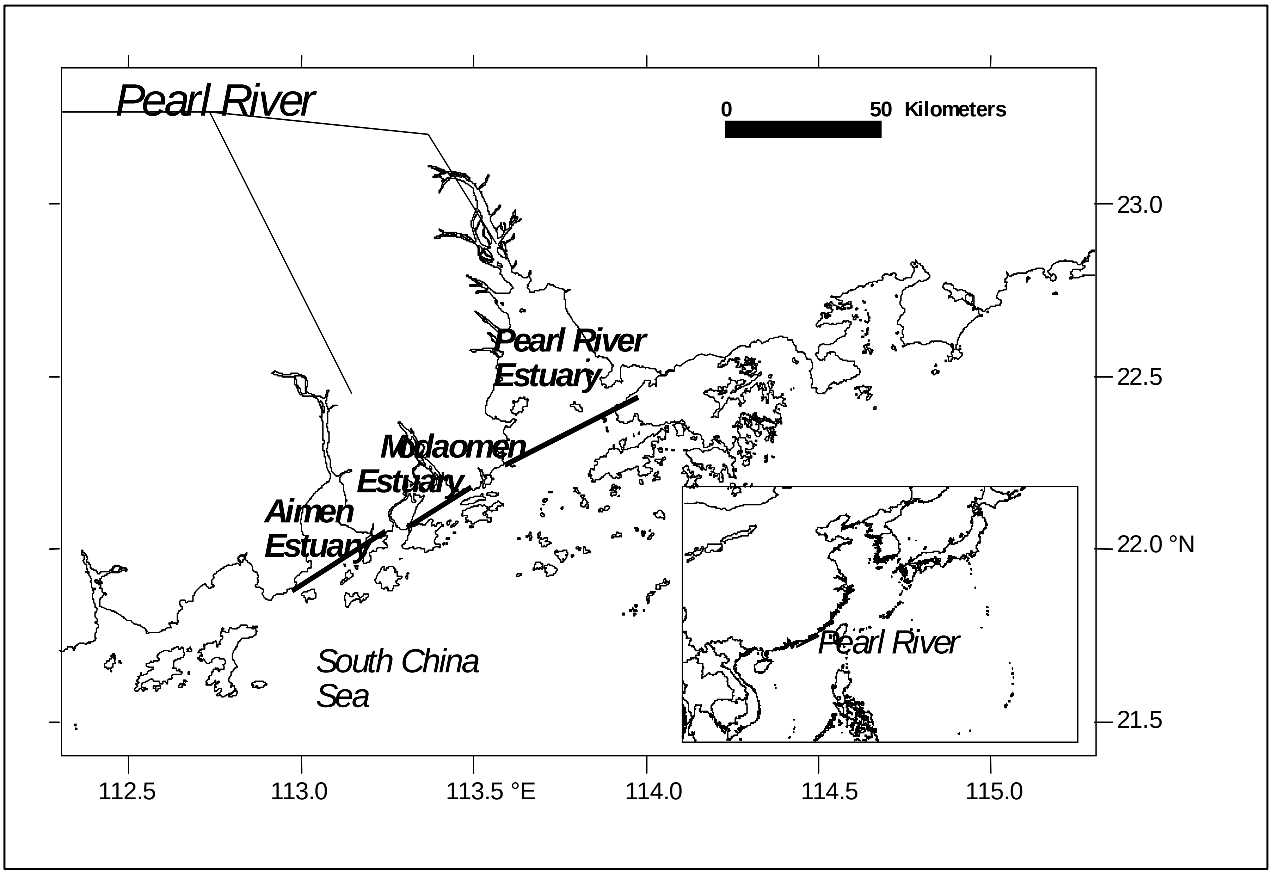


Figure 6.5. Studied estuaries in the Pearl River delta. Bars represent boundaries of the budgets**.**

A substantial area of cultivated land has given way to construction of houses, factories, highways etc. due to the rapid economic development of the area. A large amount of chemical fertilizer has been added to the remaining agricultural land and also to the reclaimed marginal land, to maintain agricultural production. The use of chemical fertilizers increased by 40% between 1986 and 1989 (Neller and Lam 1994). In addition, the use of organic wastes such as manure compost has declined, leading to accumulation of organic matter. Industrial establishments for production of textiles, paper, beverages and food, printing and dyeing works, tanneries, electroplating works etc. are abundant in the area (Wang and Peng 1993). The nutrient budget of the Pearl River estuarine waters depends on organic inputs from the river's upper channel and surface runoff. In addition, increased discharges of domestic sewage and industrial wastes from several cities in the watershed have caused eutrophication by increasing organic matter, N and P inputs (Wang and Tan 1989).

Almost 30 million people inhabit the the delta area including Hong Kong (6.7 million) and Macau (0.5 million) (see Table 6.1). There has been rapid socio-economic change, including population growth, industrialization and urbanization in the region during the past two decades. A large amount of domestic, industrial and agricultural sewage is discharged into the river system, and water quality has been a major concern. It has been estimated that up to 560 million tonnes of domestic wastes and 2 billion tonnes of industrial effluent are generated annually within the region (Chen 1994).

Table 6.1. Population and cultivated area associated with the major municipalities discharging into different estuaries in 1992 (Edmonds 1996; Luo and Liu 1996).

Estuary	**Outlet**	**Discharge percentage** (%)	**City**	**Total population** (10^3)	**Cultivated land** (km^2)	**Industrial effluent** (10^4 ton yr^{-1})	**Sewage** (10^4 t yr^{-1})
Aimen	Aimen Huttiamen	13	Jiangmen Zhaoqing	3,615 5,688	1,800 2,300	14,555 7,309	4,757 3,806
Modao-men	Modaomen Jitimen	34	Zhuhai	550	360	3,290	3,102
Pearl River	Humen Jiaomen Hongqili Hengmen	53	Guangzhou Foshan Zhongshan Dongguan Shenzhan Huizhou	6,122 2,912 1,193 1,361 2,609 2,393	1,520 1,020 530 560 100 1,370	38,934 12,121 7,651 6,628 2,097 2,647	63,924 12,008 4,167 3,550 7,613 7,348

The Pearl River Delta has eight openings, namely Aimen, Hutiaomen, Jitimen, Modaomen, Hengmen, Hongqimen, Jiaomen and Humen, through which the Pearl River waters discharge into the South China Sea. The former four outlets are located in the west: Aimen and Huitaomen drain to the Aimen estuary and Jitmen and Modaomen drain into the Modaomen estuary; while the other four outlets are located to the east and drain into the Pearl River estuary. Hong Kong is located at the eastern side of this estuary, and Macau on the western bank.

The Pearl River estuary is affected by various physical, chemical and biological processes, and is characterized by its complex nutrient distribution (Wang and Tan 1989). In our previous exercise, which studied the carbon, nitrogen and phosphorus fluxes of the Pearl River estuary (Wong and Cheung 2000), it was indicated that higher nutrient exports at the mouth of the Pearl River estuary were due to the high net residual flow and exchange flow.

The water quality is comparatively stable, but seasonal variations are obvious. In the waterway network, the pollution effect of nitrogen is greater than that of phosphorus. The highest contents of nitrogen and phosphorus are 300 µM and 7 µM, respectively, in certain parts of the adjacent coastal ocean. Red tides have occurred several times in the Pearl River estuary and coastal areas near Hong Kong in recent years (Ho and Hodgkiss 1991).

Wong and Cheung (2000) compared the biogeochemical performance of the Pearl River estuary and Mirs Bay. Mirs Bay is situated at the north-east corner of Hong Kong and is a low-flow system totally unrelated to the Pearl River system. Judging from the differences between the nutrient budgets of the Pearl River estuary and Mirs Bay, nutrients were probably not limiting for the growth of algae in this nutrient enriched system. The water exchange time and/or salinity of the estuary or the bay might be limiting factors. Water residence time and salinity in the estuary and bay are well-correlated with the frequency of red tide occurrence in the Hong Kong coastal area.

The major objective of the present exercise was to compare the nutrient budgets of the Pearl River, Aimen and Modaomen estuaries which finally discharge into the South China Sea. Attempts have been made to relate the nutrient budgets of the three areas to their respective population, agricultural area, and the discharge of domestic and industrial effluents.

Water and salt balance

At steady state, the following box model equation describes salt flux. This and the succeeding equations are from Gordon *et al*. (1996).

$$V_{syst}\frac{dS_{syst}}{dt} = 0 = V_Q S_Q - V_R S_R + V_x (S_{ocn} - S_{syst}) \qquad (1)$$

The boundaries used for budgeting boxes in this study are shown on Figure 6.5. Seasonal budgets for Aimen and Modaomen estuaries were made, due to the strong seasonality of river inflow into the estuaries. The areas and volumes of each box are shown in Table 6.2. The water composition data used for the budget calculations are summarized in Table 6.3. These tables also include information for the main estuary of the Pearl River, from Wong and Cheung (2000).

Table 6.2. Dimensions of budget boxes for the estuaries. Data for the Pearl River from Wong and Cheung (2000).

Estuary	Area **(10^6 m^2)**	Depth **(m)**	Volume **(10^6 m^3)**	***River inflow*** **(10^6 m^3 d^{-1})**	
				summer	*winter*
Aimen	**440**	**4**	**1,760**	**80**	**30**
Modaomen	**350**	**5**	**1,750**	**180**	**60**
Pearl River	**1,180**	**7**	**8,068**	**1,450**	**360**
TOTAL	**1,970**	**6**	**11,580**	**1,710**	**450**

The water and salt budgets are summarized in Figures 6.6 and 6.7. Groundwater and sewage were ignored in these water budgets. Net residual flows (V_R) at the Aimen Estuary mouth were about 81×10^6 $m^3 d^{-1}$ and 29×10^6 $m^3 d^{-1}$ in summer and winter, respectively. Net residual flow of Modaomen Estuary was higher than that of Aimen Estuary. The percentage of annual river discharge to the ocean was 13% and 34% at Aimen Estuary and Modaomen Estuary, respectively (Table 6.1). Data for river discharges are long-term averages (more than ten years). Other variables used in the budgets are measurements for several years. The water residence times in the summer were less than those in the winter for Aimen, Modaomen and Pearl River estuaries. Roughly 80% of the river inflow occurs in the summer season (April to September) for the Pearl River delta. The main stream of the Pearl River estuary has very rapid exchange flow (1,400 to $10,800\times10^6$ $m^3 d^{-1}$; Wong and Cheung 2000), in comparison with Aimen and Modaomen estuaries in both seasons. These rapid exchange fluxes limit the reliable calculation of nonconservative fluxes of nutrients for the main stream of the Pearl River estuary.

Table 6.3. Water composition data for estuary (Chen *et al*, 1993 ; Ho and Wang 1997). Data for the Pearl River from Wong and Cheung (2000).

	Summer			**Winter**		
Estuary	*Salinity* (psu)	*DIP* (μM)	*DIN* (μM)	*Salinity* (psu)	*DIP* (μM)	*DIN* (μM)
Aimen	0.5	0.3	20	22	1.1	10
Modaomen	0.0	0.4	36	15	0.8	107
Pearl River	6.3	0.9	15	21	2.2	24

<u>*Budgets of nonconservative materials*</u>

DIP and DIP balance

An equation analogous to Equation 1 is used to describe any dissolved material Y which has a source (+) or sink (-) in the system (denoted by *ΔY*, where Y is either DIP or DIN) (Gordon *et al.* 1996).

$$V_{syst}\frac{dY_{syst}}{dt} = 0 = V_Q Y_Q - V_R Y_R + V_x(Y_{ocn} - Y_{syst}) + \Delta Y \qquad (2)$$

Figures 6.8 to 6.11 summarize the DIP and DIN budgets for these systems. The nutrient fluxes in two locations were outward. The residual fluxes of DIP in the four cases (high and low flow seasons for both systems) were similar. In contrast, the Pearl River estuary in summer and winter had the highest DIP residual fluxes in the Pearl River delta (Wong and Cheung 2000). This was probably related to the population and wastewater discharge from major cities along the rivers. The order of residual fluxes of DIN in seven cases was Pearl River estuary in summer > Modaomen Estuary in summer > Modaomen Estuary in winter > Aimen Estuary in summer > Pearl River Estuary in winter > Aimen Estuary in winter.

In summer, the three estuaries appeared to act as sinks for DIP and DIN, with *ΔDIP* being from about

-100 to -500x10^3 mol d^{-1} and *ΔDIN* of -6,000 to -13,000x10^3 mol d^{-1} (Table 6.4). By contrast, outward transport occurred in winter via both residual flow and mixing, in excess of the estimated inflow from the river. Thus, there appeared to be internal sources of DIP and DIN contribution in winter. This source may be sediment recycling processes and some local inputs of DIP with agricultural activities omitted from the budgets.

Stoichiometric calculations of aspects of net system metabolism

Primary production in this system is assumed to be dominated by plankton, with a C:N:P ratio $(C:N:P)_{part}$ of about 106:16:1. This ratio is used to calculate net metabolism (primary production - respiration, [*p*-*r*]) from *ΔDIP* according to the relationship (Gordon *et al*. 1996):

$$(p\text{-}r) = -\Delta DIP \times (C:P)_{part} \qquad (3)$$

The rate of nitrogen fixation minus denitrification (*nfix-denit*) can be also be calculated from *ΔDIP*, *ΔDIN* and the N:P ratio of particulate material in the system (Gordon *et al*. 1996):

$$(nfix\text{-}denit) = \Delta DIN - \Delta DIP \times (N:P)_{part} \qquad (4)$$

The aspects of metabolism are estimated as shown in Tables 6.4 and 6.5. This analysis includes the information from the Pearl River estuary, as presented by Wong and Cheung (2000). There is also a comparison with Mirs Bay, an embayment with little freshwater inflow but heavy nutrient loading (see Figure 6.5). The budget for the whole estuary, dominated by the Pearl River, shows evidence of net production ([*p*-r] >0) in the summer and net consumption in the winter. In both cases, the rates are very high; the estimated annual metabolism apparently reflects high net respiration. The net metabolism may reflect net oxidation of organic matter, but the calculation may also be influenced by net release of DIP from suspended material delivered to the estuary from the river. Mirs Bay shows a much lower rate of net respiration in the absence of high suspended material. Both systems appear to show (*nfix-denit*) <0 (i.e., net denitrification). Again, the Mirs Bay rate is lower, perhaps reflecting less effect of suspended load on the budget calculations.

Table 6.4. Nonconservative fluxes and stoichiometric calculations for the estuaries of the Pearl River (including data from Wong and Cheung 2000).

	Summer				***Winter***			
	ΔDIP	***ΔDIN***	**(*p-r*)**	**(*nfix-denit*)**	***ΔDIP***	***ΔDIN***	***(p-r)***	**(*nfix-denit*)**
Estuary	(10^3 mol day^{-1})		(mmol m^{-2} day^{-1})		(10^3 mol day^{-1})		(mmol m^{-2} day^{-1})	
Aimen	-113	-5,612	+27	-9	-52	-3,448	+13	-6
Modaomen	-258	-10,822	+78	-19	-110	+3,879	+33	+16
Pearl River	-455	-13,214	+41	-5	+5,333	+16,745	-479	-58
TOTAL ESTUARY	-826	-29,648	+44	-8	+5,171	+17,176	-278	-33

Table 6.5. Comparison of annual nonconservative fluxes and stoichiometric calculations for the total Pearl River Estuary with Mirs Bay, a system receiving low freshwater load but high nutrient load (from Wong and Cheung, 2000).

	ΔDIP	***ΔDIN***	***(p-r)***	***(nfix-denit)***
	(10^6 mol yr^{-1})		(mol m^{-2} yr^{-1})	
Pearl River – total estuary	+793	-2,276	-43	-8
Mirs Bay	+0.1	-5.3	-0.08	-0.05

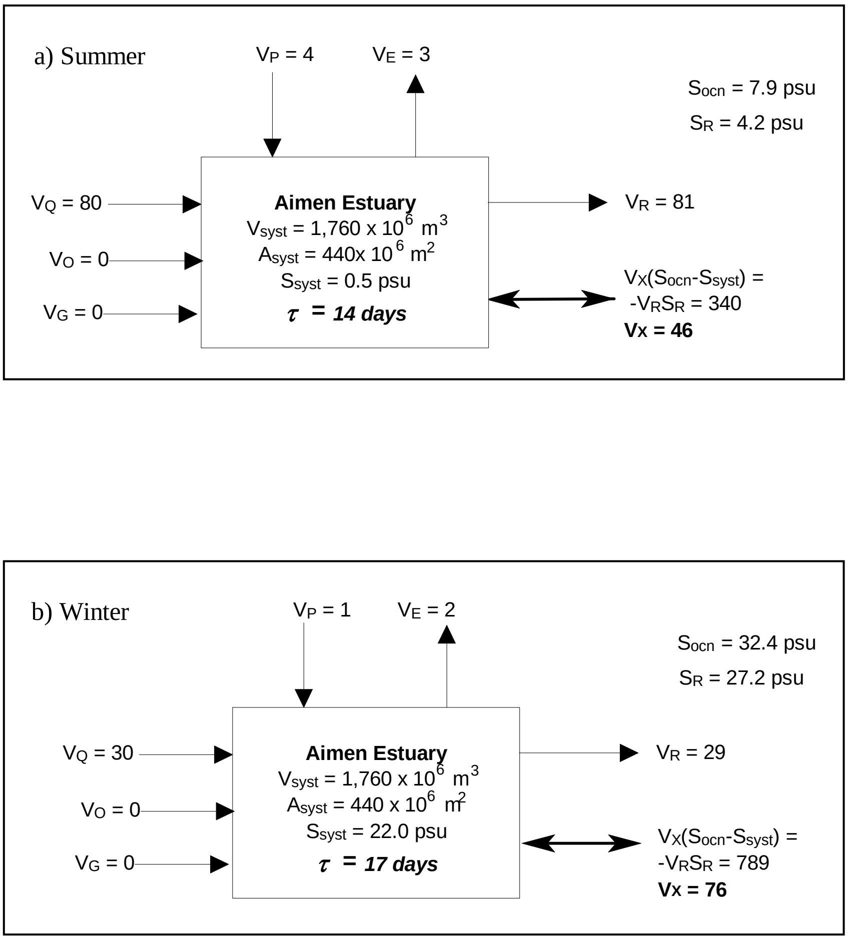


Figure 6.6. Water and salt budgets for the Aimen Estuary in summer and winter. **Water flux in 10^6 m^3 d^{-1} and salt flux in 10^6 psu-m^3 d^{-1}.**

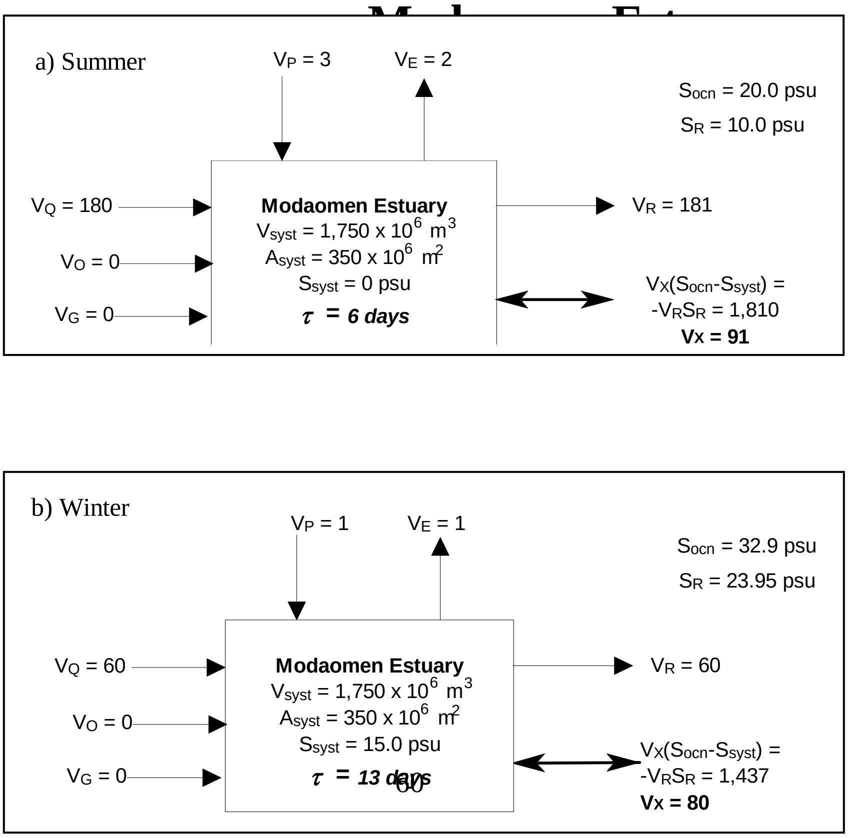


Figure 6.7. Water and salt budgets for the Modaomen Estuary in summer and winter. **Water flux in 10^6 m^3 d^{-1} and salt flux in 10^6 psu-m^3 d^{-1}.**

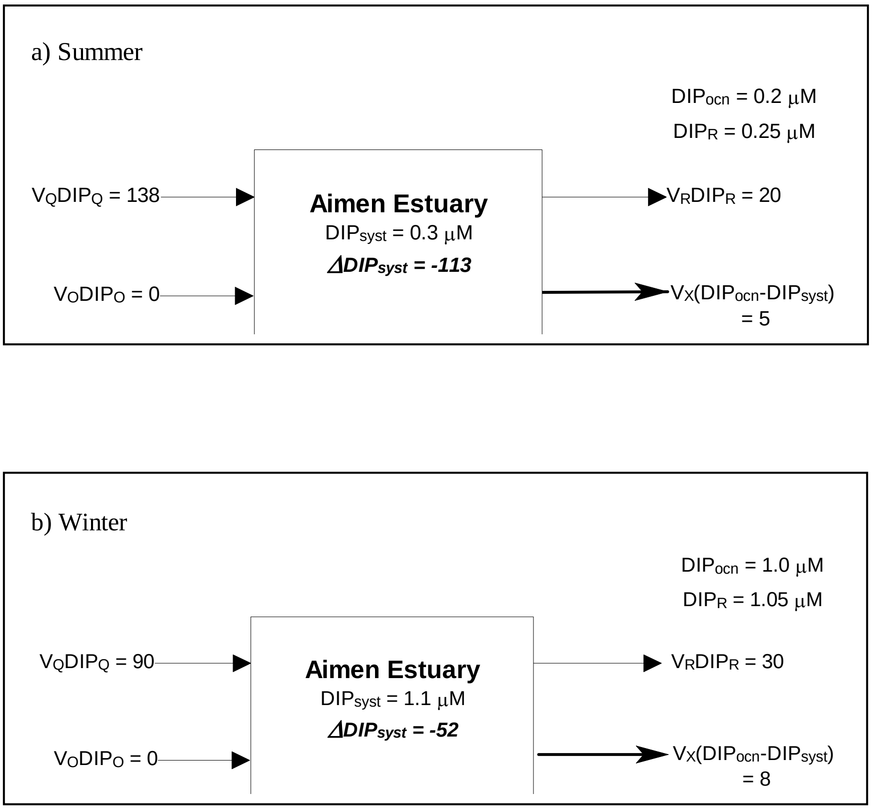


Figure 6.8. Dissolved inorganic phosphorus budget for the Aimen Estuary in summer and winter. Flux in 10^3 mol d^{-1}.

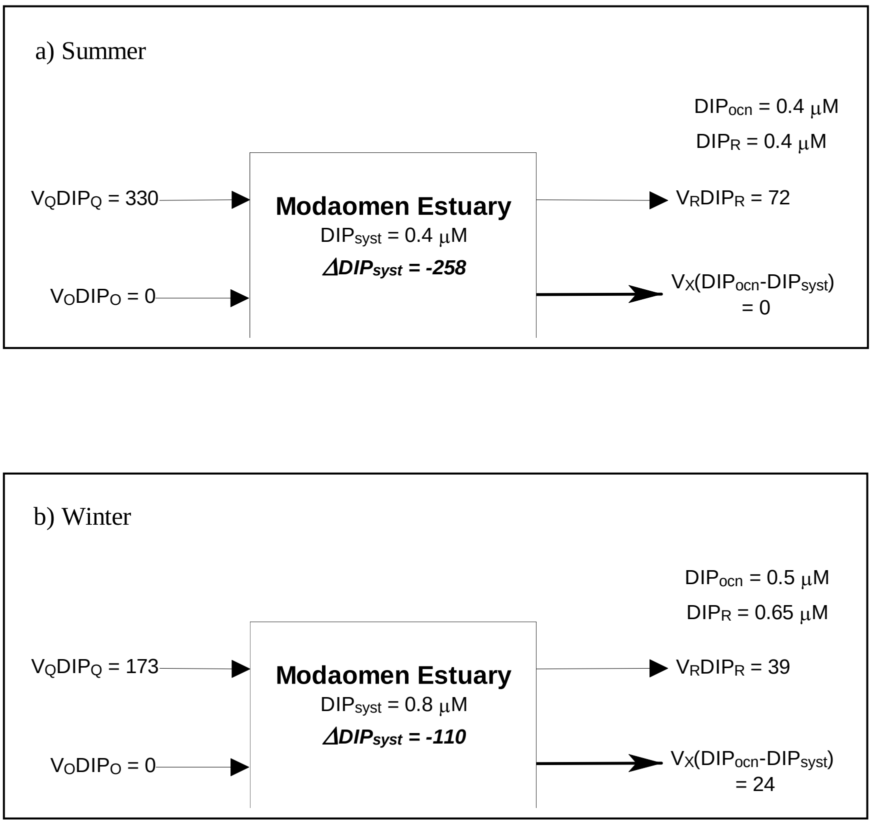


Figure 6.9. Dissolved inorganic phosphorus budget for the Modaomen Estuary in summer and winter. Flux in 10^3 mol d^{-1}.

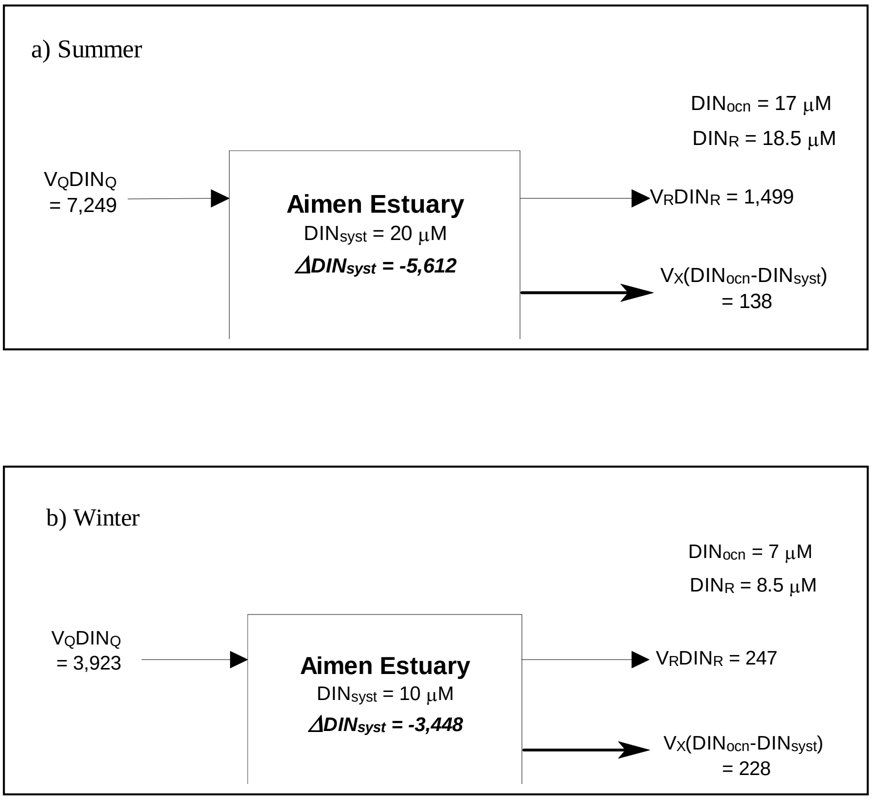


Figure 6.10. Dissolved inorganic nitrogen budget for the Aimen Estuary in summer and winter. Flux in 10^3 mol d^{-1}.

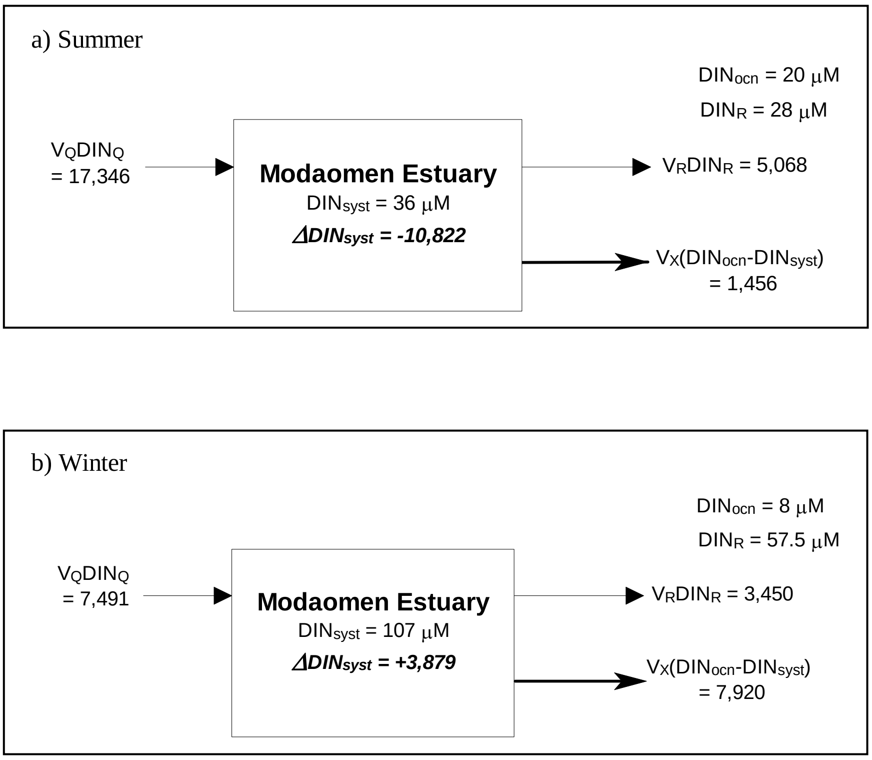


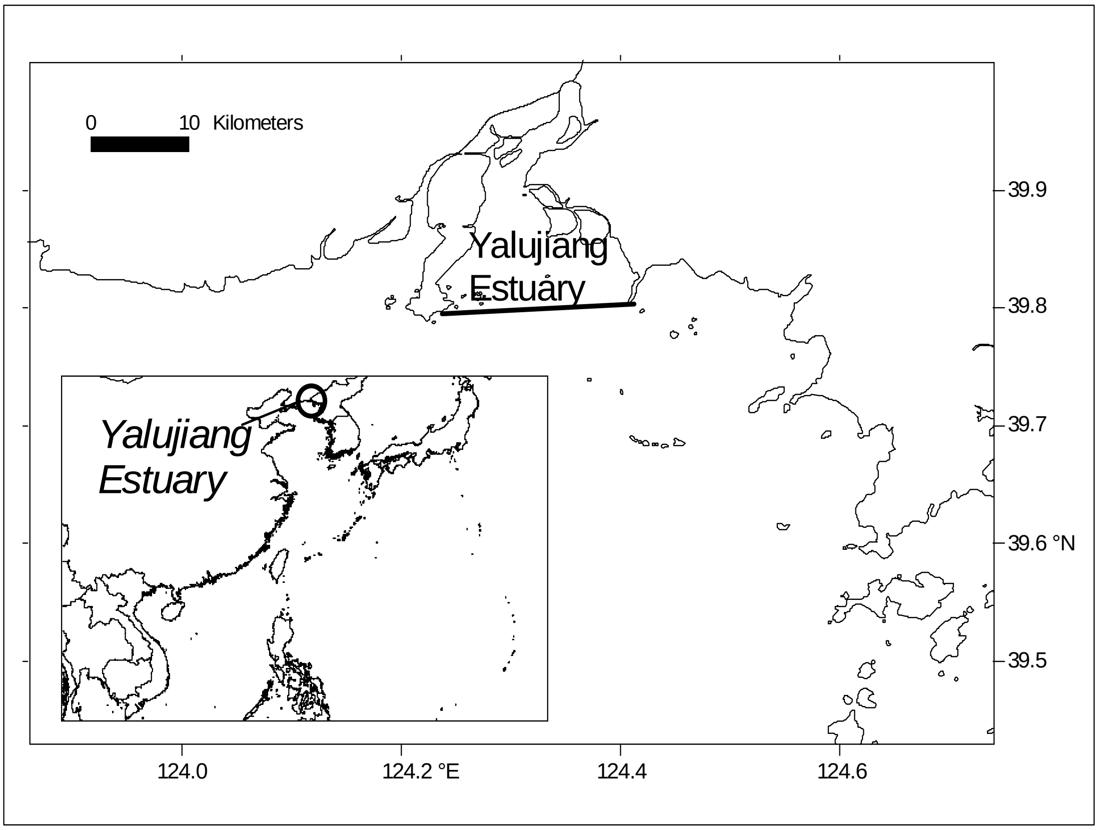
Figure 6.11. Dissolved inorganic nitrogen budget for the Modaomen Estuary in summer and winter. Flux in 10^3 mol d^{-1}.

6.3 Yalujiang River Estuary, China-North Korea

Christopher J. Crossland and Janet I. Marshall Crossland

Study site description

The Yalujiang River (catchment of 62,630 km^2) extends along the western boundary between China and North Korea, and flows from a temperate deciduous forest source (1,500 – 2,500 m elevation) through extensive agricultural areas. It discharges into the Yalujiang River estuary (Figure 6.12) on the north-east Yellow Sea coast. The Yalujiang River estuary (39.83°N, 124.33°E) comprises a main channel and a secondary channel, the latter being silted and with little water flow. The estuary is generally well-mixed as a result of a semi-diurnal tide (range up to 5m), with strong tidal currents (1.5-2.0 m sec^{-1}), which may affect the river waters up to 40 km inland. A turbidity maximum may extend up to 10 km in the upper estuary and total suspended load in the estuary can be high (>1,000 mg l^{-1}). The estuary is shallow (<5-10 m depth range). The budgeted area described here is for the main



channel and estuary (Figure 6.12) and includes 170 km^2 water surface area with an estimated average depth of 6m.

Figure 6.12. Map and location of the Yalujiang River estuary.

The Yalujiang River long-term averaged discharge rate is about 1,200 m^3 sec^{-1}or 40x10^9 m^3 yr^{-1}. The sediment load is relatively low (about 5x10^6 tonne yr^{-1}) and concentrations of suspended matter are also often low (down to 5-10 mg l^{-1}). Compared with most Chinese rivers, phosphate in the Yalujiang River

is relatively low (<0.5μM) but nitrate is very high. The river receives input from cultivated land and from urban sewage/industrial wastes, especially in its lower reaches – up to 900μM NO_3 concentration has been measure (Zhang *et al.* 1998). In the dry season, the river nutrient profile is relatively stable reflecting groundwater and tributary inputs in the upper reaches of the river and urban/industrial waste loading from the lower reaches. Heavy summer rainfall and resultant flood flow probably results in strong leaching of nutrients from agricultural lands.
The physics and chemistry of the estuarine system have been studied by oceanographic cruises particularly in the 1990's and the loads and inputs to the estuary have generally described by Zhang (1996), Zhang *et al*. (1997) and Zhang *et al.* (1998).

Water and salt balance
Water and salt budgets (Figure 6.13) are calculated for flood and dry seasons from data in Zhang *et al.* (1998). The estimated average annual discharge rate of water is $40 x 10^9 m^3 yr^{-1}$ and half the annual flow occurs during the flood season. Seasonal precipitation induces a pattern of a flood season (June to September) and a dry season (October to May). Winter ice is common from December to February. Water management (dams, reservoirs and irrigation withdrawal) in the upper and middle reaches of the river affects flow rate. System salinity values are typical of the northern Yellow Sea.

Annual precipitation (1,095 mm yr^{-1}) (1100) and evaporation (930 mm yr^{-1}) (900) data are from Chung *et al.* (this volume). The monthly pattern of rainfall shows about 70% occurring in the summer months of June-September (Ko *et al*. 1998). Precipitation contains a high amount of nutrients (Zhang and Liu 1994).

Budgets of nonconservative materials
Seasonal nutrient values for the system are derived from estuarine profiles data, and the (ocean) values are the marine (25 psu) end-members of the data sets.

Estimated DIP and DIN budgets (Figures 6.14 and 6.15) show a net efflux of P and N from the system, indicating that the estuary is a source of nutrient to the coastal sea, particularly during the flood season. DIN loads into the system are particularly high. The strong tidal forcing of the system is apparent.

The positive value for ΔDIP in the flood season is about seven times that of the dry season indicating that the estuary is a source of phosphate.
Flood season: ΔDIP for the system: $+76 x 10^3$ mol d^{-1} (or +0.4 mmol m^{-2} d^{-1}).
Dry season: ΔDIP for the system: $+13 x 10^3$ mol d^{-1} (or +0.1 $mmol^{-2}$ d^{-1}).

The ΔDIN values demonstrate that the system contributes N as an annual net sink.
Flood season: ΔDIN for the system: $-46 x 10^6$ mol d^{-1} (or -271 mmol m^{-2} d^{-1}).
Dry season: ΔDIN for the system: $+1 x 10^6$ mol d^{-1} (or +6 mmol m^{-2} d^{-1}).

Nutrient concentrations in the estuarine waters show daily, seasonal and inter-annual variability (*Zhang et al.* 1998). Nutrient concentrations during flood conditions are about twice those of the dry season; N and P generally behave nonconservatively while silicate is conservative. DIN is predominantly nitrate

(>95%); ammonia ranged up to 8μM and nitrite concentrations were insignificant (<0.1μM). The relatively high waste loads from urban and industrial sources (>10^6 tonnes yr^{-1}) into the river just upstream of the estuary undoubtedly contribute significantly to organic matter and predispose the system towards strong heterotrophic activity. N and P regeneration has been inferred from studies of the mixing zone of the estuary, especially in conjunction with the turbidity maximum, interpreted as degradation of organic matter or desorption (Zhang *et al*. 1998).

Stoichiometric calculations of aspects of net system metabolism

Stoichiometric calculations can be based on the molar C:N:P ratio of material likely to transported into the system and reacting there (Gordon *et al.* 1996). We assume that this 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 estimated as the difference between observed and expected ΔDIN, where ΔDIN_{exp} is 16 x ΔDIP.

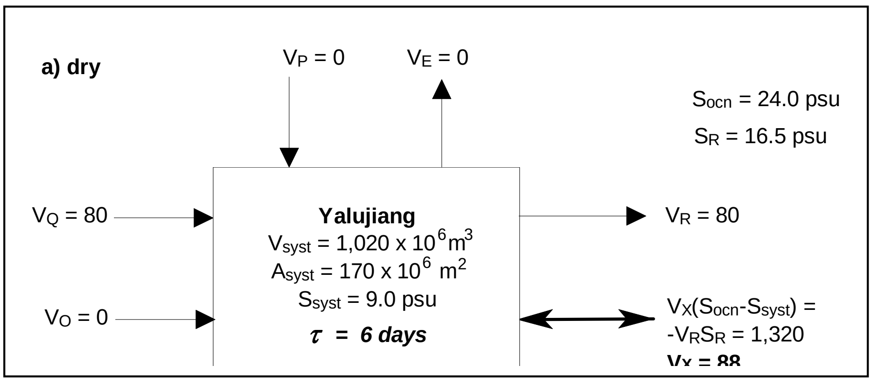
Flood season: [*nfix-denit*] = -277 mmol m^{-2} d^{-1}
Dry season: [*nfix-denit*] = +5 mmol m^{-2} d^{-1}
Annualised [*nfix-denit*] = -89 mmol m^{-2} d^{-1}

These calculations indicate that, annually, the estuary functions as a strongly net denitrifying system, especially in the flood season when N loads are extremely high. In the dry season, net nitrogen flux is little different from zero.

Net ecosystem metabolism (NEM = [*p-r*] or net production minus respiration) is derived from [*p-r*] = 106 x -ΔDIP.

Flood season: [*p-r*] = -47 mmol C m^{-2} d^{-1}
Dry season: [*p-r*] = -8 mmol C m^{-2} d^{-1}
Annualised: [*p-r*] = -21 mmol C m^{-2} d^{-1}

Thus the estuary functions as a strongly net heterotrophic system, moreso in the flood season.



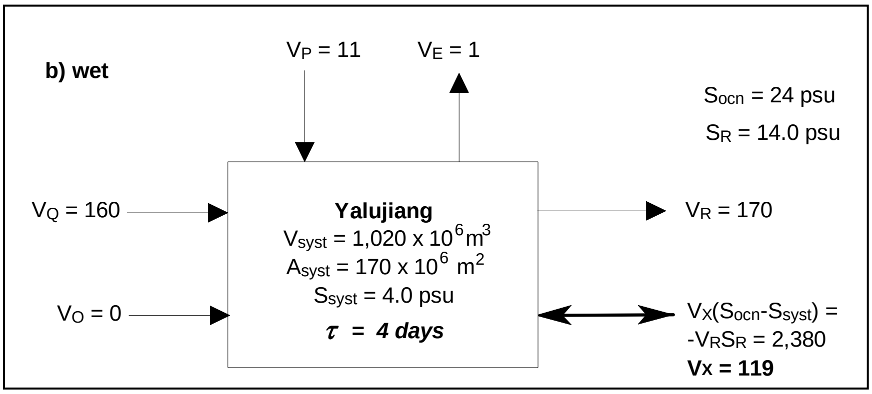


Figure 6.13. Water and salt budgets for Yalujiang River estuary, during dry (a) and wet (b) seasons. Water fluxes in 10^6 m^3 d^{-1}; salt fluxes in 10^6 psu m^3 d^{-1}.

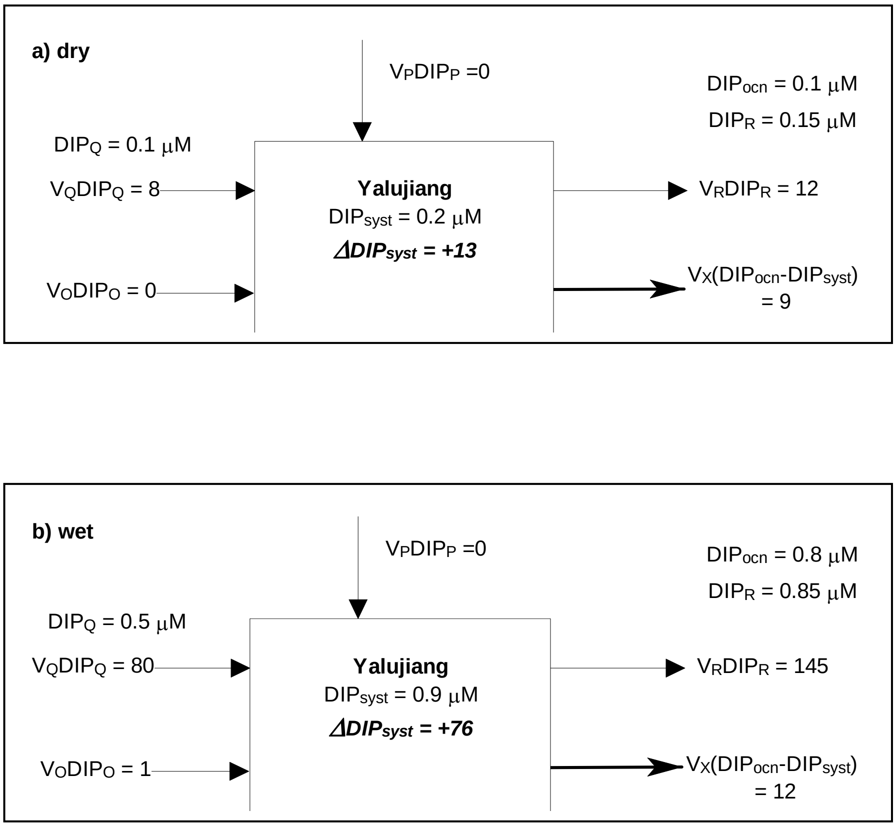


Figure 6.14. DIP budgets for the Yalujiang River estuary during dry and wet seasons. Fluxes in 10^3 mol d^{-1}.

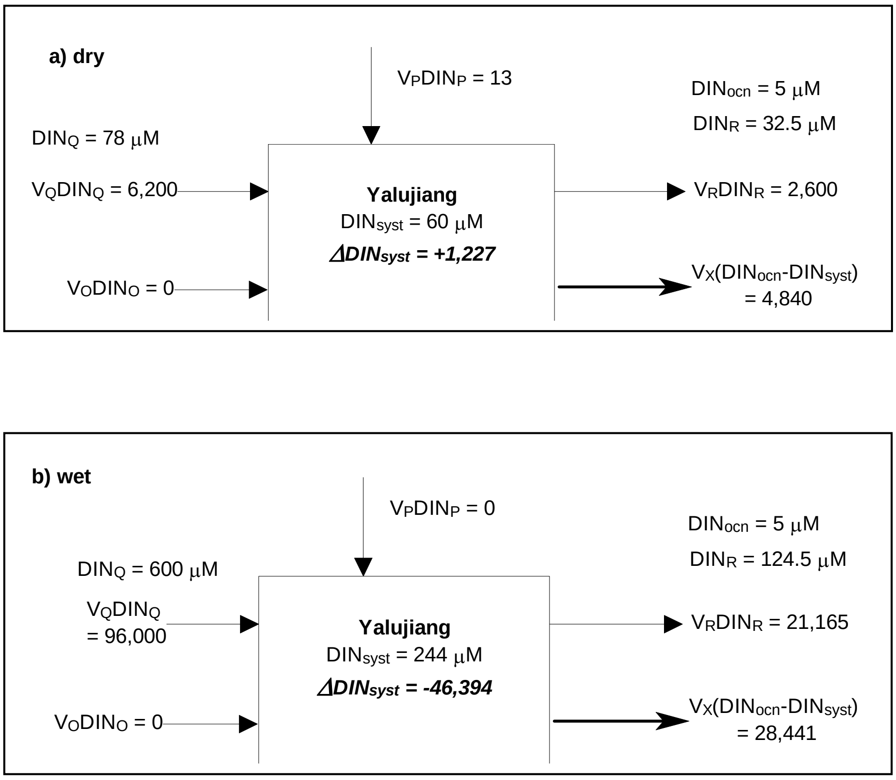


Figure 6.15. DIN budgets for the Yalujiang River during dry and flood seasons. Fluxes in 10^3 mol d^{-1}.

7. BUDGETS FOR ESTUARINE SYSTEMS IN TAIWAN

7.1 Chiku Lagoon

Jia-Jang Hung and Fancy Kuo

<u>Study area description</u>

Chiku Lagoon is a semi-enclosed coastal lagoon located on the south-western coast of Taiwan (23.16°N, 120.08°E; Figure 7.1). The lagoon is shallow (<2 m at low tide) and connected to Taiwan Strait through two narrow inlets on the sandbar. The lagoon receives freshwater mainly from the nutrient-rich Chiku River and Daliao Creek which drain agricultural soils, mangrove swamps and aquaculture ponds. The total lagoon area and volume are around 10 km^2 and 12×10^6 m^3, respectively.

The study area has a longer dry season (October–April) than wet season (May–September). Freshwater discharge ranges from 265–563x10^3 m^3 d^{-1} in the wet season and 85–240x10^3 m^3 d^{-1}in the dry season. Because of the small system volume, the system salinity is subjected to seasonal variability, ranging during the study period from 20.6 psu in September (1997) to 33.8 psu in April (1997). Water temperature ranges from 16°C in winter to 32°C in summer.

The lagoon is highly productive, primarily due to inputs of nutrient-enriched freshwater. The gross production was estimated to be about 90 mol C m^{-2} yr^{-1} or 250 mmol C m^{-2} d^{-1} (Wong 1999). The lagoon is now intensively farmed with oyster-hanging culture and is also fished for finfish, oysters and shellfish (Lin *et al*. 1999).

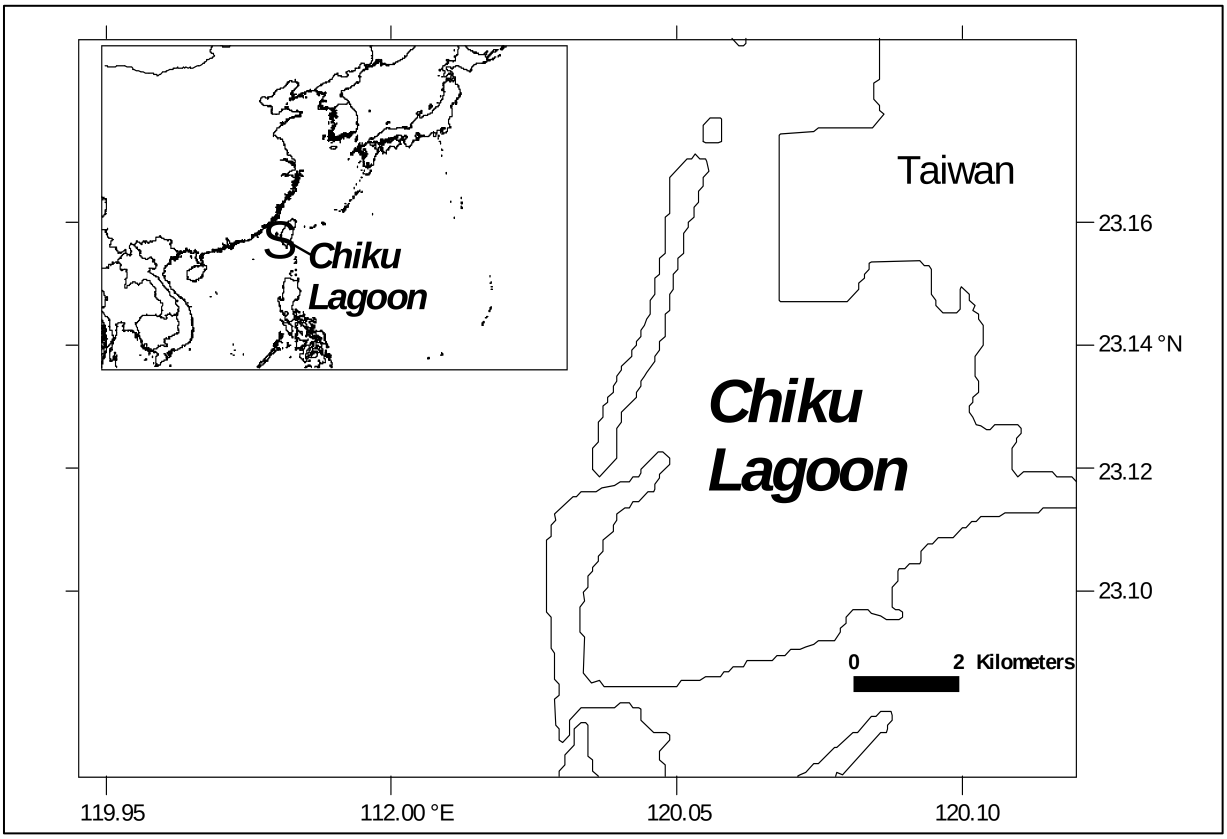


Figure 7.1. Map and location of Chiku Lagoon.

Although the lagoon is apparently healthy and productive now, it may incur changes in the future from planned petrochemical and steel industries around the watershed. Detrimental changes in the lagoon may also endanger certain biological species, including black-faced spoonbills that use the lagoon as their winter shelter. In order to study current lagoon biogeochemistry and function, water samples were collected bimonthly from November 1996 to October 1998 for hydrochemical, nutrient and trace-metal distributions. Water, nutrient and carbon budgets were developed from collected data.

<u>Water and salt balance</u>

Mixing of lagoon water is generated by semidiurnal tidal currents moving back and forth, primarily through the southern inlet and secondarily through the northern inlet (Jan *et al*. 2000). The single box model was therefore applied for budget calculation under steady-state assumptions for water and salt balances (Gordon *et al.* 1996). Because of great temporal variability in freshwater and material delivery into the lagoon (see Table 7.1), water and nutrient budgets should first be constructed for each sampling period and then averaged for final annual budgets. Such annual budgets are different from those budgets

Table 7.1. Variations of physical properties, water budgets and residence times in Chiku Lagoon during the sampling periods.

Sampling period	Freshwater input ($10^3m^3d^{-1}$)			Residual flow ($10^3m^3d^{-1}$)	Ocean salinity (psu)	Lagoon salinity (psu)	Exchange Volume ($10^3m^3d^{-1}$)	τ (day)
	River	Precipitation	Evaporation					
Nov-96	183	10	30	163	34.3	31.2	1,722	6
Jan-97	85	9	20	74	34.3	32.4	1,299	9
Apr-97	93	7	43	57	34.3	33.8	3,882	3
Jun-97	563	176	36	703	34.3	32.2	11,131	1
Sep-97	511	69	38	542	34.3	20.7	1,096	7
Nov-97	221	0	33	188	34.3	31.6	2,294	5
Feb-98	121	35	22	134	34.3	32.9	3,216	4
May-98	342	34	40	336	34.3	30.4	2,787	4
Aug-98	265	71	54	282	34.3	28.0	1,394	7
Oct-98	240	9	43	206	34.3	30.9	1,975	6
Mean	262	42	36	269	34.3	30.4	3,058	5

Figure 7.2 illustrates water and salt budgets derived from the first sampling event (November 1996) as an example of a budget calculation for Chiku Lagoon. Other sampling periods are budgeted similarly. Freshwater (S=0) inflow is summed from the precipitation, evaporation and discharges from the Chiku River and Daliao Creek. Precipitation and evaporation data were provided by the Central Weather Bureau of Taiwan. River discharges were measured from the flow velocity and the area of cross section of river. The net input of freshwater is estimated to be 163×10^3 m^3 d^{-1}. Groundwater discharge is assumed to be negligible because over-extraction is a concern in the area. Mean salinity is 31.2 psu in the lagoon and 34.3 psu in seawater adjacent to the lagoon. Seawater exchange rate is therefore estimated to be $1,722\times10^3$ m^3 d^{-1}. The exchange time (τ) of lagoon water is 6 days (Figure 7.2). The water exchange rate averaged from each sampling period is $3,058\times10^3$ m^3 d^{-1}, differing significantly from that ($2,223\times10^3$ m^3 d^{-1}) derived from final mean values of freshwater inputs and salinity in lagoon and oceanic systems (Table 7.6). However, there is no difference in the exchange time (5 days) developed from these two different methods.

Budgets of nonconservative materials

The CNP budgets calculated by the two different averaging methods are expected to be different as well. This indicates that system budgets derived simply from mean values of parameters from dry and wet seasons may not be necessarily correct if temporal variability is also significant within a season. Table 7.2 summarizes temporal distributions of DIP, DOP, DIN and DON for Chiku Lagoon. Using such data, nonconservative fluxes and budgets of CNP were derived according to the guidelines of Gordon *et al.*

(1996) and results were listed in Tables 7.3 – 7.5.

Table 7.2. Variations of nutrient concentrations in fresh, lagoon and oceanic water in Chiku Lagoon during the sampling periods.

Sample period	DIP (μM)			DOP (μM)			DIN (μM)			DON (μM)		
	Fresh	Syst	Ocn	Fresh	Syst	Ocn	Fresh	Syst	Ocn	Fresh	Syst	Ocn
Nov-96	98	6.8	0.1	-	-	-	672	8.4	2.4	131	18	10
Jan-97	271	3.4	0.1	14	0.8	0.3	576	55	11	2,071	13	12
Apr-97	237	1.9	0.5	15	0.9	0.6	2,140	1.0	0.2	247	24	13
Jun-97	12	3.6	0.9	0.4	1.0	0.7	217	11	2.1	36	19	10
Sep-97	13	2.9	0.4	14	0.7	0.2	221	11	1.2	15	23	12
Nov-97	28	3.6	0.1	4.1	0.9	0.8	140	20	8.0	303	22	18
Feb-98	83	2.1	0.1	7.4	0.1	0.2	149	9.4	3.2	818	16	12
May-98	29	2.2	0.5	5.0	0.5	0.4	298	5.5	0.6	61	17	12
Aug-98	10	1.2	0.4	2.3	0.6	0.1	317	5.4	4.8	36	8.6	5.5
Oct-98	16	2.6	0.6	5.8	0.6	0.4	338	27	12	88	13	7.1
Mean	80	3.0	0.4	7.6	0.7	0.4	507	15	4.6	381	17	11

Table 7.3. Temporal variations of nutrient fluxes in Chiku Lagoon during the sampling periods.

Sampling period	River flux (+) (10^3 mol d^{-1})				Residual flux (-) (10^3 mol d^{-1})				Mixing flux (10^3 mol d^{-1})			
	DIP	DOP	DIN	DON	DIP	DOP	DIN	DON	DIP	DOP	DIN	DON
Nov-96	18	-	123	24	1	-	1	2	12	-	10	14
Jan-97	23	1.2	49	176	0	0	2	1	4	0.6	57	1
Apr-97	22	1.4	199	23	0	0	0	1	5	1.2	3	43
Jun-97	7	0.2	122	20	2	0.6	5	10	30	3.3	99	100
Sep-97	7	7.2	113	8	1	0.2	3	9	3	0.5	11	12
Nov-97	6	0.9	31	67	0	0.2	3	4	8	0.2	28	9
Feb-98	10	0.9	18	99	0	0	1	2	6	-0.3	20	13
May-98	10	1.7	102	21	0	0.2	1	5	5	0.3	14	14
Aug-98	3	0.6	84	10	0	0.1	1	2	1	0.7	1	4
Oct-98	4	1.4	81	21	0	0.1	4	2	4	0.4	30	12
Mean (10^3mol d^{-1})	11	2	92	47	0	0	2	4	8	1	27	22
Mean (10^6mol yr^{-1})	4	1	34	17	0	0	1	1	3	0	10	8

P balance

Nonconservative fluxes of DIP (*ΔDIP*) and DOP (*ΔDOP*) are derived from nonconservative behaviors of

DIP and DOP in Chiku Lagoon. Nonconservative fluxes are negative during all sampling events except for those in June and November 1997 and October 1998. The mean value of *ΔDIP* throughout the studied period is -0.3 mmol m^{-2} d^{-1} (Table 7.5) suggesting that the lagoon is a sink for DIP. This *ΔDIP* value is equivalent to -0.1 mol m^{-2} yr^{-1}, which may result primarily from large DIP inputs from the Chiku River and Daliao Creek. Nonconservative flux of DOP (*ΔDOP*) is negligible. The *ΔTDP* (*ΔDIP* +*ΔDOP*) is equivalent to -0.1 mol m^{-2} yr^{-1}. Thus, the lagoon is overall a sink for total dissolved P during the study period.

N balance

Nonconservative fluxes of DIN (*ΔDIN*) and DON (*ΔDON*) are -6 mmol m^{-2} d^{-1} (-2 mol m^{-2} yr^{-1}) and -2 mmol m^{-2} d^{-1} (-1 mol m^{-2} yr^{-1}), respectively. *ΔDIN* is considerably greater than *ΔDON*.

Table 7.4. Nonconservative fluxes and budgets of C-N-P in Chiku Lagoon.

Time	*ΔDIP* (10^3 mol d^{-1})	*ΔDOP* (10^3 mol d^{-1})	*ΔDIN* (10^3 mol d^{-1})	*ΔDON* (10^3 mol d^{-1})	**(*p-r*)** (10^3 mol d^{-1})	**(*nfix-denit*)** (10^3 mol d^{-1})
11/1996	-5	-	-112	-8	+530	-40
01/1997	-19	-1	+10	-174	+2,014	+156
04/1997	-17	0	-196	+21	+1,802	+97
06/1997	+25	+4	-18	+90	-2,650	-392
09/1997	-3	-7	-99	+13	+318	+74
11/1997	+2	-1	0	-54	-212	-70
02/1998	-4	-1	+3	-84	+424	-3
05/1998	-5	-1	-87	-2	+530	+7
08/1998	-2	0	-82	-4	+212	-54
10/1998	0	-1	-47	-7	0	-38
Mean (10^3 mol d^{-1})	-3	-1	-63	-21	+318	-20
Mean (10^6 mol yr^{-1})	-1	0	-23	-8	+106	-15

Table 7.5. Nonconservative fluxes and budgets of C-N-P in Chiku Lagoon.

Time	*ΔDIP* (mmol $m^{-2}d^{-1}$)	*ΔDOP* (mmol $m^{-2}d^{-1}$)	*ΔDIN* (mmol $m^{-2}d^{-1}$)	*ΔDON* (mmol $m^{-2}d^{-1}$)	**(*p-r*)** (mmol $m^{-2}d^{-1}$)	**(*nfix-denit*)** (mmol $m^{-2}d^{-1}$)
11/1996	-0.5	-	-11	-1	+53	-4
01/1997	-1.9	-0.1	+1	-17	+201	+15
04/1997	-1.7	0	-20	+2	+180	+10
06/1997	+2.5	+0.4	-2	+9	-265	-39
09/1997	-0.3	-0.7	-10	+1	+32	+7
11/1997	+0.2	-0.1	0	-5	-21	-8
02/1998	-0.4	-0.1	0	-8	+42	0

05/1998	-0.5	-0.1	-9	0	+53	+1
08/1998	-0.2	0	-8	0	+21	-5
10/1998	0	-0.1	-5	-1	0	-4
Mean (mmol m^{-2} d^{-1})	-0.3	-0.1	-6	-2	+32	-2
Mean (mol m^{-2} yr^{-1})	-0.1	0	-2	-1	+11	-1
Lagoon area: 10 km^2						
Lagoon volume: 12×10^6 m^3						

Stoichiometric calculations of aspects of net system metabolism

The net ecosystem metabolism (NEM, [*p-r*]) is estimated from *ΔDIP* and C:P ratio in particulate organic matter (POM) with the assumption that the internal reaction flux of DIP is proportional to production and consumption of POM (Gordon *et al*. 1996). Particulate C:P ratio is assumed to be 106:1 because plankton metabolism dominates NEP in the system. Thus:

$(p\text{-}r) = -106 \times \Delta DIP = -106 \times (-0.1 \text{ mol m}^{-2} \text{ yr}^{-1}) = +11 \text{ mol m}^{-2} \text{ yr}^{-1}$.

Apparently, Chiku Lagoon is an autotrophic system. The net carbon production is approximately 11 mol m^{-2} yr^{-1}. This value is approximately equivalent to 12 % annual gross production (90 mol C m^{-2} yr^{-1}) in the lagoon. The magnitude of net production is reasonably consistent with the fact that the system is highly productive.

Net nitrogen fixation or denitrification (*nfix-denit*) is calculated from the difference between observed and expected *ΔTDN*. Expected *ΔTDN* is *ΔTDP* multiplied by N:P ratio of particulate organic matter. The particulate N:P ratio is assumed to be 16. Thus:

$(nfix\text{-}denit) = -3 \text{ mol m}^{-2} \text{ yr}^{-1} - (-0.1\times16) \text{ mol m}^{-2} \text{ yr}^{-1} = -1 \text{ mol m}^{-2} \text{ yr}^{-1}$

The result indicates that Chiku Lagoon is denitrifying at rate of -1 mol m^{-2} yr^{-1}. This value is within the range found previously in the Asian region (Dupra *et al*. 2000).

Meanwhile, Table 7.6 demonstrates the difference of system budgets ([*p-r*] and [*nfix-denit*]) derived from water and salt budgets using different methods. (*p-r*) is +58 mole m^{-2} yr^{-1} and (*nfix-denit*) is +2.6 mole m^{-2} yr^{-1} budgeting from temporal means of various parameters.

Table 7.6. Comparison of system budgets calculated from two different methods.

Method	**Water exchange** (m^3 d^{-1})	**Exchange Time** τ (day)	***(p-r)*** (mol m^{-2} yr^{-1})	***(nfix-denit)*** (mol m^{-2} yr^{-1})
Mean of modelled results from each sampling event	$3,058\times10^3$	5	+11	-1
Modelling results from temporal means of various parameters	$2,223\times10^3$	5	+58	+3

The implication is that system budgets derived merely from two contrasting seasons (dry and wet) may not be correct if temporal variation is highly significant throughout a year. Some system budgets previously reported were simply developed from mean values of various parameters averaged from dry and wet seasons. Justification and interpretation must be cautious to avoid uncertainty involved in temporal variations.

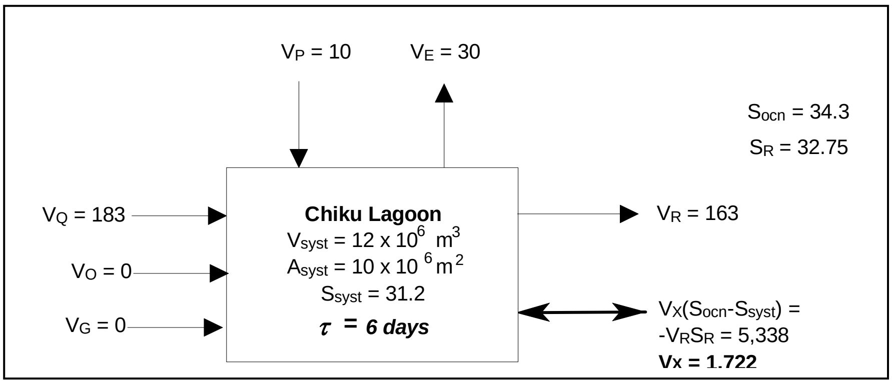


Figure 7.2. An example of water and salt budgets modelled from the first sampling event for the Chiku Lagoon. Water flux in 10^3 m^3 d^{-1} and salt flux in 10^3 psu-m^3 d^{-1}.

7.2 Tanshui River estuary

Jia-Jang Hung, T.-H. Fang, F. Kuo and C.-P. Chen

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

The Tanshui River estuary (25.16°N, 121.42°E) is located on the north-western coast of Taiwan (Figure 7.3). The river drains a watershed ranging from mountainous to metropolitan (Taipei) regimes with a total area about 2,726 km^2. The estuarine area (water with salinity greater than 0.2 psu) is approximately 17 km^2 and the volume is about 75×10^6 m^3. The major freshwater inputs are Tanshui River water and wastewater from the Taipei metropolitan area. The dry season ranges from November to April and the wet season ranges from May to October. Temperature ranges from 15°C (January) to 29°C (July) and rainfall is about 3,000 mm yr^{-1}.

The sewage inputs from the Taipei area may significantly influence the CNP biogeochemical processes in the estuary. However, the study of estuarine biogeochemistry is still underway, and estuarine budgets developed from available data are preliminary, as uncertainty may be introduced by creating annual budgets simply from dry and wet seasons (see discussion in the Chiku Lagoon budget).

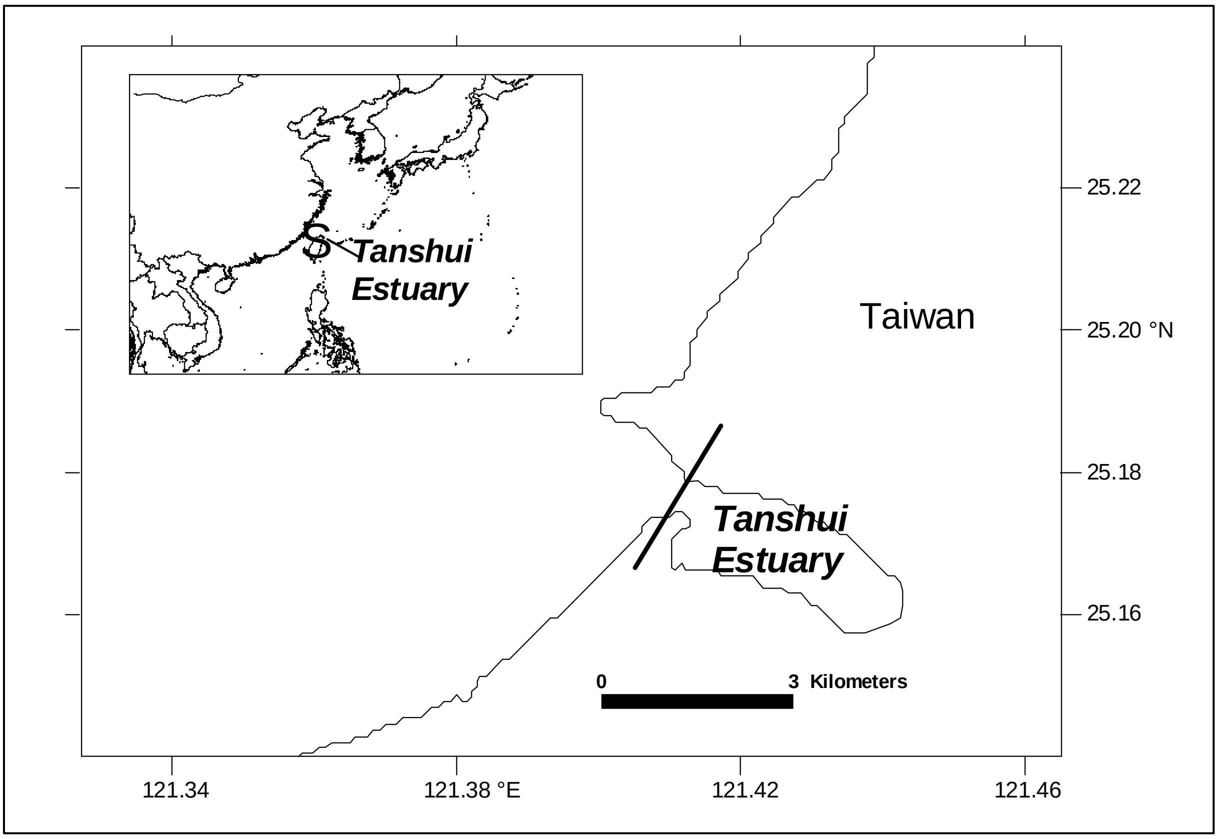


Figure 7.3. Map and location of Tanshui River estuary, Taiwan. The boundary of the budgeted area is marked

Water and salt balance

Figure 7.4 demonstrates water and salt budgets in the Tanshui River estuary during the dry (March 1998) and wet (May 1998) seasons. Freshwater inputs are summed from precipitation, evaporation and discharges from the Tanshui River and metropolitan sewage. River discharges are measured from water gauges installed and operated by the Water Resources Planning Commission (Taiwan), primarily from three major branches (Keelung River, Tahan Stream and Hsintien Stream). Total riverwater discharge into the estuary is not known, as water gauges are all installed at upper reaches of streams. Therefore, the riverwater discharges used for the budget derivation (Figure 7.4) are estimated values. Domestic wastewater released from the Taipei area is estimated to be 920×10^3 m^3 d^{-1} (http://www.sew.gov.tw). However, we have not used this data for budget construction because a significant part of wastewater may be lost during transport and/or release directly into Taiwan Strait. Therefore, only 70 % of the total amount (650×10^3 t d^{-1}) is regarded as direct input into the estuary. The total freshwater input is about $6{,}730\times10^3$ m^3 d^{-1} in the dry season (March 1998) and about $8{,}670\times10^3$ m^3 d^{-1} in the wet season (May 1998). The mean system salinity is about 16.6 psu during the dry season and 15.1 psu during the wet season. These data result in a larger water exchange rate for the wet season ($-9{,}976\times10^3$ m^3 d^{-1}) than for the dry season ($-6{,}730\times10^3$ m^3 d^{-1}), and about the same water exchange time for both seasons (4 days).

Budgets of nonconservative materials

Table 7.7 summarizes distributions of mean salinity and nutrients in estuarine water and wastewater. Budgets of CNP were constructed from such data and water budgets (Figure 7.4). Distributions of system salinity and nutrients are apparently influenced by the extent of freshwater input; concentrations are generally greater in the dry season than in the wet season. Nutrient concentrations in wastewater are adapted from a report by Wu (1997).

P balance

Nonconservative fluxes of DIP and DOP are estimated from the sum of total inputs (river, rain and wastewater) and total outputs (residual and exchange rates) listed in Table 7.8. The calculated results (Table 7.9) show that *ΔDIP* and *ΔDOP* are negative in both dry and wet seasons. When the nonconservative fluxes are normalized to the estuarine area, they are equivalent to -0.6 mmol m^{-2} d^{-1} (-0.2 mol m^{-2} yr^{-1}) for *ΔDIP* and -0.4 mmol m^{-2} d^{-1} (-0.1 mol m^{-2} yr^{-1}) for *ΔDOP* (Table 7.9). The magnitude is greater in the wet season than in the dry season. This *ΔDIP* indicates that the Tanshui River estuary is a large sink for DIP.

However, the Tanshui River estuary is relatively turbid and more than 80 % of particulate phosphorus in the surficial sediment is reported as inorganic forms (Fang 2000). Apparently, geochemical processes are involved significantly in the removal of DIP from the estuarine system. This is also reflected in the low

DOP concentration throughout the estuary. Therefore, it is possible that only 30 % of the total *ΔDIP* should be regarded as derived from biochemical processes (-0.06 mol m^{-2} yr^{-1}). Following such consideration, *ΔDOP* would be approximately -0.03 mol m^{-2} yr^{-1}.

N balance

Following the guidelines for budget calculations, nonconservative fluxes of DIN and DON are all negative (Table 7.9), indicating that the estuary is also a sink for DIN and DON. The annual mean values are -13 mol m^{-2} yr^{-1} for *ΔDIN* and -14 mol m^{-2} yr^{-1} for *ΔDON*. Such large values of nonconservative fluxes are primarily due to rather high concentrations of DIN and DON in riverwater and wastewater (Table 7.7), which result in great inputs of DIN and DON.

Stoichiometric calculations of aspects of net system metabolism

The net ecosystem metabolism (NEM = [*p-r*]) in the estuary can be estimated from ΔDIP and C:P ratio in particulate organic matter. The Redfield ratio for phytoplankton (106:1) is applied because plankton probably dominate the system metabolism.

(p-r) = $-\Delta DIC_o$ = 0.2 mol m^{-2} yr^{-1} x 106 = +21 mol m^{-2} yr^{-1}

If only 30% of the *ΔDIP* is regarded as due to biotic activity, this rate would drop to 6 mol m^{-2} yr^{-1}.

Table 7.7. Distributions of salinity and nutrients in riverine, estuarine and waste waters of the Tanshui River estuary during the study period.

	Dry season	**Wet season**
Salinity		
Estuary	16.6	15.1
Ocean	33.5	33.4
DIP (µM)		
River	4.5	5.1
Sewage	26	26
Estuary	2.8	3.1
Ocean	0.3	0.5
DOP (µM)		
River	0.9	0.6
Sewage	6.7	6.7
Estuary	0.6	0.2
Ocean	0.2	0.2
DIN (µM)		
River	366	89
Sewage	1440	1440

Estuary	180	65
Ocean	0.8	0.8
DON (μM)		
River	146	182
Sewage	1330	1330
Estuary	86	108
Ocean	6.2	6.2

The result implies that the Tanshui River estuary is an autotrophic system with a net production rate between about +6 and 21 mol m^{-2} yr^{-1}. This value is on the upper limit of rates found in the southern Tsengwen River estuary (1-6 mol m^{-2} yr^{-1}). Regardless of uncertainties associated with only two investigations within a year, the large NEM could be due to nutrient enrichment in the estuary. Relatively high NEM would result in a high accumulation of organic carbon in sediments, which also induces a hypoxic/anoxic condition in bottom water of upper to middle estuaries (Jeng and Han 1996; Fang 2000). Nitrite concentrations are inversely correlated significantly with dissolved oxygen. Dissolved oxygen was also depleted in sediments near the middle to upper boundary of the estuary (Jeng and Han 1996).

Net nitrogen fixation or denitrification *(nfix-denit)* is derived from the difference between observed and expected ΔN, where the expected value is calculated from *ΔTDP* multiplied by the N:P ratio of the decomposing organic matter. The Redfield ratio 16:1 is assumed for the decomposing organic matter.

Table 7.8. Nutrient fluxes during dry and wet seasons of the Tanshui River estuary during the study period.

	Dry season	**Wet season**
DIP flux (10^3 mole d^{-1})		
river	27	41
sewage	17	17
residual	-10	-16
mixing	-25	-30
DOP flux (10^3 mole d^{-1})		
river	5	5
sewage	4	4
residual	-3	-2
mixing	-4	0
DIN flux (10^3 mole d^{-1})		
river	2,196	712
sewage	936	936
residual	-608	-285
mixing	-1,788	-738
DON flux (10^3 mole d^{-1})		
river	876	1456
sewage	865	865
residual	-310	-495
mixing	-796	-1170

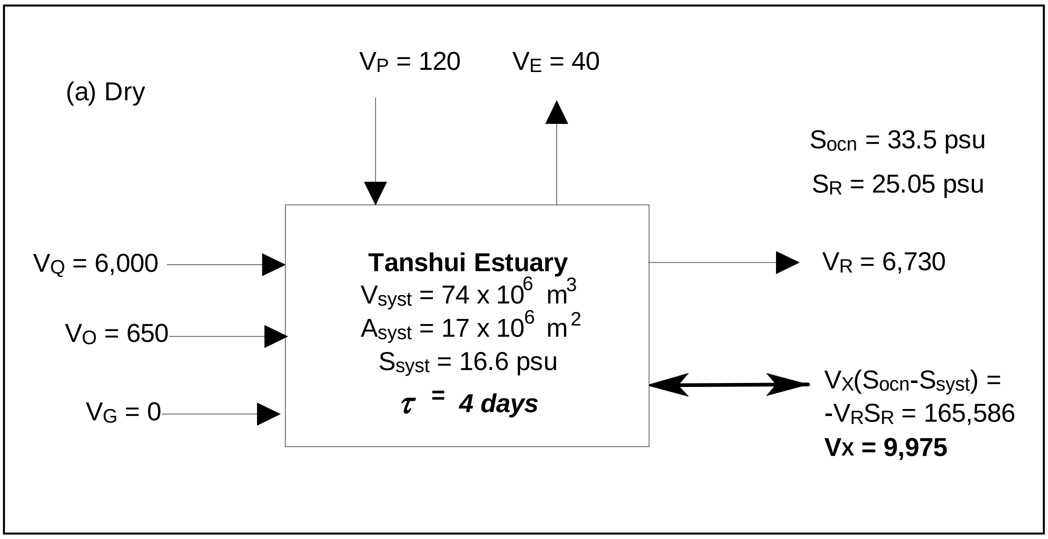
Thus,

$$(nfix\text{-}denit) = -31 \text{ mol m}^{-2} \text{ yr}^{-1} - (-0.09 \text{ mol m}^{-2} \text{ yr}^{-1} \times 16) = -26 \text{ mol m}^{-2} \text{ yr}^{-1}$$

The Tanshui River estuary is now denitrifying with a relatively high rate at 26 mol m^{-2} yr^{-1}. This magnitude of denitrification seems to be reasonable as the estuarine system receives large inputs of nitrogen and most bottom waters of the upper to middle estuaries are now in hypoxic to anoxic conditions. This system possesses the highest values of denitrification among the coastal systems reported to date from Taiwan. It appears that anthropogenic activities around the watershed of the system exert a significant influence on C-N-P budgets in the system.

Table 7.9. Nonconservative fluxes and budgets of C-N-P in the Tanshui River estuary during the study period.

	ΔDIP	*ΔDOP*	*ΔDIN*	*ΔDON*	*(p-r)*	*(nfix-denit)*
Dry season (10^3 mole d^{-1})	-9	-2	-736	-635	+954	-1,195
Wet season (10^3 mole d^{-1})	-12	-7	-625	-656	+1,272	-977
Mean (10^3 mole d^{-1})	-11	-5	-681	-646	+1,166	-1,071
Mean (10^6 mole yr^{-1})	-4	-2	-249	-236	+424	-389
mean (mmole m^{-2} d^{-1})	-0.6	-0.4	-36	-38	+64	-58
mean (mole m^{-2} yr^{-1})	-0.2 (-0.06)*	-0.1 (-0.03)*	-13	-14	+21(+6) *	-22 (-26)*
* see text explanation						
Tanshui River estuary area: 17 km^2						
Tanshui River estuary volume: 75×10^6 m^3						



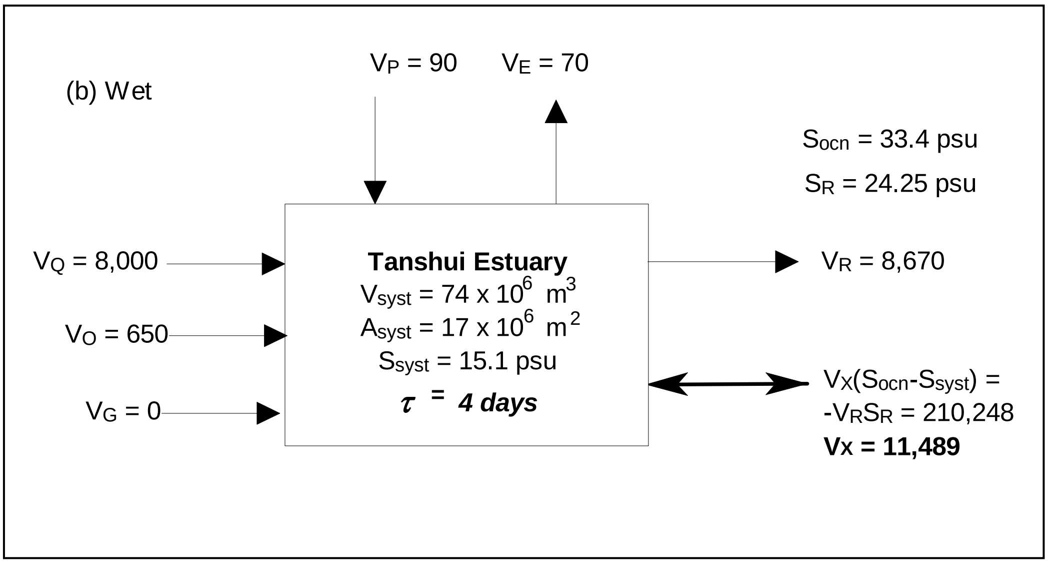


Figure 7.4. Water and salt budgets for the Tanshui River estuary during dry (a) and wet (b)

seasons. Water flux in 10^3 m^3 d^{-1} and salt flux in10^3 psu-m^3 d^{-1}.

7.3 Tapong Bay

J.-J. Hung and P.-Y. Hung

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

Tapong Bay (22.69°N, 120.26°E) is a semi-enclosed shallow lagoon (average depth ~2 m) located on the south-western coast of Taiwan (Figure 7.5). The bay is largely surrounded by aquaculture ponds, and military and urban facilities. The surface area of bay is about 5 km^2, occupied largely by oyster-hanging and fish-caging cultures. Water exchange between the bay and Taiwan Strait is determined primarily by a semidiurnal tidal action through a narrow inlet. There is no river associated with the bay. In addition to precipitation, the major input water is brackish from urban runoff and aquaculture wastewater with salinity greater than 20. The dry season generally extends from October to April, and the wet season from May to September. Water temperature ranges from about 18°C (winter) to 33°C (summer).

The bottom water of the inner bay becomes hypoxic during certain seasons due to high organic loading and poor seawater exchange. the study is still underway, but currently available data cover the periods of dry and wet seasons. Data from four sampling events were used to develop annual budgets.

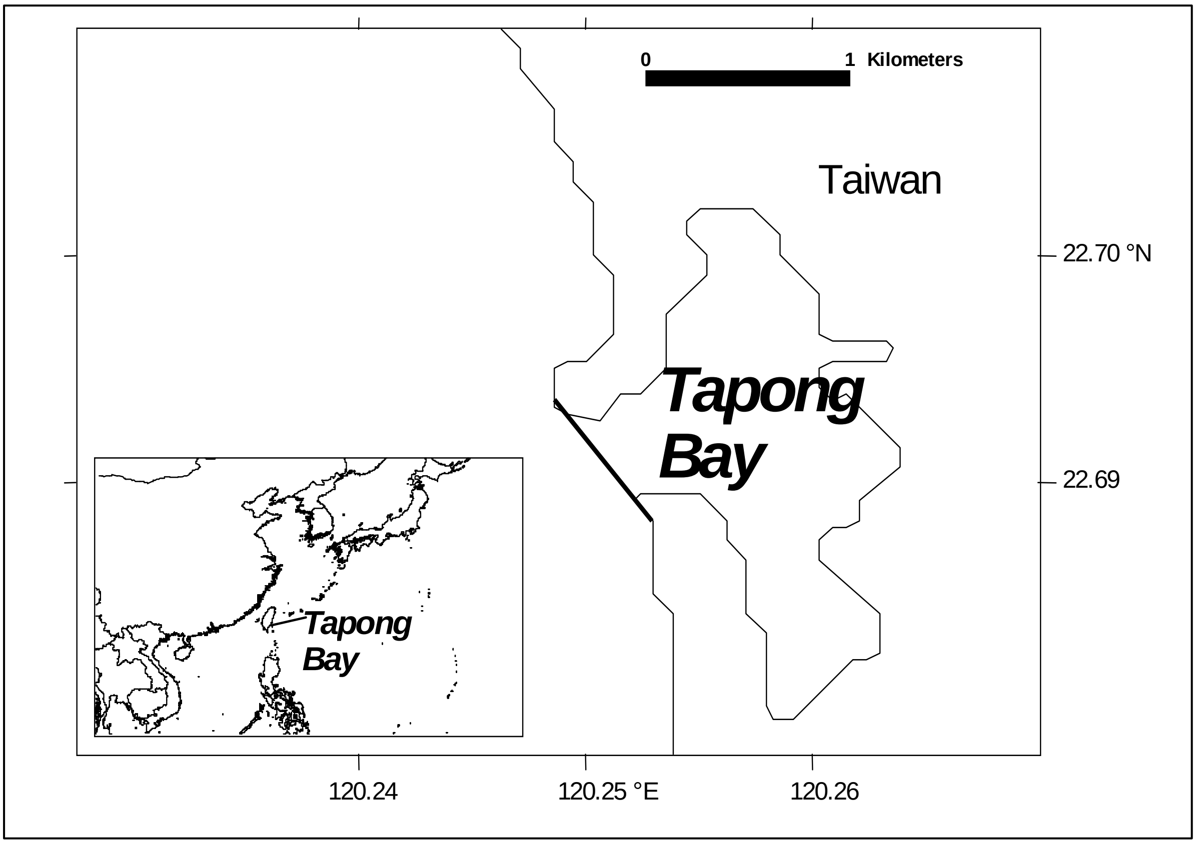


Figure 7.5. Map and location of Tapong Bay. The boundary of the budgeted area is indicated.

Water and salt balance

Using the LOICZ modelling guidelines (Gordon *et al.* 1996), water budgets of each sampling period in the bay are developed from salt balance using data of precipitation (V_P, S = 0), wastewater discharge (V_O, S > 20) and evaporation (V_E, S = 0). Groundwater input is assumed to be negligible as over-pumping is a serious problem in the area. Figure 7.6 presents an example of a water budget calculated from the salt balance for the first sampling event (August 1999); water budgets for other sampling events can be obtained by following the same calculation method. Data are given in Table 7.10.

Exchange time for Tapong Bay is longer (11 days) than for Chiku Lagoon (5 days). This may be due to relatively poor flushing of seawater in Tapong Bay, also resulting in hypoxic conditions in the bottom water of the inner bay. The system salinity is lower in the wet season than in the dry season primarily due to precipitation.

Table 7.10. Variations of physical properties, water budgets and water exchange times in Tapong Bay and the adjacent Taiwan Strait.

Sampling period	**Freshwater input** ($10^3 m^3 d^{-1}$)			**Residual flow** ($10^3 m^3 d^{-1}$)	**Waste salinity** (psu)	**Ocean salinity** (psu)	**Lagoon salinity** (psu)	**Exchange volume** ($10^3 m^3 d^{-1}$)	**τ** (day)
	V_O	V_P	V_E						
Aug-99	145	90	22	213	24.2	34.3	31.3	1,159	9
Oct-99	145	28	16	157	24.2	34.3	31.8	672	14
Dec-99	145	4	12	137	24.2	34.3	32.9	781	13
Feb-00	145	4	12	137	24.2	34.3	33.3	1,122	10
Mean	145	45	17	173	24.2	34.3	32.1	984	11

Budgets of nonconservative materials

Table 7.11 summarizes the distributions of phosphorus and nitrogen in Tapong Bay and in the adjacent seawater end-member during various sampling periods. Concentrations of various nutrients in seawater are similar during the two sampling periods (August and December 1999); therefore, the same concentrations are adopted for the seawater end-member. Nonconservative fluxes of phosphorus and nitrogen for the bay are derived from data in Tables 7.10-7.12 and listed in Tables 7.13 and 7.14.

Table 7.11. Variations of nutrient concentrations in fresh, lagoon and oceanic water in Tapong Bay during the sampling periods.

Sampling period	DIP (μM)			DOP (μM)			DIN (μM)			DON (μM)		
	Fresh	Syst	Ocn	Fresh	Syst	Ocn	Fresh	Syst	Ocn	Fresh	Syst	Ocn
Aug-99	28	2.5	0.1	16	2.7	0.4	119	12	1	41	21	7
Oct-99	28	3.1	0.1	16	4.9	0.4	119	18	1	41	14	7
Dec-99	28	2.4	0.1	16	0.7	0.4	119	13	1	41	32	7
Feb-00	28	5.1	0.1	16	0.5	0.4	119	20	1	41	35	7
Mean	28	3.1	0.1	16	2.3	0.4	119	15	1	41	25	7

P balance

Data for DIP in precipitation (rainfall) are not available in the study area. This input is likely to be small; so DIP inputs are estimated solely from wastewater volume discharges and DIP concentrations in the wastewater. Although the volume of precipitation is rather significant in comparison with wastewater input during the wet season (August), the DIP concentration is much lower in rainwater (worldwide typical concentration) than in wastewater. Balance calculation shows that inputs of dissolved inorganic nutrients (DIP, DIN) generally exceed the outputs of nutrients from the system, except in February.

Table 7.12. Temporal variations of nutrient fluxes in Tapong Bay during the sampling periods.

Sampling Period	River flux(+) (10^3 mol d^{-1})				Residual flux(-) (10^3 mol d^{-1})				Mixing flux(-) (10^3 mol d^{-1})			
	DIP	DOP	DIN	DON	DIP	DOP	DIN	DON	DIP	DOP	DIN	DON
Aug-99	4.1	2.3	17	6	0.3	0.3	1	3	2.8	2.7	13	17
Oct-99	4.1	2.3	17	6	0.3	0.4	1	2	2.0	3.0	11	5
Dec-99	4.1	2.3	17	6	0.2	0.1	1	3	1.8	0.2	9	20
Feb-00	4.1	2.3	17	6	0.4	0.1	1	3	5.6	0.1	21	32
Mean (10^3mol d^{-1})	4.1	2.3	17	6	0.3	0.2	1	3	3.1	1.5	14	18
Mean (10^6mol y^{-1})	1.5	0.8	6	2	0.1	0.07	0	1	1.1	0.5	5	7

The annual nonconservative flux of DIP (*ΔDIP*) is a mean value of time-weighed *ΔDIP* from the dry season (August 1999) and the wet season (October 1999, December 1999 and February 2000). The *ΔDIP* in the bay is -0.2 mmol m^{-2} d^{-1} which is equivalent to -0.06 mol m^{-2} yr^{-1}, indicating that the system is a sink for DIP. Nonconservative flux of total dissolved P (*ΔDIP +ΔDOP*) is -0.08 mol m^{-2} yr^{-1}, also indicating that the system is a sink for total dissolved phosphorus (TDP).

Table 7.13. Nonconservative fluxes and budgets of C-N-P in Tapong Bay.

Time	*ΔDIP* (10^3 mol d^{-1})	*ΔDOP* (10^3 mol d^{-1})	*ΔDIN* (10^3 mol d^{-1})	*ΔDON* (10^3 mol d^{-1})	***(p-r)*** (10^3 mol d^{-1})	***(nfix-denit)*** (10^3 mol d^{-1})
Aug-99	-1.0	+0.7	-3	+14	+106	+16

Oct-99	-1.8	+1.1	-5	+1	+191	+7
Dec-99	-2.1	-2.0	-7	+17	+223	+77
Feb-00	+1.9	-2.1	+5	+29	-201	+37
Mean (10^3 mol d^{-1})	-0.8	-0.3	-2	+15	+84	+31
Mean (10^6 mol yr^{-1})	-0.3	-0.1	-0.7	+6	+31	+11

N balance

Nonconservative fluxes of DIN (*ΔDIN*) are estimated by a similar method as for *ΔDIP*, except that data for DIN in rainwater is available and included in *ΔDIN* calculations. *ΔDIN* is about -0.4 mmole m^{-2} d^{-1} that is equivalent to -0.1 mol m^{-2} yr^{-1} indicating that the system is a sink for DIN. However, *ΔDON* is positive with a rate of +1.1 mol m^{-2} yr^{-1}, which result in a positive rate (+1.0 mole m^{-2} yr^{-1}) for TDN. The system is a substantial source for TDN.

Stoichiometric calculations of aspects of net system metabolism

Net ecosystem metabolism is the difference between primary production and respiration (*p-r*), which is estimated from the negative of *ΔDIP* multiplied by the C:P ratio of particulate organic matter (POM). The C:P ratio of POM is assumed to be 106:1 as plankton metabolism dominates the net ecosystem metabolism. Thus:

$$(p\text{-}r) = -106 \times \Delta DIP = -106 \times (-0.06 \text{ mol m}^{-2} \text{ yr}^{-1}) = +6 \text{ mol m}^{-2} \text{ yr}^{-1}.$$

It appears that annual production is greater than annual respiration extrapolated over the study period. This value is smaller than that found in Chiku Lagoon.

Table 7.14. Nonconservative fluxes and budgets of C-N-P in Tapong Bay.

Time	***ΔDIP*** (mmol $m^{-2}d^{-1}$)	***ΔDOP*** (mmol $m^{-2}d^{-1}$)	***ΔDIN*** (mmol $m^{-2}d^{-1}$)	***ΔDON*** (mmol $m^{-2}d^{-1}$)	**(*p-r*)** (mmol $m^{-2}d^{-1}$)	**(*nfix-denit*)** (mmol $m^{-2}d^{-1}$)
Aug-99	-0.2	+0.1	-0.6	+2.8	+21	+3
Oct-99	-0.4	+0.2	-1.0	+0.2	+38	+1
Dec-99	-0.4	-0.4	-1.4	+3.4	+45	+15
Feb-00	+0.4	-0.4	+1.0	+5.8	-40	+7
Mean (mmol m^{-2} d^{-1})	-0.2	-0.1	-0.4	+3.0	+17	+6
Mean (mol m^{-2} yr^{-1})	-0.06	-0.02	-0.1	+1.1	+6	+2
Lagoon area: 5 km^2						
Lagoon volume: 12×10^6 m^3						

Net nitrogen fixation or denitrification (*nfix- denit*) is calculated from the difference between observed and expected ΔN. The expected ΔN is ΔP multiplied by N:P ratio of particulate organic matter. Particulate N:P ratio is assumed to be 16. Thus:

$$(nfix\text{-}denit) = 1.0 \text{ mol m}^{-2} \text{ yr}^{-1} - (-0.08\text{x}16) \text{ mol m}^{-2} \text{ yr}^{-1} = +2 \text{ mol m}^{-2} \text{ yr}^{-1}$$

The system is apparently more active in nitrogen fixation than in denitrification with a net rate at +2 mole m^{-2} yr^{-1}. This value is generally in the range reported previously from the Asian regions (Dupra *et al.* 2000).

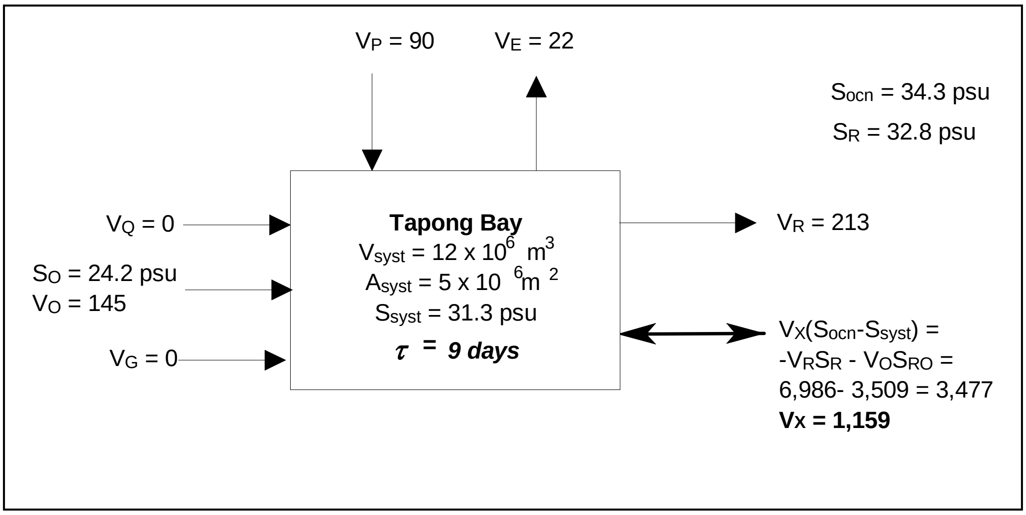


Figure 7.6. Water and salt balance for Tapong Bay during August 1999. Water flux in 10^3 m^3 d^{-1} and salt flux in 10^3 psu-m^3 d^{-1}.

7.4 Tsengwen River estuary

Jia-Jang Hung

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

The Tsengwen River estuary (Figure 7.7) is located on the south-western coast of Taiwan (23.05°N, 120.15°E). The river drains a watershed of suburban, rural and agricultural land with a total area of 1,177 km^2 (Water Resources Planning Commission 1995). The river empties into the Taiwan Strait. The estuarine zone, defined in this study as waters with salinity greater than 0.2 psu, ranges approximately 10 km to 25 km from the river mouth, depending on river discharge. Therefore, the estuarine area ranges from 2 km^2 in the flood season, 3 km^2 in the wet season to 4 km^2 in the dry season. The average annual rainfall for the drainage basin is 2,643 mm with a contrasting rainfall pattern between the dry (low) and wet (high) seasons. As a result, river discharge varies seasonally, with high discharge during the wet season (May–September, $V_Q = 411x10^3\ m^3\ d^{-1}$) and low discharge during the dry season (October–April, $V_Q = 14x10^3\ m^3\ d^{-1}$). During the wet season, episodic floods caused from heavy monsoon rain and typhoons are not unusual and critically influence water discharge and suspended load. The contribution of groundwater to total freshwater discharge is negligible, as groundwater is usually over-extracted in the area. Anthropogenic inputs to the estuary are assumed to be delivered mainly through the river.

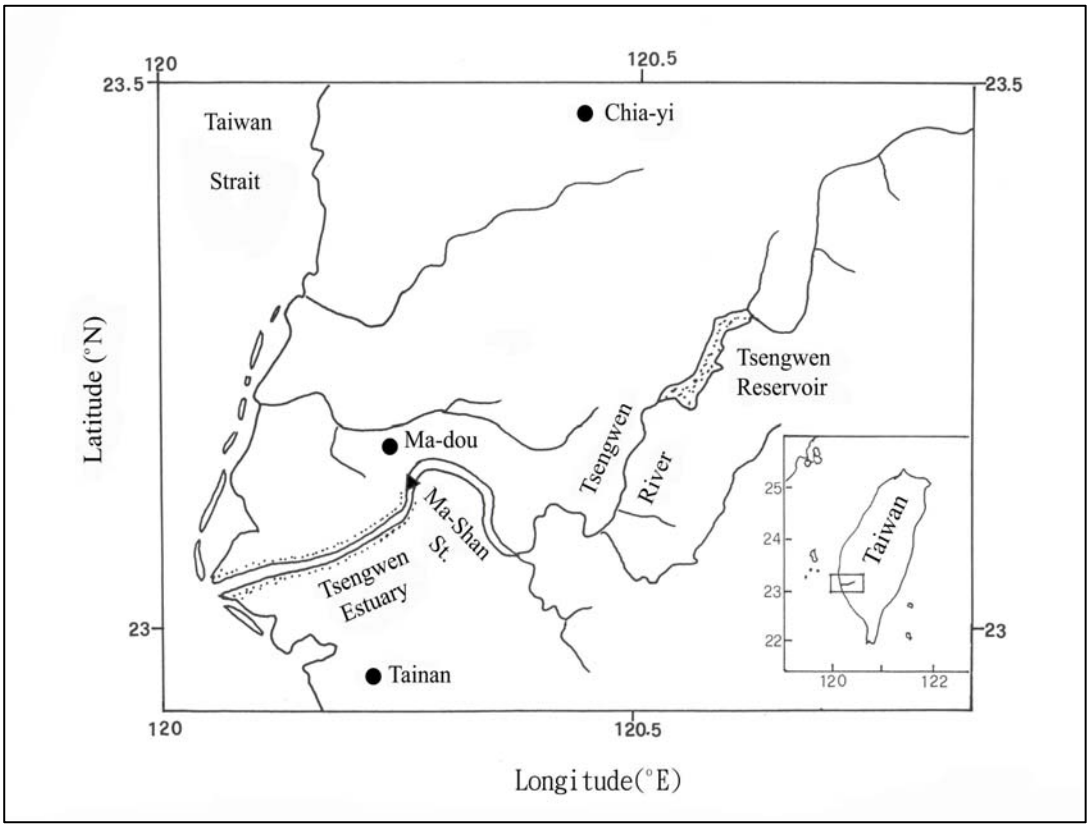


Figure 7.7. Map and location of Tsengwen River estuary.

Water and salt balance

Water and salt budgets were constructed on the basis of data collected from the estuary during dry, wet and flood seasons. A steady-state single box model (Gordon *et al*. 1996) was used for modelling water and salt balance. Table 7.15 illustrates the distributions of salinity and nutrients in riverine, estuarine and oceanic waters.

Table 7.15. Distributions of salinity and nutrients in riverine, estuarine and ocean waters of the Tsengwen River.

	Dry season	**Flood season**	**Wet season**
Salinity (psu)			
River	0	0	0
Estuary	18.6	13.6	16.9
Ocean	33.7	30.8	32.0
DIP (μM)			
River	1.7	1.9	1.7
Estuary	0.7	0.7	0.7
Ocean	0.4	0.4	0.4
DOP (μM)			
River	2.9	2.3	2.6
Estuary	1.0	1.7	1.3
Ocean	0.7	0.7	0.7
DIN (μM)			
River	86	150	85
Estuary	90	67	32
Ocean	2.2	2.7	2.2
DON (μM)			
River	96	62	74
Estuary	37	29	34
Ocean	12	12	12

Table 7.16 lists water and nutrient budgets during three seasons. Rates of total freshwater input, residual flow and exchange flow are lowest during the dry season, highest during the flood season and intermediate during the wet season. Total freshwater input is about $14 x 10^3$ m^3 d^{-1} for the dry season, $411 x 10^3$ m^3 d^{-1} for the wet season and $1{,}957 x 10^3$ m^3 d^{-1} for the flood season. The exchange flows are proportional to the total freshwater inputs (residual flows), and are about $24 x 10^3$ m^3 d^{-1} for the dry season, $668 x 10^3$ m^3 d^{-1} for the wet season and $2{,}526 x 10^3$ m^3 d^{-1} for the flood period. Exchange time of estuarine water is about 184 days for the dry season, 6 days for the wet season and 1 day for the flood period.

Because of the very rapid water exchange time during the flood period, a budget for the flood period is not included in estimating the annual budget. It is not possible to calculate the nonconservative fluxes of nutrients reliably when water exchange time is very short.

Budgets of nonconservative materials

Table 7.16 summarizes the DIP, DOP, DIN and DON budgets for the Tsengwen River estuary.

Table 7.16. Water, nitrogen and phosphorus budgets in the Tsengwen River estuary during 1995.

	Dry season (210 days)	**Flood season** (15 days)	**Wet season** (135 days)
Estuarine area (10^6 m^2)	4	2	3
Estuarine volume (10^6 m^3)	7	5	6
V_Q (runoff) 10^3 m^3 d^{-1}	14	1,957	411
V_R (residual flow) 10^3 m^3 d^{-1}	-14	-1,957	-411
V_X (exchange flow) 10^3 m^3 d^{-1}	24	2,523	668
ΔDIP (mmol m^{-2} d^{-1})	-0.002	-0.9	-0.1
ΔDOP (mmol m^{-2} d^{-1})	-0.006	+0.2	-0.1
ΔDIN (mmol m^{-2} d^{-1})	+0.4	-31	-2.7
ΔDON (mmol m^{-2} d^{-1})	-0.1	-19	-2.1
(*p-r*) (ΔDIC_O) (mmol m^{-2} d^{-1})	+0.2	-	+11
(*nfix-denit*) (mmol m^{-2} d^{-1})	+0.4	-	-1.6

P balance

Nonconservative flux of DIP (*ΔDIP*) for the estuary is negative, -0.002 mmol m^{-2} d^{-1} in the dry season, -0.1 mmol m^{-2} d^{-1} in the wet season and -0.9 mmol m^{-2} d^{-1} in the flood period. The annual nonconservative flux is estimated to be about -0.01 mol m^{-2} yr^{-1} for DIP and about -0.01 mol m^{-2} yr^{-1} for DOP (Table 7.16) in 1995. These annual budgets do not include *ΔDIP* and *ΔDOP* in the flood period because both *ΔDIP* and *ΔDOP* in the flood period may be simply resulted from geochemical processes due to very high turbidity and very short exchange time of estuarine water. The estuary appears to be a sink for DIP and DOP. Nonconservative fluxes of DIP and DOP in 1996 (Table 7.17) are derived from measured riverine fluxes in 1996 and estuarine removal rates found in 1995. Nonconservative fluxes of DIP and DOP appear to be larger in 1996 than in 1995, which may result from an El Nino influence on 1996.

Table 7.17. Average annual nonconservative fluxes and CNP budgets in the Tsengwen River estuary, scaled up from seasonal measurements in 1995.

Variable	Mean flux (mol m^{-2} yr^{-1})
ΔDIP (1995)	-0.01

ΔDOP (1995)	-0.01
ΔDIP (1996)	-0.06
ΔDOP (1996)	-0.03
$(p\text{-}r)_{1995}$ (particulate C/P=106)	+1
$(p\text{-}r)_{1996}$ (particulate C/P=106)	+6
(nfix-denit) (1995, particulate N/P = 16)	-0.3
(nfix-denit) (1996, particulate N/P = 16)	-1
[(*p-r*); (*nfix-denit*)] Tomales Bay (USA)[a]	[-6.06; -1.42]
[(*p-r*); (*nfix-denit*)] Hakata Bay (Japan)[b]	[+10.1; -0.27]
[(*p-r*); (*nfix-denit*)] Spencer Gulf (Australia)[c]	[+0.5; +0.07]
[(*p-r*); (*nfix-denit*)] Lingayen Gulf (Philippines)[d]	[+6; +0.5]
[(*p-r*); (*nfix-denit*)] Manila Bay (Philippines)[d]	[-2; -1.13]

a. Smith *et al*. 1991; b. Yanagi 1999; c. Gordon *et al*. 1996; d. Dupra *et al*. 2000.

N balance

Using a similar calculation as for ΔDIP and ΔDOP, nonconservative fluxes of DIN (ΔDIN) and DON (ΔDON) in 1995 are -0.3 and -0.3 mol m^{-2} yr^{-1}, respectively. This indicates that the system is a sink for DIN and TDN.

Stoichiometric calculations of aspects of net system metabolism

The net ecosystem metabolism (NEM, [*p-r*]) is estimated from ΔDIP and C:P ratio in particulate organic matter. The Redfield ratio of C:P (106) is applied for stoichiometric calculation as planktons are primary producers in the estuary. Thus,

$$(p\text{-}r) = -106 \text{ x } \Delta DIP = -106 \text{ x } (-0.01 \text{ mol m}^{-2} \text{ yr}^{-1}) = +1 \text{ mol m}^{-2} \text{ yr}^{-1}$$

This shows that the Tsengwen River estuary is an autotrophic system. The net carbon production is about 1mol m^{-2} yr^{-1}. Meanwhile, the (*p-r*) in 1996 is estimated to be about +6 mol m^{-2} yr^{-1} if the same estuarine removal rates as for 1995 are used for budget calculation. The estuary was autotrophic in both 1995 and 1996, with higher autotrophy in 1996 than in 1995. The increased DIP flux in 1996 is caused primarily from increased river discharge and probably comes from diffuse sources within the watershed.

The net nitrogen fixation or denitrification (*nfix-denit*) is calculated from the difference between observed and expected ΔN. Expected ΔN is ΔP multiplied by the N:P ratio of particulate organic matter. The Redfield N:P ratio (16) is used for calculation. Thus,

$$(nfix\text{-}denit) = -0.6 \text{ mol m}^{-2} \text{ yr}^{-1} - (-0.02 \text{ mol m}^{-2} \text{ yr}^{-1} \text{ x } 16) = -0.3 \text{ mol m}^{-2} \text{ yr}^{-1}$$

This result indicates that the Tsengwen River estuary is denitrifying at a rate of -0.3 mol m^{-2} yr^{-1} in 1995. The net denitrification rate is larger in 1996 than in 1995 (Table 7.16), probably resulting from a larger nitrogen source in 1996. Nevertheless, the magnitudes of (*p-r*) and (*nfix-denit*) are in the range reported from the Asian region (Table 7.17).

8. BUDGETS FOR ESTUARIES IN VIETNAM

8.1 PhanThiet Bay

Nguyen Huu Huan, Bui Hong Long and Phan Minh Thu

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

PhanThiet Bay is located between 10.7° and 10.9°N, and 108.0° and 108.3°E, near the center of upwelling waters in the south of Vietnam (Figure 8.1). It has an area of about 370 km^2 and a total volume of about 5,500x10^6 m^3 (Vo Van Lanh 1996; Bui Hong Long 1999). The bay has a maximum depth of 25 m with an average depth of about 15 m. The area has a tropical monsoon weather regime, with two seasons: the wet season from June to November (maximum precipitation in July and October) and the dry season from December to May. The annual average range of precipitation is between 1,000 to 1,300 mm; with about 90% falling during the wet season. Annual evaporation is relatively high, about 2,200 mm, of which about 5 mm d^{-1} occurs in the wet season and about 7 mm d^{-1} in the dry season (Meteorological and Hydrographical Station of Southern Center 1996).

There are two main river systems flowing into PhanThiet Bay: the Cai and CaTy Rivers. From the Cai River, the annual average discharge of water is about 3,300x10^6 m^3 of which 8x10^6 m^3 d^{-1} flows in the wet season and 2x10^6 m^3 d^{-1} in the dry season. From the CaTy River, the annual average river discharge is about 3,700x10^6 m^3 of which 9x10^6 m^3 d^{-1} flows in the wet season and 1x10^6 m^3 d^{-1} in the dry season (Meteorological and Hydrographical Station of Southern Center 1996).

The population in the PhanThiet Bay region is about 403,000, involved mainly in agriculture and fishing (Bui Hong Long 1999).

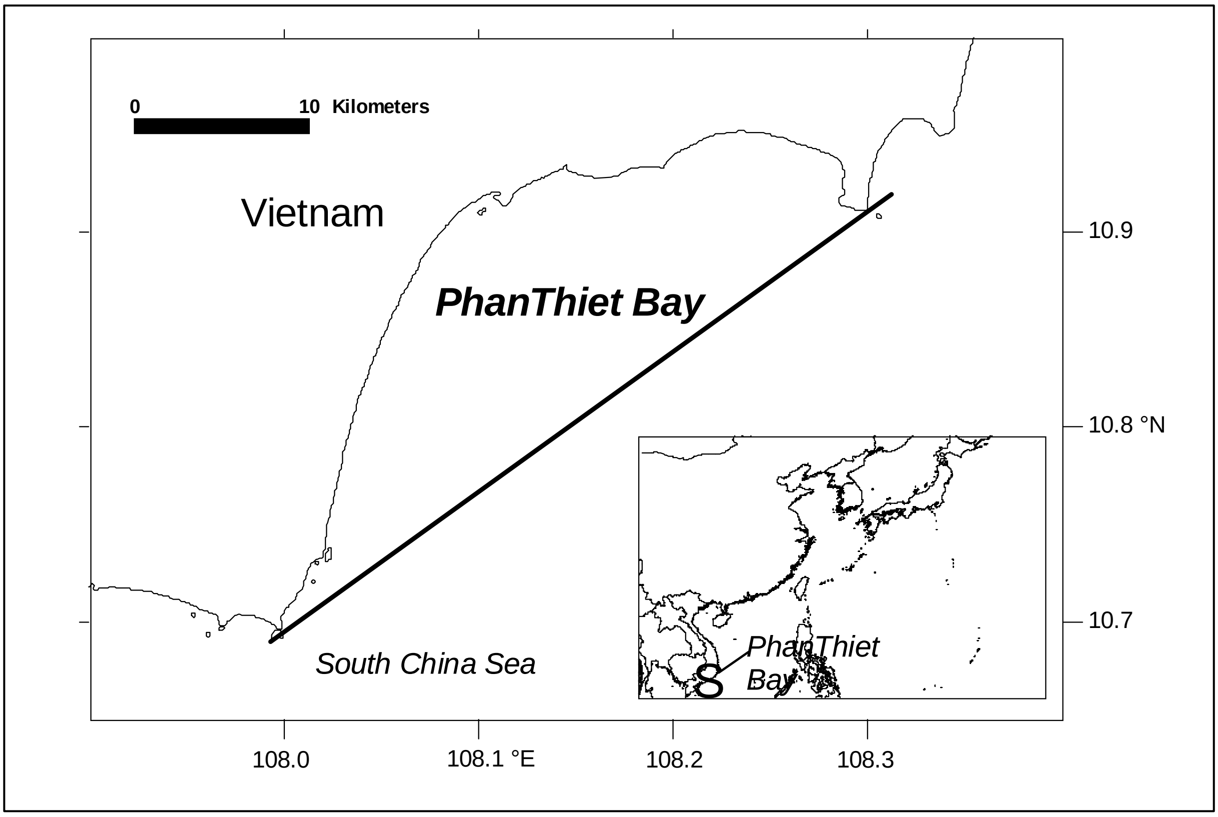


Figure 8.1. Map and location of PhanThiet Bay. The solid bar shows the boundary of the budgeted area of the bay.

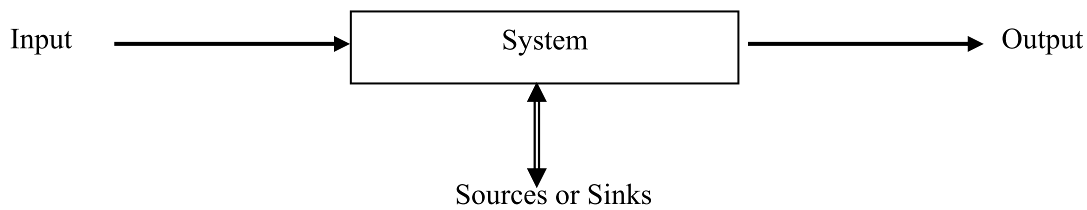
This paper presents the budgets for PhanThiet Bay using the LOICZ Biogeochemical Modelling Guidelines (Gordon *et al*. 1996) and using data of water, salt and nutrients collected during 1998 and 1999 (Tables 8.1 and 8.2). The budgeted area of PhanThiet Bay is shown in Figure 8.1.

Table 8.1. Water fluxes for PhanThiet Bay.

Water flux	Dry season (10^6 m^3 d^{-1})	Wet season (10^6 m^3 d^{-1})
V_P	0.3	2
V_E	3	2
V_O	≈ 0 (assumed)	≈ 0 (assumed)
V_G	≈ 0 (assumed)	≈ 0 (assumed)
V_Q	3	17
V_R	0.3	17
V_X	100	912

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

The conceptual model for transport of materials in a system is:



We can describe that process by:

$$\frac{dM}{dt} = \sum input - \sum Output + \sum (Sources - Sinks) \qquad (1)$$

Where: *dM/dt* is a change of mass of material of interest. Assuming that the system of interest is at steady state (*dM/dt = 0*), water and salt budgets for PhanThiet Bay are presented in Figures 8.2 and 8.3 for the dry and wet seasons, respectively.

The water exchange time in the system (τ) can be calculated as the total water volume of the system (V_{syst}) divided by the sum of the absolute value of residual flow ($|V_R|$) and mixing volume (V_X). Thus, in the dry season:
$\tau_{dry} = V_{Syst.}/(|V_{R1}| + V_{X1}) = [5{,}500 \times 10^6]/[100 \times 10^6] = 55$ days.

Similarly, in the wet season:
$\tau_{wet} = V_{Syst.}/(|V_{R2}| + V_{X2}) = [5{,}500 \times 10^6]/[929 \times 10^6] = 6$ days.

<u>*Budgets for nonconservative materials*</u>
The data collected for phosphorus (P) and nitrogen (N) are shown in Table 8.2. Note that sources of DIP and DIN from human sewage (also called other sources) are calculated using a C:N:P ratio of 95:15:1 in domestic waste: DIP/TP ≈ 0.5; DIN/TN ≈ 0.5 (Jacinto *et al*. 1998) and using the WHO estimate of 20 kg per person per year BOD (Economopoulos 1993). It was assumed that the same amount of nutrients from waste reached the system for both seasons.

Table 8.2. The nutrient concentrations for water fluxes in PhanThiet Bay.

Sources	Seasons	Dry (µM)	Wet (µM)
Runoff	DIP	0.3	0.2
	DIN	8.2	18.1
System	DIP	0.4	0.3
	DIN	7.8	6.3
Ocean	DIP	0.2	0.2
	DIN	7.2	9.9

The calculated fluxes for the nonconservative materials are shown in Figures 8.3 – 8.7. The system is a net source for DIP and a net sink for DIN for both seasons.

Stoichiometric calculation of aspects of net system metabolism

The nutrient budgets can be used to estimate values of (*p-r*) and (*nfix-denit*). Net ecosystem metabolism (*p-r*) is estimated from *ΔDIP* and the ratio of C:P as follow:

$$(p - r) = - \Delta DIP \times (C:P)_{part} \quad (2)$$

using $(C:P)_{part}$ is (106:1) using the Redfield ratio for phytoplankton.

The estimated results are presented in Table 8.3. Table 8.3 shows *ΔDIP* = $+8 \times 10^3$ mol d^{-1} or +0.02 mmol m^{-2} d^{-1} in the dry season and *ΔDIP* = $+81 \times 10^3$ mol d^{-1} or + 0.2 mmol m^{-2} d^{-1} in the rainy season. From equation (2), (*p-r*) is -848×10^3 mole C d^{-1} or -2 mmol C m^{-2} d^{-1} in the dry season, and about -8,586 mmol C d^{-1} or -23 mmol C m^{-2} d^{-1} in the rainy season. The system is heterotrophic for both seasons.

Table 8.3. Net ecosystem metabolizm (NEM) for PhanThiet Bay.

Seasons	***ΔDIP***		**NEM (*p-r*)**	
	10^3 mol P d^{-1}	mmol P m^{-2} d^{-1}	10^3 mol C d^{-1}	mmol C m^{-2} d^{-1}
Dry	+8	+0.02	-848	-2
Wet	+81	+0.22	-8,586	-23
Annual	+45	+0.12	-4,717	-13

The difference between nitrogen fixation and denitrification (*nfix-denit*) is estimated from the difference between the observed value of *ΔDIN* and that of expected *ΔDIN*. That is:

$$(nfix\text{-}denit) = \Delta DIN_{obs} - \Delta DIN_{exp} = \Delta DIN_{obs} - \Delta DIP \times (N:P)_{part} \quad (3)$$

using $(N:P)_{part}$ ratio is 16:1 (Redfield ratio). The estimated results are presented in Table 8.4.

Table 8.4. The estimated value of (*nfix-denit*) for PhanThiet Bay.

Seasons	***ΔDIN**$_{obs}$*		***ΔDIN**$_{exp}$*		**(*nfix - denit*)**	
	10^3 mol N day^{-1}	mmol N m^{-2} day^{-1}	10^3 mol N day^{-1}	mmol N m^{-2} day^{-1}	10^3 mol N day^{-1}	mmol N m^{-2} day^{-1}
Dry	-120	- 0.3	+128	+ 0.3	-248	- 0.7
Wet	-3,610	-9.8	+1,296	+ 3.5	-4,906	-13.3
Annual	-1865	-5.1	+712	+1.9	-2,577	-7.0

These results indicate that the system is net denitrifying in the both seasons at a net rate of about -258x10^3 mol N d^{-1}or -0.7 mmol N m^{-2} d^{-1} in the dry season and about -4,914x10^3 mol N d^{-1} or -13.3 mmol N m^{-2} d^{-1} in the rainy season.

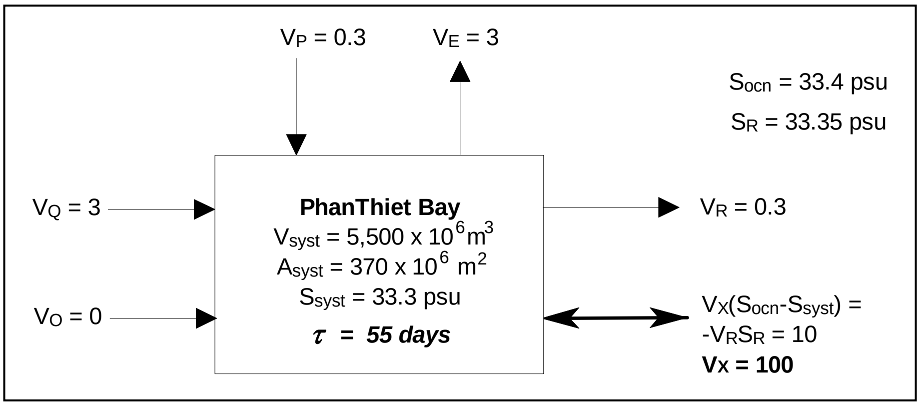


Figure 8.2. Water and salt budgets for PhanThiet Bay in the dry season. Water flux in 10^6 m^3 d^{-1} and salt flux in 10^6 psu-m^3 d^{-1}.

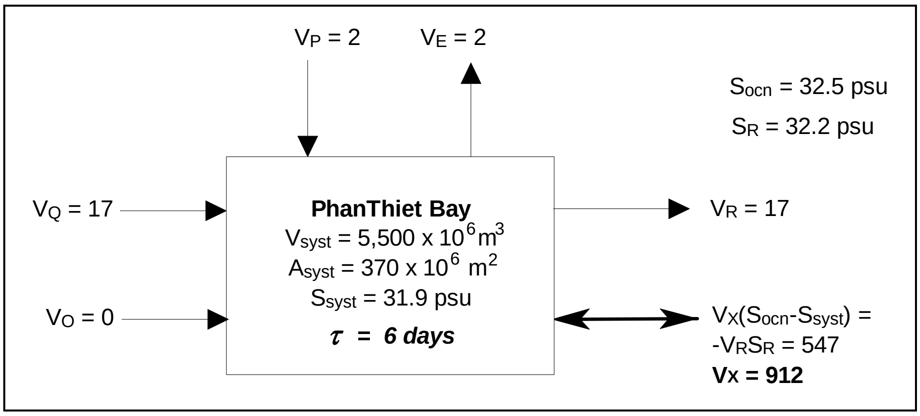


Figure 8.3. Water and salt budgets for PhanThiet Bay in the wet season. Water flux in 10^6 m^3 d^{-1} and salt flux in 10^6 psu-m^3 d^{-1}.

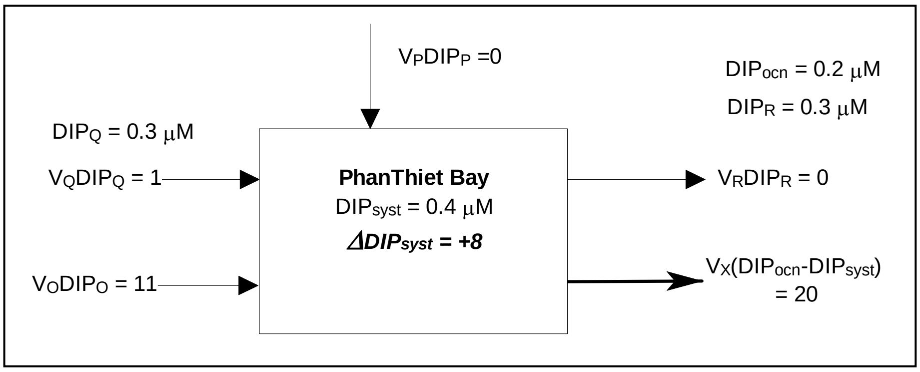


Figure 8.4. Dissolved inorganic phosphorus (DIP) budget for PhanThiet Bay in the dry season. Flux in 10^3 mol d^{-1}.

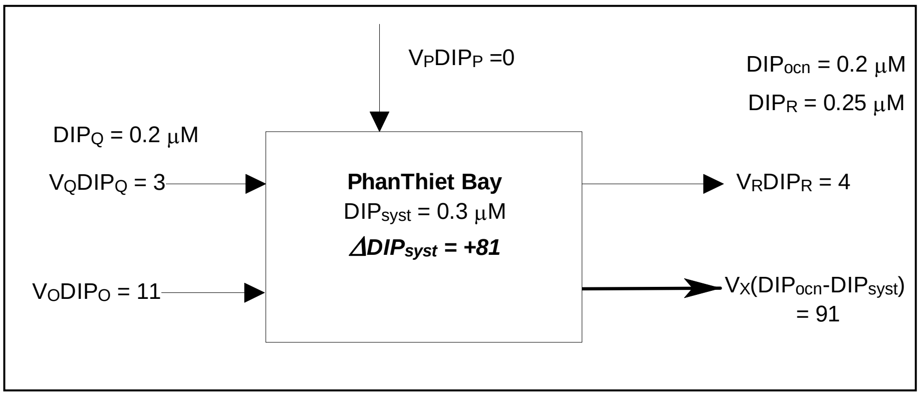


Figure 8.5. Dissolved inorganic phosphorus (DIP) budget for PhanThiet Bay in the wet season. Flux in 10^3 mol d^{-1}.

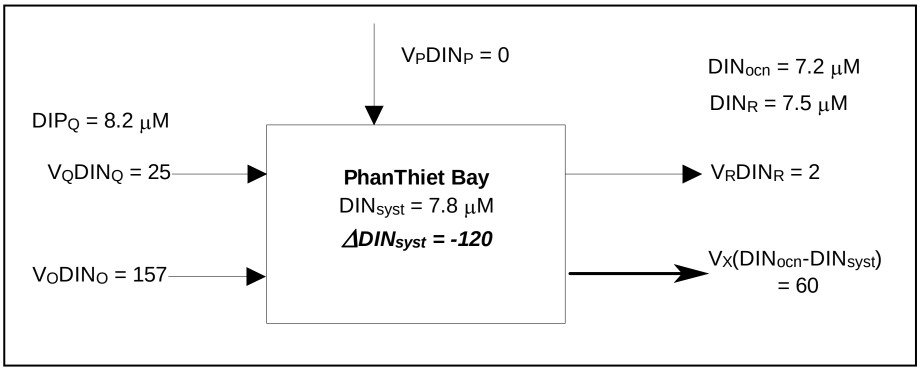


Figure 8.6. Dissolved inorganic nitrogen (DIN) budget for PhanThiet Bay in the dry season. Flux in 10^3 mol d^{-1}.

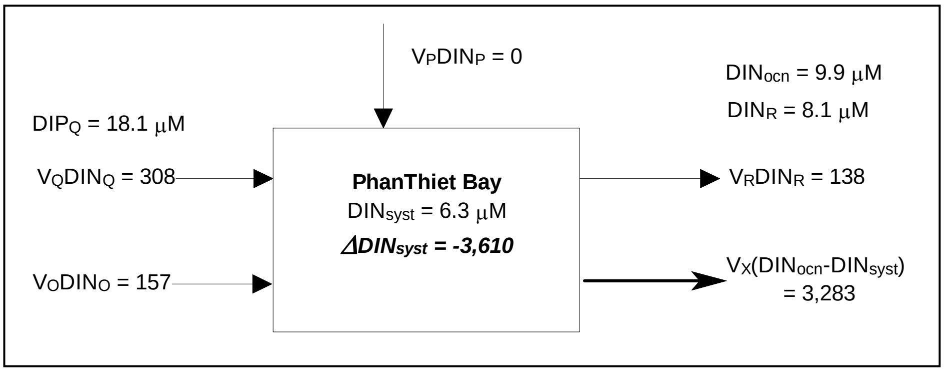


Figure 8.7. Dissolved inorganic nitrogen (DON) budget for PhanThiet Bay in the wet season. Flux in 10^3 mol d^{-1}.

8.2 ThuBon River estuary

Nguyen Huu Huan

Study area description

The ThuBon River system rises in mountains reaching an elevation of over 1,500 m in KonTum Province. The river is about 200 km from its source to its mouth at HoiAn in QuangNam Province (15.88°N,108.8°E, Figure 8.8). The catchment area (from GiaoThuy a distance of 30 km to HoiAn) is about 3,800 km^2. The ThuBon River flows through KonTum Province for about 38 km with a catchment area of about 500 km^2. There are three main tributaries: Tranh River (length 130 km, catchment area about 1,640 km^2), Khang River (length 100 km, catchment area about 790 km^2) and Truong River (length 30 km, catchment area about 450 km^2) (Tran Dinh Hung 1995).

The boundary of the budgeted area is shown in Figure 8.8. The water area is about 12 km^2. The average depth is about 9 m in the rainy season and 4 m in the dry season with water volume of about 110×10^6 m^3 and 50×10^6 m^3, respectively (Nguyen Tac An 1995). The system flows through many inhabited and agricultural areas.

Located in the monsoon tropical semi-equatorial climate zone, the ThuBon River region experiences two seasons: the wet season (August to December) and the dry season (January to July). Average precipitation is about 14 mm d^{-1} in the wet season and 2 mm d^{-1} in the dry season. Average evaporation is about 3 mm d^{-1} and 4 mm d^{-1} for wet and dry seasons, respectively (Pham Ngoc Toan and Phan Tat Dac 1975; Tran Dinh Hung 1995).

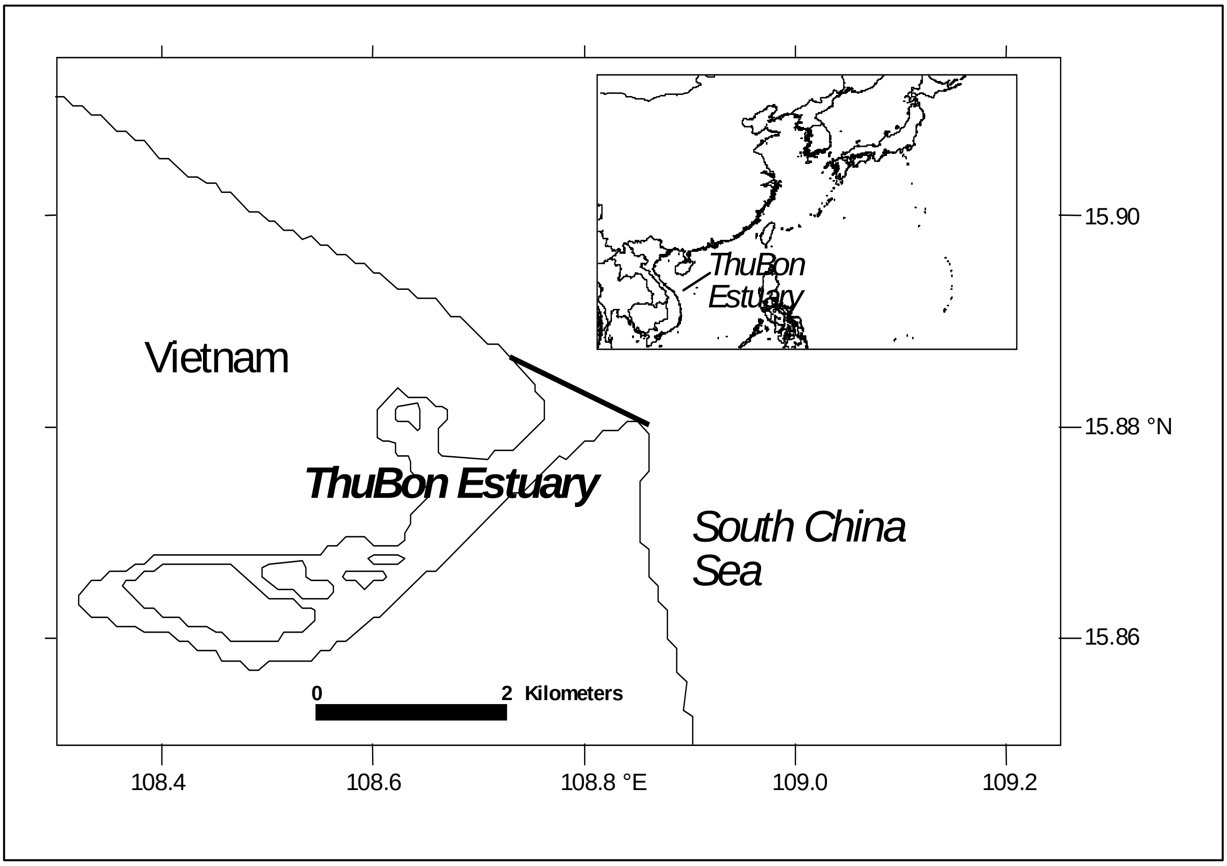


Figure 8.8. Map of the ThuBon River estuary. The solid bar shows the boundary of the budgeted area.

Collected data (from a project studying pollution derived from rivers) in March 1995 were used to budget N and P fluxes applying the LOICZ Biogeochemical Modelling Guidelines (Gordon *et al*. 1996). The mass balance budgets and stoichiometric calculations of aspects of net system metabolism are presented in this report.

Water and salt balance

The salinity data illustrate that the ThuBon River estuary is not vertically homogeneous, but instead has a two-layer flow. Pritchard (1969) developed a model for transport in such a two-layer system that allowed for the estimation of entrainment and mixing between the layers from conservation of salt and water (Webster *et al*. 1999). For budget calculations, the two-layer estuary concept was used, as shown in schematic form in Figure 8.9.

Exchange between the upper and lower layers occurs through the entrainment term $V_{deep}Y_{syst-d}$ and through the mixing term $V_Z(Y_{syst-d}-Y_{syst-s})$. Y_{syst-s} and $Y_{systs-d}$ are the concentrations in the upper and lower layers, respectively. Net freshwater discharge into the upper layer is expressed as $V_{R'}$. At steady state, the water balance is expressed as:

$$V_{R'} + V_{surf} + V_{deep} = 0 \qquad (1)$$

Where V_{surf} is surface flow, which is the outflow from the upper layer and V_{deep} is the inflow to the lower layer. We define material flows into an estuary compartment as positive.

The material budgets for the upper and lower layers are:

$$Y_{R'}V_{R'} + V_{surf}Y_{syst-s} + V_{deep}Y_{syst-d} + V_Z(Y_{syst-d} - Y_{syst-s}) + \Delta Y_{syst-s} = 0 \qquad (2)$$

$$V_{deep}Y_{syst-d} - V_{deep}Y_{syst-d} - V_Z(Y_{syst-d} - Y_{syst-s}) + \Delta Y_{syst-d} = 0 \qquad (3)$$

Adding equations 2 and 3 and using equation 1 to eliminate $V_{deep'}$, we obtain:

$$V_{R'}Y_{R'} + V_{surf}Y_{syst-s} + V_{deep}Y_{ocn-d} + \Delta Y_{syst-s} + \Delta Y_{syst-d} = 0 \qquad (4)$$

The terms of ΔY_{syst-s} and ΔY_{syst-d} are net internal sources or sinks of the substance within the upper and lower layer, respectively. For salt balance, we set Y to be S, S_Q and $\Delta S = 0$. Solving Equation 4 for the advective out flow in the upper layer gives:

$$V_{surf} = V_{R'}(S_{syst-s})/(S_{ocn-d}-S_{syst-s}) \qquad (5)$$

Based on calculation above, and using collected data for March 1995 (Table 8.5), the budgets of water and salt for the ThuBon River estuary are showed in Figure 8.10.

Table 8.5. Water fluxes for the ThuBon River estuary in the dry season.

Factors	Upper layer	Lower layer
Precipitation (10^6 m^3 d^{-1})	0	≈ 0
Evaporation (10^6 m^3 d^{-1})	0	≈ 0
Runoff (10^6 m^3 d^{-1})	10	≈ 0
Groundwater, other sources	≈ 0 (assumed)	≈ 0

The water exchange time for the ThuBon River estuary in the dry season can be calculated by:

$$\tau = V_{syst}/V_{surf} \qquad (6)$$

which gives: $\tau = (50x10^6)/(173x10^6) \approx 4$ days. Thus, the water exchange time in ThuBon River estuary is very short.

DIP and DIN budgets

The average concentrations of inorganic nitrogen and phosphorus in the ThuBon River estuary for the dry season are shown in Table 8.6. N and P budgets are presented in Figures 8.11 and 8.12. Both ΔDIN and ΔDIP are negative. This denotes that the ThuBon River estuary is a net sink for both DIN and DIP in the dry season.

Table 8.6. DIN and DIP concentrations in ThuBon River estuary in the dry season.

Sources	DIP (µM)	DIN (µM)
Runoff	32.4	87.5
Precipitation	≈ 0 (assumed)	≈ 0 (assumed)
Evaporation	≈ 0 (assumed)	≈ 0 (assumed)
Ocean	0.1	19.6
System		
Upper	1.4	8.7
Lower	0.2	16.6

Stoichiometric calculation of aspects of net ecosystem metabolism

With the assumption that all the behavior of nonconservative materials is a result of biological processes, then the value of ΔDIP can be a measure of the net productivity of the system. The net ecosystem metabolism (NEM = [*p-r*]) is calculated as the negative ΔDIP multiplied by the C:P ratio of the reacting organic matter. Assuming that the bulk of the reacting organic matter is phytoplankton, the C:P ratio is 106:1. So,

$$(p\text{-}r) = -106 \times \Delta DIP \qquad (9)$$

For the ThuBon River estuary, the value of (*p-r*) is shown in Table 8.7. Calculated net metabolic rate for the system is very high, which indicates that processes other than biological dominate the system.

Table 8.7. Net ecosystem metabolizm (NEM or [*p-r*]) for the ThuBon River estuary in the dry season.

Areas	ΔDIP (10^3 mol P d^{-1})	(*p-r*) (10^3 mol C d^{-1})
Upper layer	- 307	+3,254
Lower layer	0	0
Whole system	- 307	+3,254

Based on the Redfield N:P ratio, ΔDIP_{exp} is 16 x ΔDIP. The ΔDIN estimated from the water and salt balances presents the ΔDIN_{obs}. Therefore, the difference between ΔDIP_{exp} and ΔDIN_{obs} represents the difference between nitrogen fixation and denitrification, that is:

$$(nfix - denit) = \Delta DIN_{obs} - \Delta DIP_{exp.} \qquad (7)$$

or: $(nfix - denit) = \Delta DIN_{obs} - \Delta DIP x(N:P)_{part}$ (8)

Results are presented in Table 8.8. These results indicate that the system is net nitrogen fixing in the dry season, (*nfix-denit*) = +342 mmole N $m^{-2} d^{-1}$).

Table 8.8. The estimated value of (*nfix-denit*) for the ThuBon River estuary in the dry season.

Areas	***ΔDIN$_{obs}$***	***ΔDIN$_{exp}$***	**(*nfix - denit*)**
	(10^3 mol N d^{-1})	(10^3 mol N d^{-1})	(10^3 mol N d^{-1})
Upper layer	-803	-4,912	+4109
Lower layer	-3	0	-3
Whole system	-806	-4,912	+4106

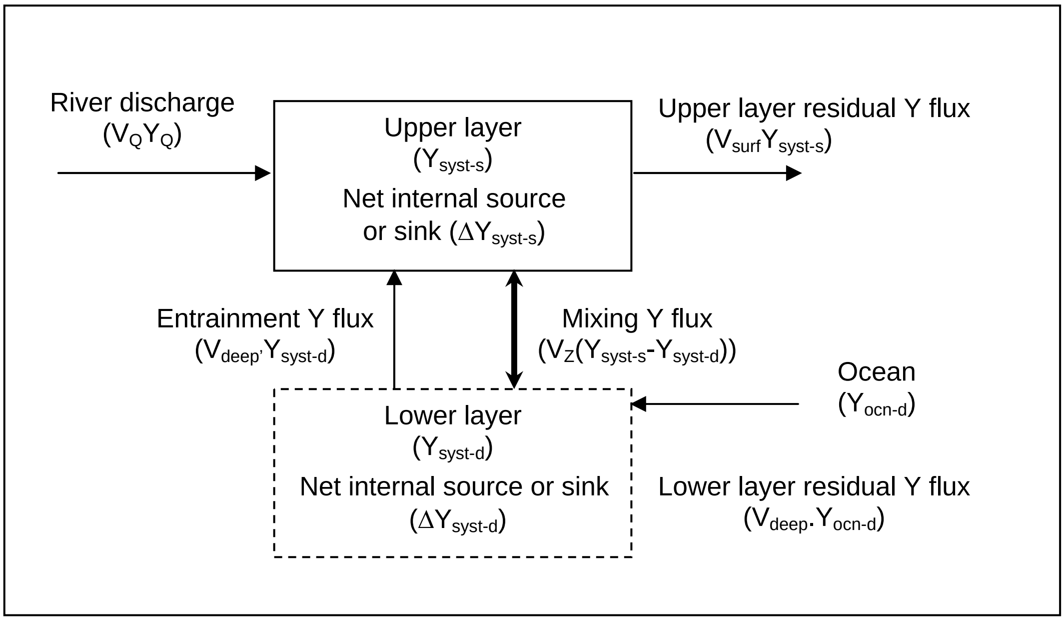


Figure 8.9. Schematic of a two-layer budget model.

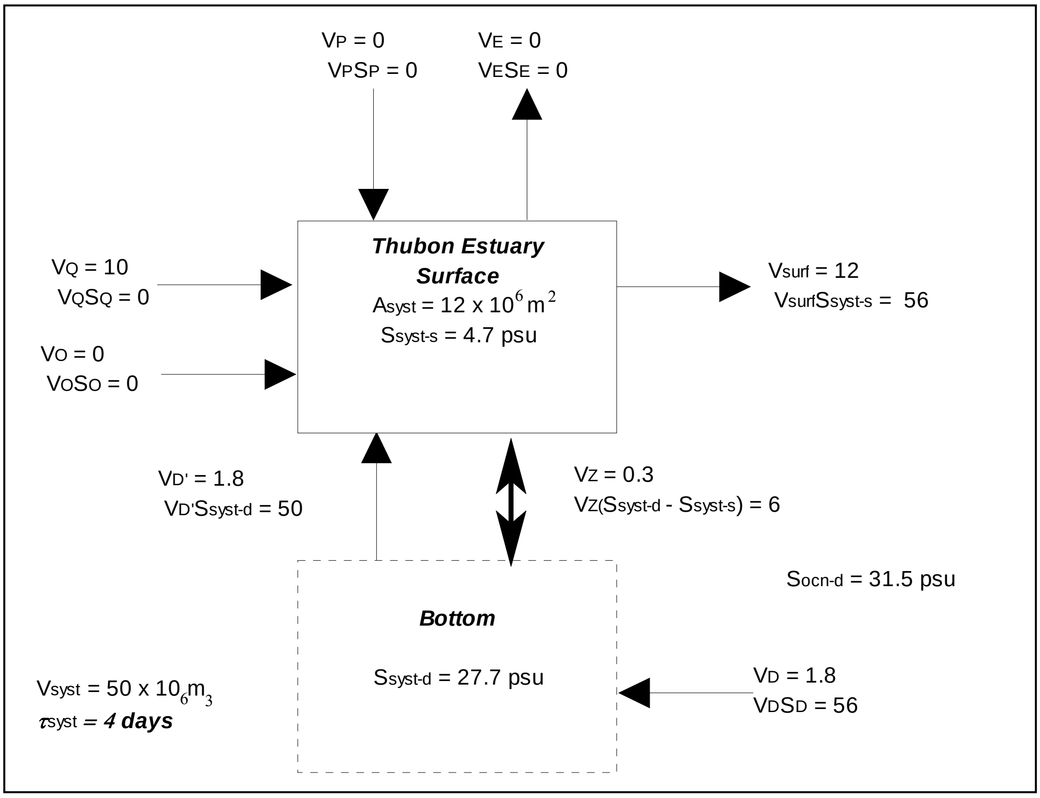


Figure 8.10. Two-layer water and salt budgets for the ThuBon River estuaries in the dry season. The box outlined with dashed lines represents lower layer of the system. Water flux in 10^6 m^3 d^{-1}, and salt flux in 10^6 psu-m^3 d^{-1}.

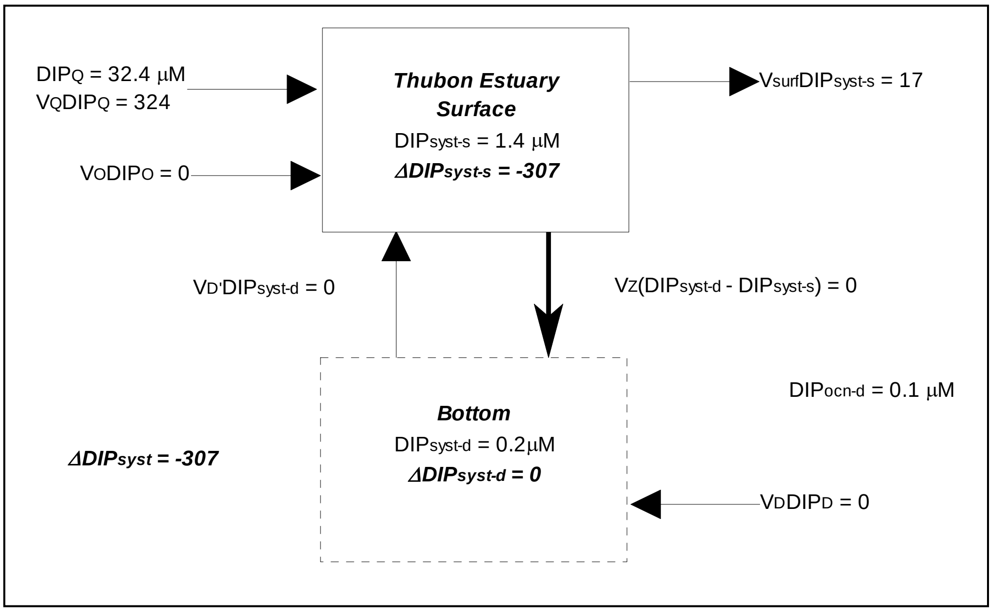


Figure 8.11. Two-layer dissolved inorganic phosphorus budget for the ThuBon River estuary in the dry season. The box outlined with dashed lines represents lower layer of the system. Flux in 10^3 mol d^{-1}.

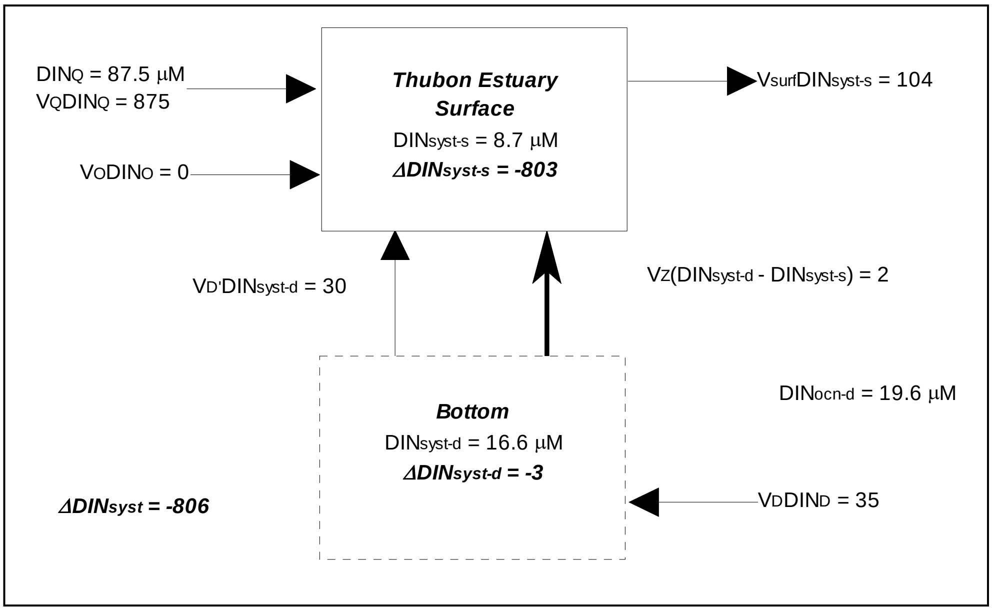


Figure 8.12. Two-layer dissolved inorganic nitrogen budget for the ThuBon River estuary for the dry season. The box outlined with dashed lines represents lower layer of the system. Flux in 10^3 mol d^{-1}.

8.3 Tien River Estuary, Mekong River Delta

Nguyen Huu Huan and Phan Minh Thu

Study area description

The Mekong River is one of the longest river system in the world with a length of about 4,000 km, running through 6 countries: China, Myanmar, Laos, Thailand, Cambodia and Vietnam. Hydrography in its lower basin is complicated. Water supplied by Boloven Rain Center (Laos) is 10% of the total water input into the river. The flow in 5 months of flood period reaches 75% of total annual flow. In the dry period, the hydrography of the river is affected by the BienHo and South China Seas (Nguyen Tac An 1997; To Van Truong 1997).

The Mekong River runs through Vietnam for a distance of more than 200 km and basin area of 45,000 km^2. The river divides into 2 branches: Tien and Hau. The Hau runs into the ocean through three estuaries: DinhAn, TranhDe and BatXac; the Tien runs into through six estuaries: Tieu, Dai, BaLai, HamLuong, CoChien and CungHau. The main water volume (over 79%) flows into the Tien River estuary. The Mekong Delta is a part of the basin of the Mekong River (Nguyen Tac An 1997).

The population density in the Mekong Delta is relatively high with an average of 400 inhabitants per km^2, which may reach as much as 1,000 inhabitants per km^2 in many villages along the main branches and canals of the delta. Most of sewage is discharged directly into the delta.

The Mekong Delta is a major agricultural region of Vietnam, where about 2,000-6,000 tonnes of chemical pesticides including organophosphate, carbonates, synthetic cyperthoids and even persistent organochlorine are now used annually in the cultivated fields. The use of pesticides significantly increases every year. Annually 500,000 - 800,000 tonnes of chemical fertilizers (phosphate and nitrate) are used, which represents a diffuse source of contaminants to the delta.

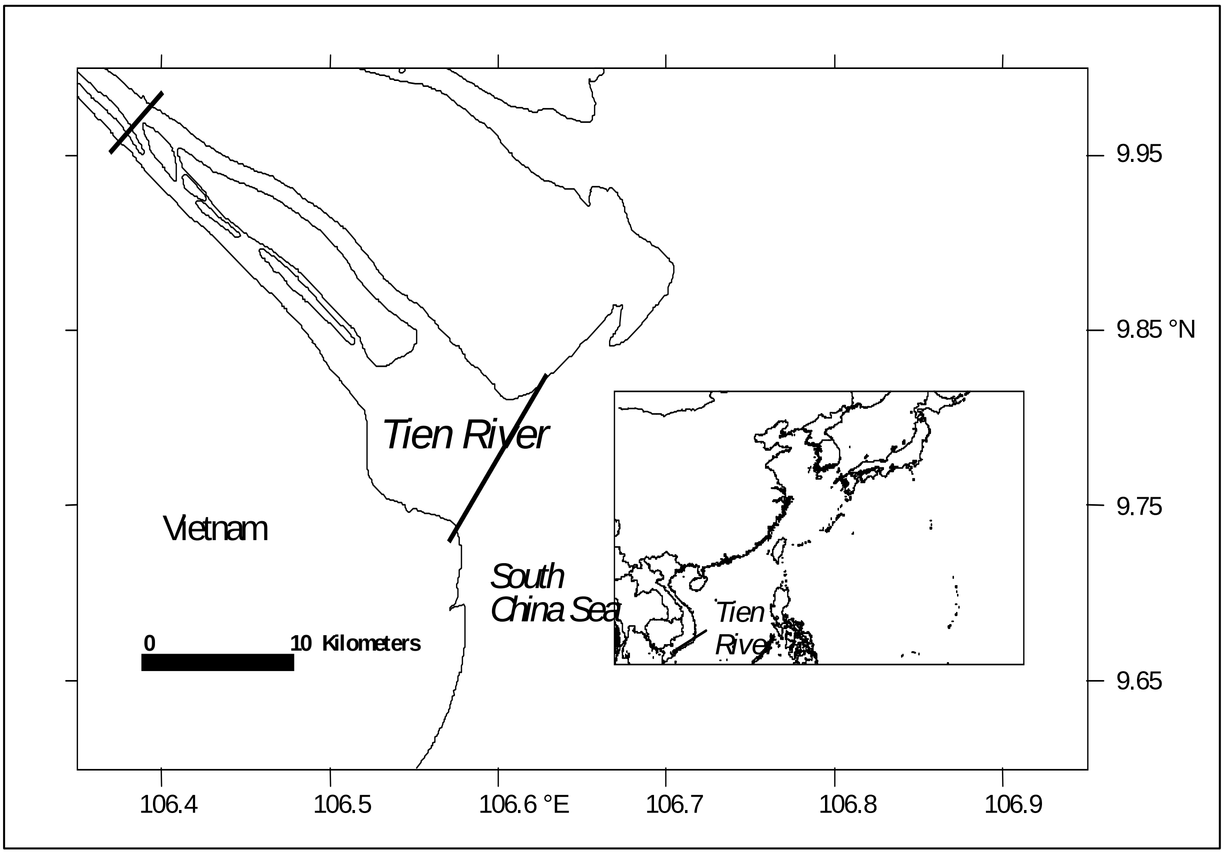


Figure 8.13. Location and map of the budgeted area of the Tien River estuary.

The Mekong River mainly depends on the rain regime on the basin, which has two seasons: the wet season from May to November which provides about 75% of total water volume for the whole year and the dry season from December to April. The relative humidity is about 85-87% in the rainy season and below 80% in the dry season. The annual evaporation varies from 1,000 to 1,800 mm by the Piche Tool and as much as 1,500 - 1,800 mm using "A" pan or the Penman formula. The annual range of precipitation is about 1,400-1,500 mm. In CanTho Province, the annual average evaporation is about 1,560 mm with about 4 mm d^{-1} in the rainy season and the annual average evaporation is about 1,100 mm with about 1 mm d^{-1} in the rainy season (Pham Ngoc Toan and Phan Tat Dac 1975).

The budgeted area is bounded by CoChien and CungHau mouths in the Tien River estuary (9.81°N and 106.56°E). Its area is about 230 km^2 with the average depth of 6 m (see Figure 8.13). The general methodology used here is as described by Gordon *et al.* (1996).

The following equation for conservation of mass is applied to any system:

$$dM/dt = \Sigma Inputs - \Sigma Sinks + \Sigma(Sources - Sinks) \qquad (1)$$

Where: *dM/dt* is a change of mass of the material. This equation represents the rates and quantities of materials movement through the system including the effects of internal sources and sinks. For estuaries with a two-layer flow (stratified water column), Pritchard (1969) developed a model for transport in such system that allowed for the estimation of entrainment and mixing between the layers from conservation of salt and water (Webster *et al.* 1999). For budget calculation, the two-layer estuary is used, as in the schematic diagram in Figure 8.14.

Water exchange between the upper and lower layers occurs through the entrainment term $V_{deep}Y_{syst-d}$ and through the mixing term $V_Z(Y_{syst-d} - Y_{syst-s})$. Y_{syst-s} and Y_{syst-d} are the concentrations in the upper and lower layer, respectively. Net freshwater discharge into the upper layer is expressed as $V_{R'}$. At steady state, the water balance is expressed as:

$$V_{R'} - V_{surf} + V_{deep} = 0 \qquad (2)$$

where V_{surf} is the outflow from the upper layer and V_{deep} is the inflow into the lower layer. Here, we define material flows as being positive for flows into an estuary compartment and negative for flows out from a compartment.

The material budgets for the upper and lower layers are:

$$V_{R'}Y_{R'} + V_{surf}Y_{syst-s} + V_{deep}Y_{syst-d} + V_Z(Y_{syst-d} - Y_{syst-s}) + \Delta Y_{syst-s} = 0 \qquad (3)$$

$$V_{deep}Y_{ocn-d} - V_{deep}Y_{syst-d} - V_Z(Y_{syst-d} - Y_{syst-s}) + \Delta Y_{syst-d} = 0 \qquad (4)$$

Adding equations 3 and 4 and using equation 2 to eliminate V_{deep}, we obtain:

$$V_{R'}Y_{R'} + V_{surf}Y_{syst-s} + V_{deep}Y_{ocn-d} + \Delta Y_{syst-s} + \Delta Y_{syst-d} = 0 \qquad (5)$$

The terms ΔY_{syst-s} and ΔY_{syst-d} are net internal sources or sinks of the substance within the upper and lower layers, respectively. For salt balance, we set Y to be S, S_Q and $\Delta S = 0$. Solving equation 5 for the advective outflow in the upper layer gives:

$$V_{surf} = V_{R'}(S_{syst-d})/(S_{syst-s} - S_{ocn-d}). \qquad (6)$$

<u>Water and salt balance</u>

Based on the calculation above, and using data collected in 1995 and 1996 presented in Table 8.9, the water and salt budgets in the Tien estuary are shown in Figures 8.15 and 8.16.

Table 8.9. Water fluxes for the Tien River estuary.

Water Flux	**Dry season** (10^6 m^3 d^{-1})	**Wet season** (10^6 m^3 d^{-1})
	Upper layer	Whole system
Precipitation (V_P)	0	2
Evaporation (V_E)	1	1
Runoff (V_Q)	77	567
Groundwater, other sources	≈ 0 (assumed)	≈ 0 (assumed)

The water exchange times within the Tien River estuary can be calculated by:

$$\tau = V_{syst} / \left| V_{surf} \right|$$

So, in the dry season: $\tau_1 = [(1{,}400x10^6)/(77x10^6)] = 11$ days.

In the wet season: $\tau_2 = [(1{,}400x10^6)/(1{,}136x10^6)] = 1$ day.

Thus, water exchange time in the Tien River estuary is very short, especially in wet season.

<u>DIN and DIP budgets</u>

The average concentrations of dissolved inorganic nitrogen and phosphorus in the Tien River estuary are presented in Table 8.10. N and P budgets are presented in Figures 8.17-8.20. With the assumption that all nutrients loads were included in the river discharge, the results indicate that the system is a net source in the dry season and a net sink in the wet season for DIP. The system is a net source of DIN for both seasons.

Table 8.10. Nutrient concentrations in the Tien River estuary.

Sources	**Seasons**	**DIP** (µM)	**DIN** (µM)
Runoff	Dry	0.7	4.1
	Wet	1.7	29.6
System	Dry (Upper layer)	0.7	7.0
	Dry (Lower layer)	0.6	4.5
	Wet	0.9	27.9
Ocean	Dry	0.2	6.1
	Wet	1.6 (Surface) 1.0 (Bottom)	28.3 (Surface) 16.7 (Bottom)

Stoichiometric calculation of aspects of net ecosystem metabolism

Ecosystem metabolism was calculated only for the dry season when water exchange time was long enough to allow the nutrients to be processed by organisms. If it is assumed that all the behaviors of nonconservative materials are biological processes, then the value of *ΔDIP* can be a measure of the net productivity of the system.

The net ecosystem metabolism (NEM = [*p-r*]) is calculated as the negative *ΔDIP* multiplied by the C:P ratio of the reacting organic matter. Assuming that the bulk of the reacting organic matter is phytoplankton, the C:P ratio is 106:1. Thus, *(p-r)* = -106 x *ΔDIP*

The value for (*p-r*) in the dry season is shown in Table 8.11. The estimated results denote that the system is net heterotrophic.

Table 8.11. Net ecosystem metabolism, NEM (*p-r*) in the Tien River estuary in the dry season.

Areas	ΔDIP		NEM (*p-r*)	
	10^3 mol P d^{-1}	mmol P m^{-2} d^{-1}	10^3 mol C d^{-1}	mmol C m^{-2} d^{-1}
Upper layer	+20	+0.09	-2,120	-9
Lower layer	+3	+0.01	-318	-1
Whole system	+23	+0.10	+2,438	-10

Based on the N:P Redfield ratio, expected nonconservative DIN (ΔDIN_{exp}) can calculated to be 16 x ΔDIP. On the other hand, the ΔDIN estimated from the water and salt balances presents the ΔDIN_{obs}. Therefore, the difference between ΔDIP_{exp} and ΔDIN_{obs} represents the difference between nitrogen fixation and denitrification, that is;

(nfix-denit) = ΔDIN_{obs} - ΔDIP_{exp} Or: *(nfix-denit)* = ΔDIN_{obs} - $\Delta DIPx(N:P)_{part}$. The results indicate that the system is net denitrifying (Table 8.12).

Table 8.12. Estimated value of (*nfix - denit*) for the Tien River estuary in the dry season.

	ΔDIN_{obs}		ΔDIN_{exp}		(*nfix-denit*)	
	10^3 mol N d^{-1}	mmol N m^{-2} d^{-1}	10^3 mol N d^{-1}	mmol N m^{-2} d^{-1}	10^3 mol N d^{-1}	mmol N m^{-2} d^{-1}
Upper	+728	+3.2	+320	+1.4	+408	+1.8
Lower	-470	-2.0	+48	+0.2	-518	-2.3
Whole system	+258	+1.2	+368	+1.6	-110	-0.5

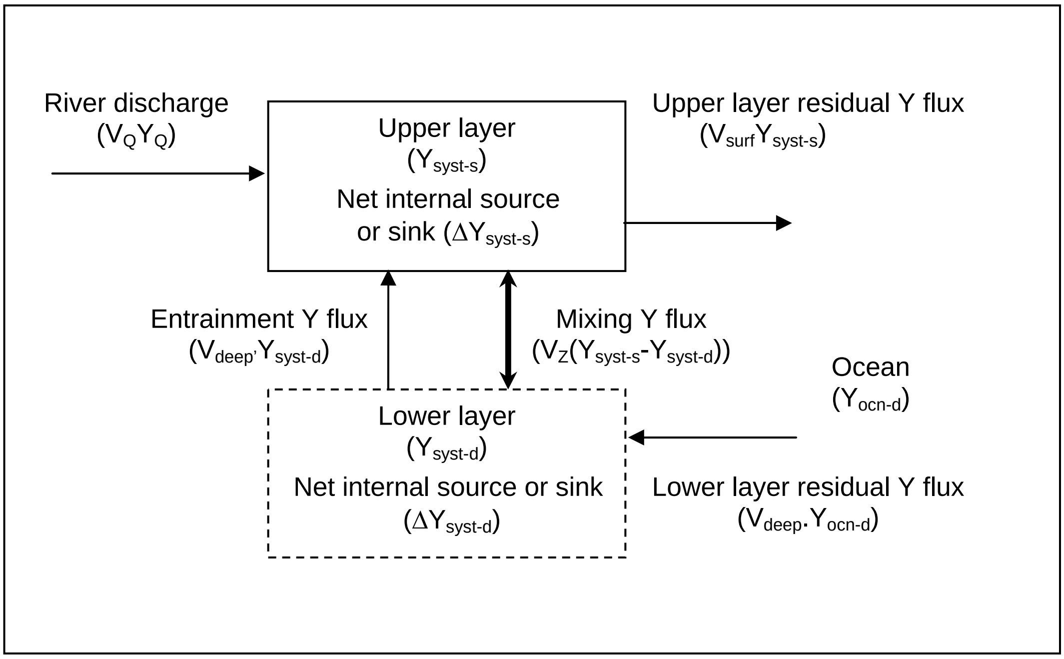


Figure 8.14. Schematic of a two-layer budget model.

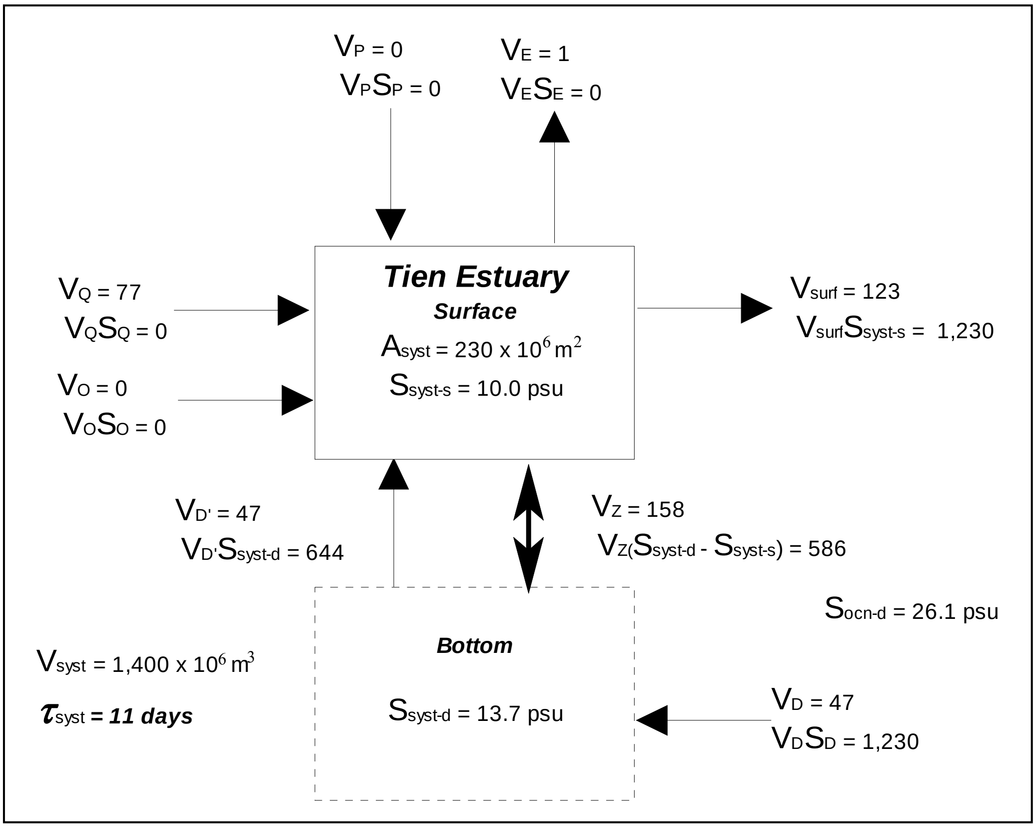


Figure 8.15. Two-layer water and salt budgets for the Tien River estuary in the dry season. Box outlined with dashed lines represents lower layer of the system. Water flux in 10^6 m^3 d^{-1} and salt flux in 10^6 psu-m^3 d^{-1}.

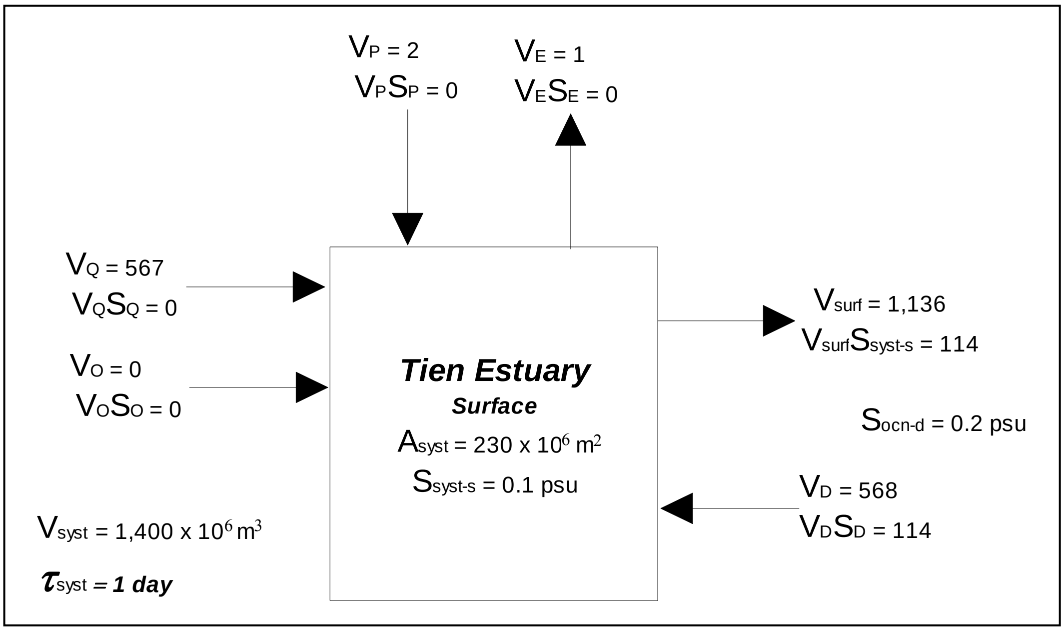


Figure 8.16. Water and salt budgets for the Tien River estuary for the wet season. Water flux in 10^6 m^3 d^{-1} and salt flux in 10^6 psu-m^3 d^{-1}.

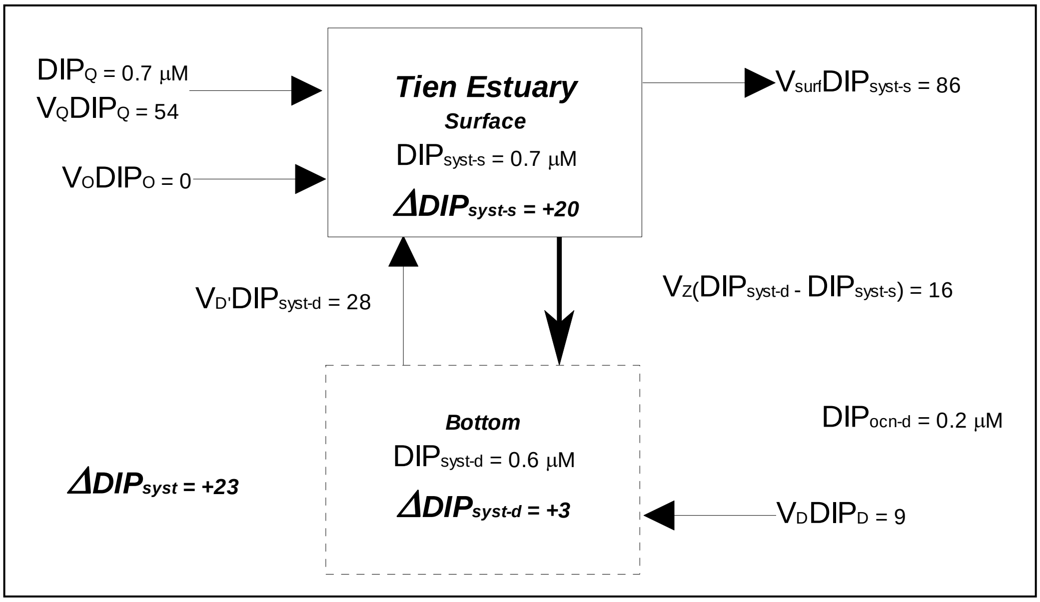


Figure 8.17. Two-layer dissolved inorganic phosphorus budget for the Tien River estuary in the dry season. The box outlined with dashed lines represents lower layer of the system. Fluxes in 10^3 mol d^{-1}.

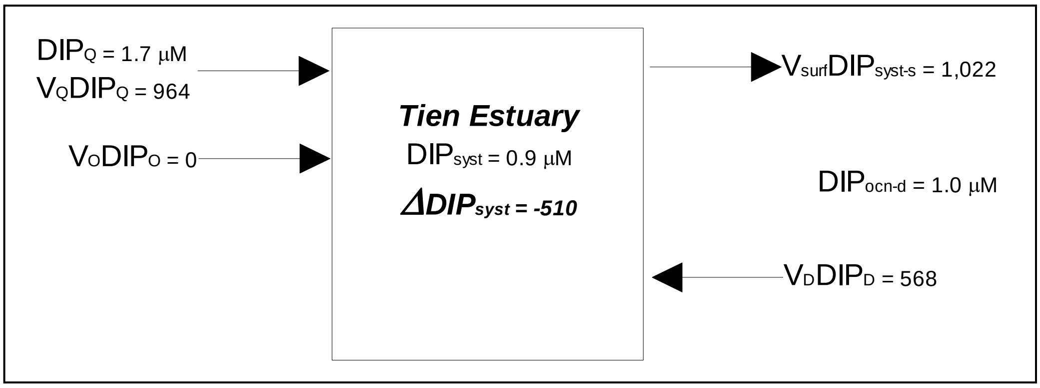


Figure 8.18. Two-layer dissolved inorganic phosphorus budget for the Tien River estuary in the wet season. Flux in 10^3 mol d^{-1}.

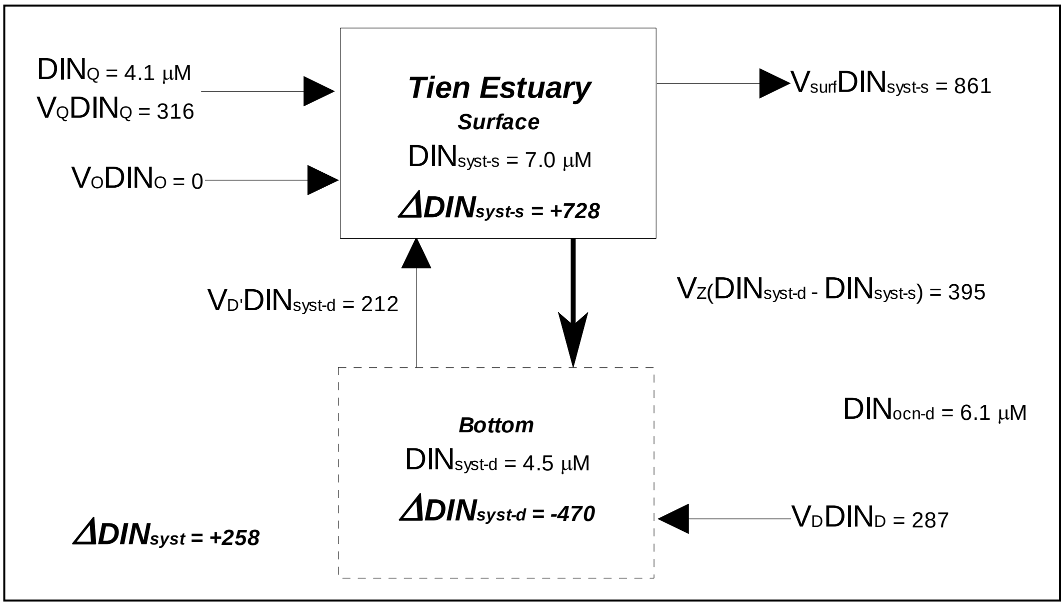


Figure 8.19. Two-layer dissolved inorganic nitrogen budget for the Tien River estuary for the dry season. The box with dashed outlines represents lower layer of the system. Flux in 10^3 mol d^{-1}.

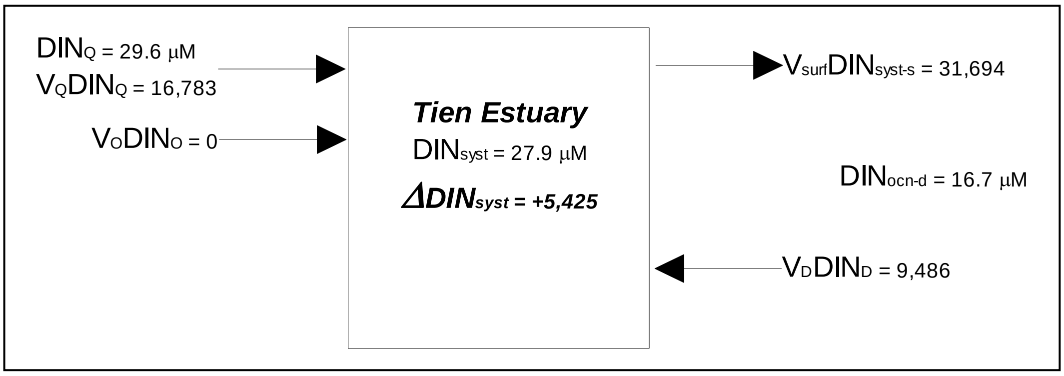


Figure 8.20. Two-layer dissolved inorganic nitrogen budget for the Tien River estuary for the wet season. Flux in 10^3 mol d^{-1}.

8.4 VanPhong Bay, Vietnam

Nguyen Huu Huan and Nguyen Tac An

Study area description

VanPhong Bay is situated in the northern part of KhanhHoa Province between 12.4° and 12.8 °N, and 109.3° and 109.8 °E. The bay has a total area of approximately 460 km^2 of which the total area of the islands is about 50 km^2. The average depth of the bay is about 17 m and the total of water volume is about $7x10^9$ m^3 (Nguyen Tac An 1996; Bui Hong Long 1996). The budgeted area of the bay is shown in Figure 8.21.

TruongSonNam Mountain is located at a distance of about 25 km from the western shore of the bay. To the north-east of the bay is HonGom Peninsula, a range of small mountains and banks of sand, which extend 30 km. VanPhong Bay has two connections to the sea: Be mouth (in the south of HonGom Peninsula), more than 2 km wide and VanPhong mouth, about 17 km wide.

Annual average precipitation is about 1,300 mm with about 117 rainy days. Normally, the wet season lasts from September to December, and the dry season from January to July. Average annual evaporation is about 1,400 mm, which exceeds annual precipitation. In the dry season, salinity in VanPhong Bay is usually higher than in the ocean (Nguyen Khoa Dieu Huong 1995).

The population density along the coast of the bay is low. The standard of living is relatively low in this area. Economic activities in and around VanPhong Bay include agriculture, marine exploitation, aquaculture, and salt production. Some economic centers are being constructed, including HonKhoi Cement Factory, DamMon Port for sand export and Hyundai-Vinashin Ship Manufactory.

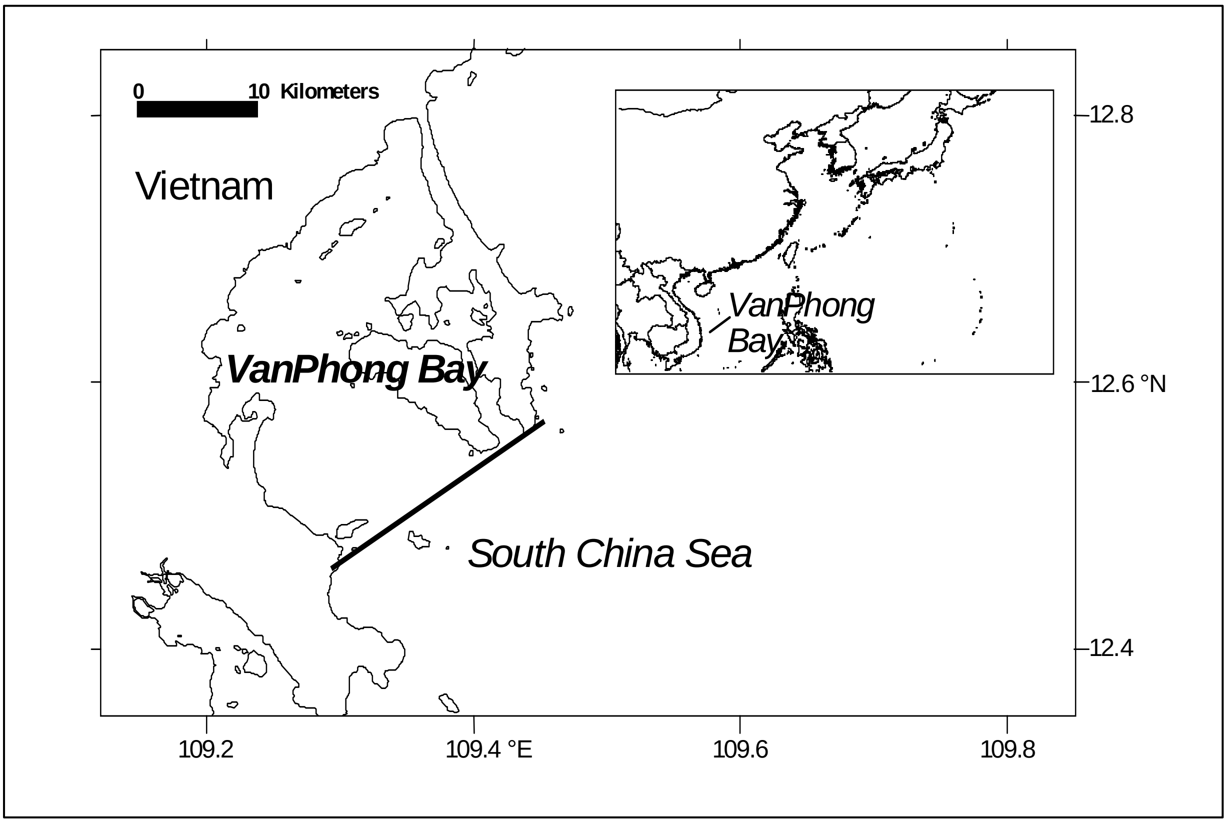
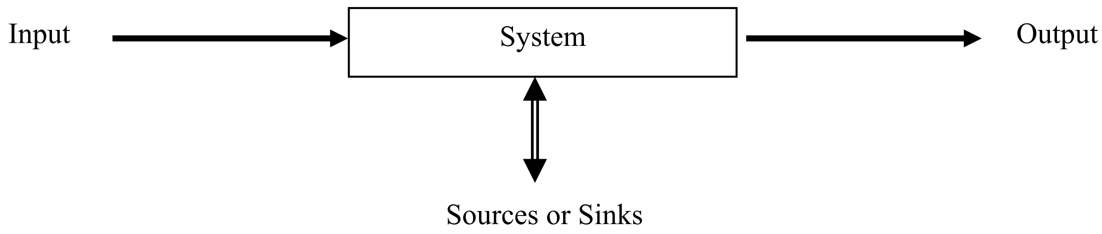


Figure 8.21. Map and location of VanPhong Bay. Solid bar shows the boundary of the budgeted area of the bay.

The LOICZ Biogeochemical Modelling Guidelines (Gordon *et al*. 1996) were applied to the data collected from 1994 to 1998 in VanPhong Bay.

Water and salt balance

The conceptual model for transport of materials in a system is:



We can describe the process by:

$$\frac{dM}{dt} = \sum input - \sum Output + \sum (Sources - Sinks) \qquad (1)$$

where dM/dt is the change of mass of material of interest. Assuming the system of interest is at steady state (dM/dt = 0), based on data in Table 8.13, the balances of water and salt are shown in Figures 8.22 and 8.23.

The water exchange time in the system (τ) can be calculated as the total volume of the system divided by the sum of the absolute value of residual ($|V_R|$) and volume of mixing (V_X). Thus:

In the dry season: $\tau_2 = V_{syst.} /(|V_{R2}| + V_{X2}) = 7x10^9/(1 \text{ x } 10^6 + 113x10^6) = 61$ days.

In the rainy season: $\tau_1 = V_{syst.} /(|V_{R1}| + V_{X1}) = 7x10^9/(1 \text{ x } 10^6 + 160 \text{ x } 10^6) = 43$ days.

Table 8.13. Water fluxes for VanPhong Bay.

Factors	Dry season	Wet season
$V_P (10^6 m^3 d^{-1})$	1	3
$V_E (10^6 m^3 d^{-1})$	2	2
$V_O (10^6 m^3 d^{-1})$	≈ 0 (assumed)	≈ 0 (assumed)
$V_G (10^6 m^3 d^{-1})$	≈ 0 (assumed)	≈ 0 (assumed)
$V_Q (10^6 m^3 d^{-1})$	≈ 0 (assumed)	≈ 0 (assumed)

As VanPhong Bay is a relatively closed system (without any river), water exchange time is only affected by evaporation, precipitation and tidal regime.

DIP and DIN budgets

The balance of any nonconservative material (Y) at steady state is calculated as follows:

$$d(VY)/dt = V_QY_Q + V_PY_P + V_GY_G + V_EY_E + V_RY_R + V_X(Y_{ocn} - Y_{syst}) + \Delta Y \qquad (2)$$

where the various "VY" terms involve fluxes of Y with water sources and ΔY represents the net internal source or sink of element Y. In the case of VanPhong Bay, the equation (2) can be simplified and solved for ΔY as follow:

$$d(VY)/dt = V_RY_R + V_X(Y_{ocn} - Y_{syst}) + \Delta Y \qquad (3)$$

Assuming that at steady state in any system: d(VY)/dt = 0, solving for ΔY from equation (3):

$$\Delta Y = - V_R Y_R - V_X(Y_{ocn} - Y_{syst}) \tag{4}$$

From equation (4) and data in Table 8.6, we can calculate ΔY (DIP and DIN) as shown in Figures 8.24 – 8.27. The results show that the system is a net source in the rainy season and a net sink in the dry season for DIP. The system is a net source for DIN for both seasons.

Table 8.14. Nutrient concentrations of water fluxes in VanPhong Bay.

	Seasons	DIP (µM)	DIN (µM)
System	Dry	0.1	19.5
	Wet	0.1	5.6
Ocean	Dry	0.1	7.9
	Wet	0.1	4.6

Stoichiometric calculation of aspects of net system metabolism
With the assumption that the behavior of nonconservative materials is primarily due to biological processes, the value of ΔDIP is a measure of the net productivity in the system. The net ecosystem metabolism (NEM = [*p-r*]) is calculated as the negative ΔDIP multiplied by the C:P ratio of the reacting organic matter. Assuming that the bulk of the reacting organic matter is phytoplankton, the C:P ratio is 106:1. Thus, $(p\text{-}r) = - 106 \times \Delta DIP$

In the case of VanPhong Bay, the net ecosystem metabolism (*p-r*) is very low for both seasons. This suggests that the system seems to balance production and respiration (see Table 8.15).

Table 8.15. Net ecosystem metabolism (NEM) for VanPhong Bay.

Seasons	ΔDIP		NEM (*p-r*)	
	10^3 mol P d^{-1}	mmol P m^{-2} d^{-1}	10^3 mol C d^{-1}	mmol C m^{-2} d^{-1}
Dry	-0.1	0	+10.6	+0.03
Wet	+0.1	0	-10.6	-0.03
Annual	0	0	+2.9	+0.01

Based on the (N:P) Redfield Ratio, we can calculate ΔDIP_{exp} to be 16(ΔDIP). On the other hand, the ΔDIN estimated from the water and salt balances presents the ΔDIN_{obs}. Therefore, the difference between ΔDIP_{exp} and ΔDIN_{obs} represents the difference between nitrogen fixation and denitrification, that is, $(nfix\text{-}denit) = \Delta DIN_{obs} - \Delta DIP_{exp}$ Or: $(nfix\text{-}denit) = \Delta DIN_{obs} - \Delta DIP \times (N{:}P)_{part.}$

The estimated results are presented in Table 8.16. (*nfix-denit*) is +163x10^3 mol N d^{-1} or +0.4 mmol N $m^{-2}d^{-1}$ in the wet season and +1,299x10^3 mol N d^{-1} or +3.2 mmol N m^{-2} d^{-1} in the dry season. VanPhong Bay appears to be a net nitrogen fixing system with annual *(nfix-denit)* of +2.2 mmol N $m^{-2}d^{-1}$.

Table 8.16. The estimated value of (*nfix - denit*) for VanPhong Bay.

Seasons	ΔDIN		ΔDIP(N:P)		(*nfix - denit*)	
	10^3 mol N day^{-1}	mmol N m^{-2} day^{-1}	10^3 mol N day^{-1}	mmol N m^{-2} day^{-1}	10^3 mol N day^{-1}	mmol N m^{-2} day^{-1}
Dry	+1,297	+3.2	-2	0	+1,299	+3.2
Wet	+165	+0.4	+2	0	+163	+0.4
Annual	+885	+2.2	-0.5	0	+885	+2.2

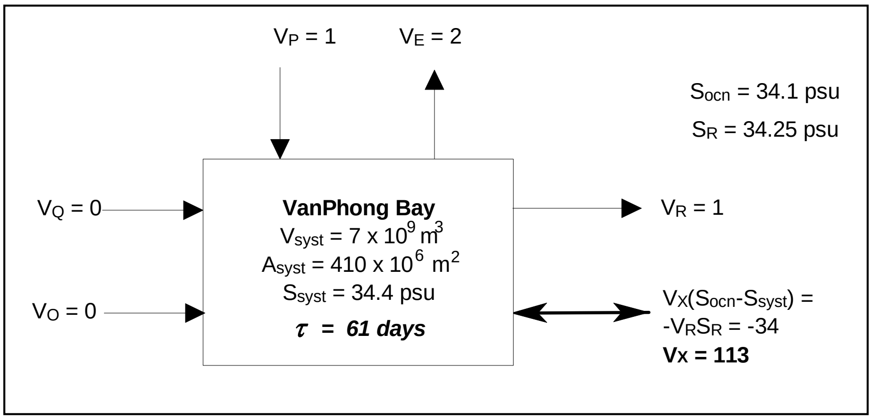


Figure 8.22. Water and salt budgets for VanPhong Bay in the dry season. Water flux in 10^6 m^3 d^{-1} and salt flux in 10^6 psu-m^3 d^{-1}.

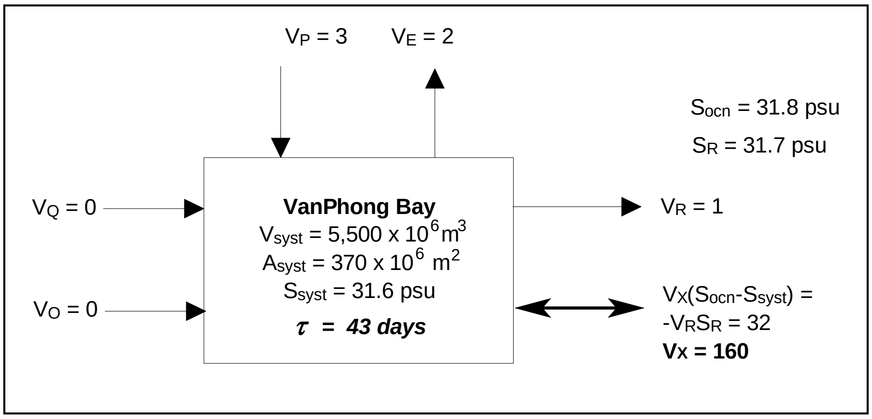


Figure 8.23. Water and salt budgets for VanPhong Bay in the wet season. Water flux in 10^6 m^3 d^{-1} and salt flux in 10^6 psu-m^3 d^{-1}.

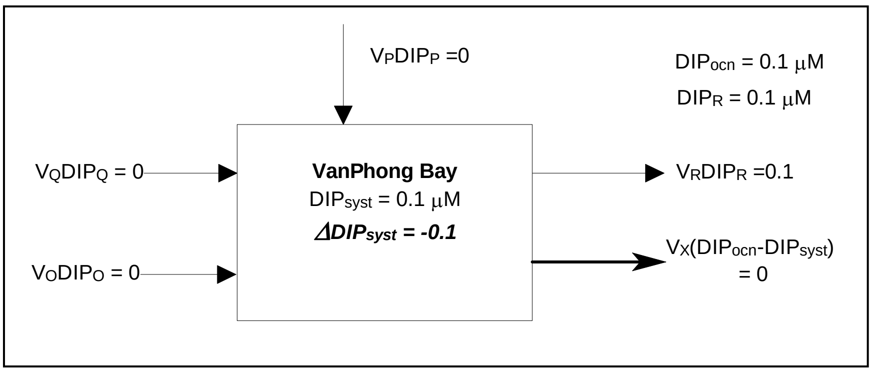


Figure 8.24. Dissolved inorganic phosphorus budget for VanPhong Bay in the dry season. Flux in 10^3 mol d^{-1}.

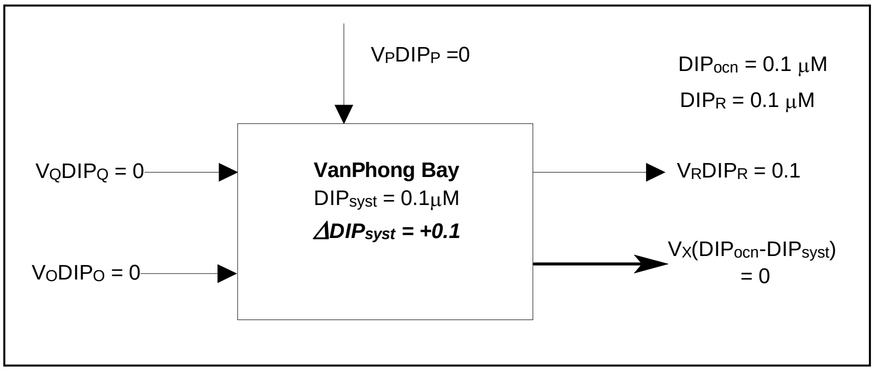


Figure 8.25. Dissolved inorganic phosphorus budget for VanPhong Bay in the wet season. Flux in 10^3 mol d^{-1}.

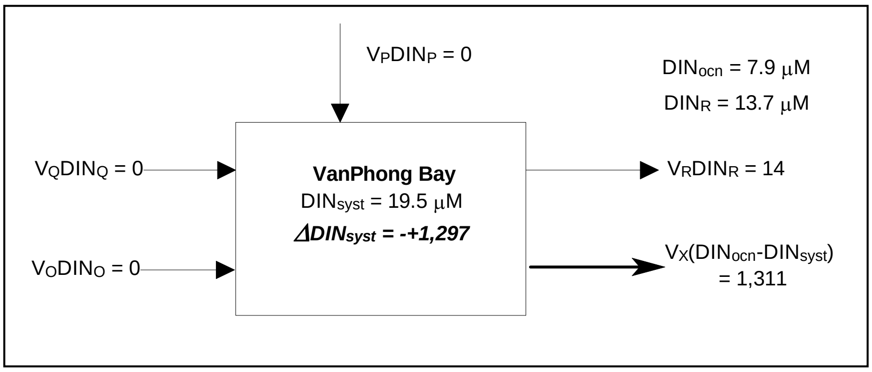


Figure 8.26. Dissolved inorganic nitrogen budget for VanPhong Bay in the dry season. Flux in 10^3 mol d^{-1}.

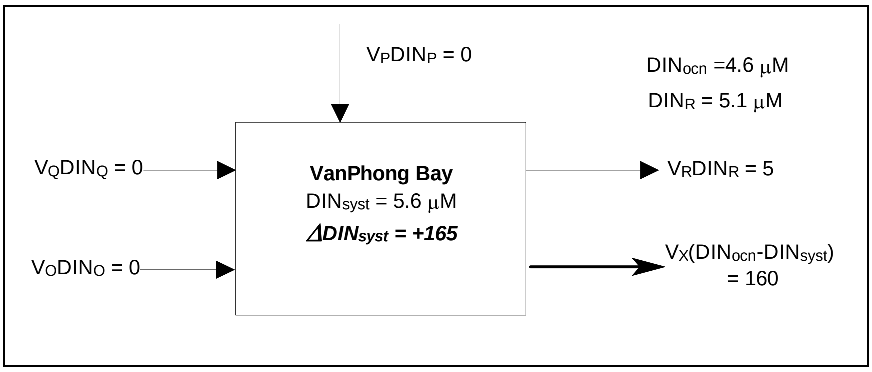


Figure 8.27. Dissolved inorganic nitrogen budget for VanPhong Bay in the wet season. Flux in 10^3 mol d^{-1}.

9. BUDGETS FOR ESTUARIES IN INDONESIA

9.1 Teluk Banten: water and salt budgets, and implications for the nutrient budgets

Han Lindeboom, Jan van Ooijen, S. V. Smith, V. Dupra and T. Yanagi

<u>Study area description</u>

Teluk Banten (Banten Bay; surface area ~ 150 km^2; Figure 9.1) is a relatively shallow (7 m average depth) embayment on the north-west coast of the Indonesian island of Java. This system provides an interesting insight into critical analysis of data in the budgeting of water exchange and nutrient dynamics.

Biotic communities in the bay include coral reef and seagrass beds. The land adjacent to the bay, approximately 60 km west of Jakarta, is becoming rapidly industrialized. At present, however, domestic and agricultural wastes apparently dominate the discharge of nutrients into the system. Runoff into the system totals about $1\text{-}2\times10^6$ m^3 d^{-1}; we assume that this freshwater input dominates in the system, and we use the lower value for the analysis presented here. From regional data, we estimate that rainfall and evaporation each average < 10^6 m^3 d^{-1} across the bay area, approximately balancing one another in the water budget.

Water composition data have been collected by both Dutch and Indonesian scientists, and there are some substantial discrepancies between the two sets of data. There is no real difference between the Dutch and Indonesian data for salinity. The salinity difference between the coastal stations and the open sea (32.4-32.6 psu, with no coherent pattern) is too small to be used for quantitatively reliable salt budget calculations.

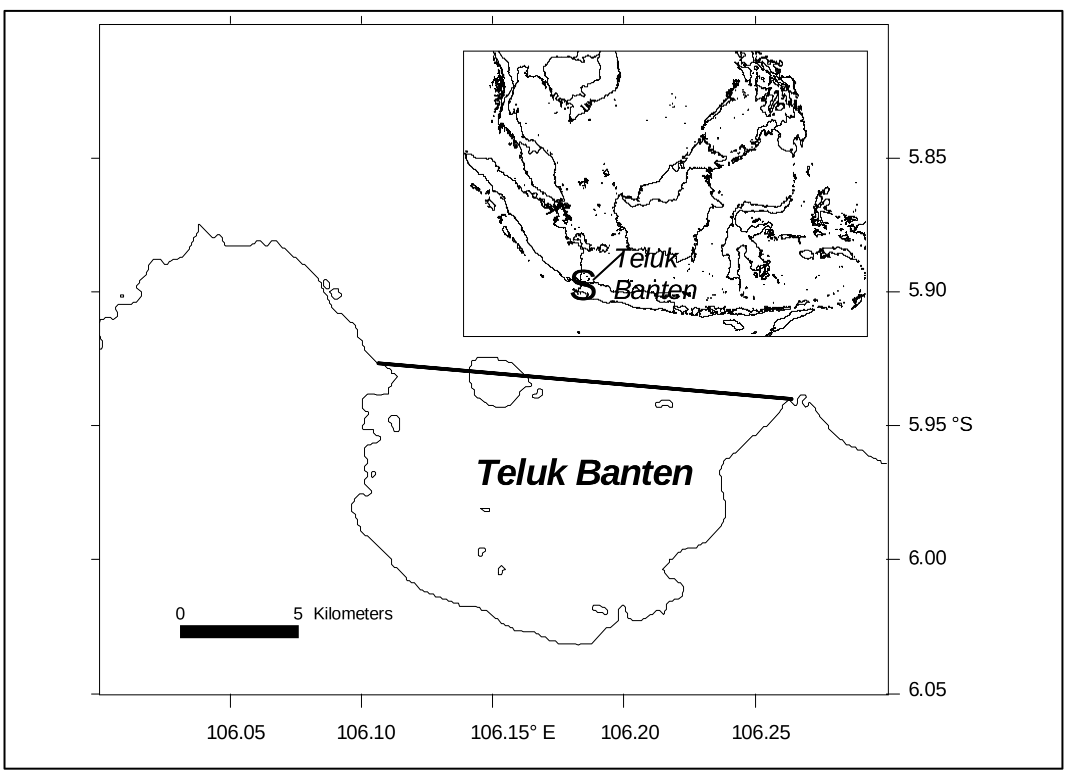


Figure 9.1. Map of Teluk Banten (Banten Bay). Solid bar shows the boundary of the budgeted area.

Water exchange for Teluk Banten cannot be calculated via water and salt budgets, because there is an insignificant salinity difference between the bay and ocean. Mixing (V_X) cannot be determined. However, independently of the salt budget, the Dutch scientists estimate that the exchange time is about 10 days; this should be further resolved with a detailed numerical hydrographical model (P. Hoekstra, personal communication). In the meantime, we will demonstrate that we think this is too long; that is, the value for V_X is significantly underestimated with that exchange time.

From the LOICZ modelling guidelines (Gordon *et al.* 1996) water exchange time (τ) is defined as:

$$\tau = \frac{V_{syst}}{\left(V_X + |V_R|\right)} \qquad (1)$$

where V_{syst}, V_X, and V_R are the system volume, daily mixing volume and residual flow, respectively. Further, ignoring rainfall and evaporation, $V_R = -V_Q$, where V_Q = daily runoff. Rounded off, $V_{syst} \approx 1\text{x}10^9$ m^3, and $V_Q \approx 1\text{x}10^6$ m^3 d^{-1}. At salinity values near oceanic, V_X dominates and we can ignore V_R in equation (1). Taking $\tau \approx 10$ days, we derive $V_X \approx 100 \text{ x } 10^6$ m^3 d^{-1}, roughly 1000 times as large as V_R. We now demonstrate that V_X is probably larger than this value.

Salt flux associated with V_R is calculated as:

$$V_R S_R \approx -10^6 m^3\_d^{-1} \times 32 psu \approx -30 \times 10^6 psu\_m^3\_d^{-1} \qquad (2)$$

This outward salt flux must be balanced by inward salt mixing:

$$V_X \left(S_{ocn} - S_{syst}\right) = -V_R S_R \qquad (3)$$

Usually we solve equation (3) for V_X; this requires knowledge of the salinity difference, and that this difference be non-0. In the present case, we assume that we know V_X and solve for the salinity difference (S_{ocn}-S_{syst}):

$$\left(S_{ocn} - S_{syst}\right) \approx \frac{30 \times 10^6}{V_X} \approx 0.3\_psu \qquad (3a)$$

This salinity difference is much larger than implied by either the Dutch or the Indonesian salinity data. Taking that difference to be closer to 0.1 psu (and perhaps smaller) and solving for V_X, we approximate

$$V_X \approx \frac{30 \times 10^6}{(\leq 0.1)} \geq 300 \times 10^6\_m^3\_d^{-1} \qquad (3b)$$

Returning to equation (1), τ is ≤ 3 days.

V_X can also be estimated independently of a salt budget, as given by Yanagi (2000). Yanagi has presented an algorithm based on standard mixing equations derived from Okubo (1971). Water mixing across the open boundary of the system is governed by dispersion (shear diffusion). In the case of dominant horizontal shear (a wide and shallow coastal system, such as Teluk Banten), the horizontal dispersion coefficient D_h is calculated as:

$$D_h = \frac{1}{120} \frac{W^4}{K_h} \left(\frac{U}{W}\right)^2 \qquad (4a)$$

where U is the residual flow velocity at the surface layer of the open boundary; W is the width of the open boundary of the system ($15x10^3$ m); and K_h is the horizontal diffusivity (~13 m^2 sec^{-1}, from Figure 2 and equation (4) of Okubo 1971). Assuming U ≈ 0.1 m $sec^{-1}$and solving (4a), D_h is about 1,400 m^2 sec^{-1}, or about $120x10^6$ m^2 d^{-1}.

The horizontal dispersion coefficient is then converted to V_X, in the LOICZ notation, by the following equation:

$$V_X = \frac{D_h A}{d} \qquad (4b)$$

Here *A* denotes the cross sectional area of the open boundary of the system and *d* the length between the center of the system and the observation point of the ocean salinity. *A* is approximately 10^5 m^2 and *d* is approximately10^4 m. With this algorithm, the estimated value for V_X is about $1,200x10^6$ m^3 d^{-1}.

To be consistent with equation (3a), this would imply a salinity difference between the coastal ocean and the system of about 0.03 psu. This very low salinity difference (i.e., not different from 0) is consistent with the data, while demonstrating why a salt budget might not work in this system. The further points to note from these calculations are that τ = 10 days seems too long, and that any value for τ less than about 3 days would result in a bay-to-ocean salinity difference of 0.1 psu or less.

Estimation of the correct exchange time becomes significant to the nutrient budgets, as demonstrated in the table that follows. In this table, the estimated fluxes for independent variables other than V_X (i.e., V_R and the nutrient concentrations) are held constant. At V_X values varying from one that seems low (V_X = $100x10^6$ m^3 d^{-1}; based on τ = 10 days) mixing is the dominating term in the nutrient budgets; as estimated V_X grows, this term becomes more important. Even though this system receives a substantial nutrient input from land, the oceanic source is larger. We take V_X = $300x10^6$ m^3 d^{-1} (τ = 3 days) to be the best estimate of water exchange.

Further, regardless of uncertainty in the absolute values for nonconservative nutrient fluxes, these fluxes per unit area are modest, even with the highest value for V_X. Rates of estimated (*p-r*) and (*nfix-denit*) are also given. Rates of these processes are calculated on the assumption that plankton dominate the net metabolism. Net ecosystem metabolism (*p-r*) ranges between +1.1 and +9.5 mmol m^{-2} d^{-1}, depending on the estimated mixing (best estimate yields 3.2 mmol m^{-2} d^{-1}). Estimates of (*nfix-denit*) range between –0.04 and –0.86 mmol m^{-2} d^{-1} (best estimate = -0.12). In all cases, the system appears to be net autotrophic and a net denitrifier; the rates appear reasonable for a reef system with a significant planktonic component.

Nonconservative nutrient fluxes calculated from the Indonesian data are too high to be believed, especially at the higher estimates of water exchange and are inconsistent in sign between two data sets. These problems are useful reminders that, insofar as possible, data analytical quality should be considered during budgetary analyses.

All data on the dissolved nutrients indicate that the Teluk Banten system is a net organic carbon producing system and a nitrogen removing system, with an active transport of nitrogen from outside the bay towards the inner bay. There might be a simple explanation for the relatively high nitrogen input from outside the bay. Along the coast there is a net westward transport of water, which is strong during the wet monsoon and rather weak during the dry monsoon. This leads to a transport along the coast of the output of Jakarta and the Ciujung river towards Teluk Banten. Part of the nitrogen discharged into the Java Sea may re-enter Banten Bay, indicating that this bay acts as a clean up system for the Jakarta input.

Given the present nutrient concentrations in the bay, and the observation that the nutrient inputs from the small rivers are very rapidly taken up by the biological system in the bay, it is expected that an increase of the nutrient flux due to development of the urban and industrial areas, will not lead to major nutrient problems in the bay as a whole. However, high discharges and elevated concentrations near the shoreline may certainly lead to local problems of anaerobic events with local fish kills and bad odors.

Table 9.1. Estimated fluxes of water, salt, and nutrients, based on differing estimates of V_X.

Variable	V_X = 100 x 10^6 m^3 d^{-1}	V_X = 300 x 10^6 m^3 d^{-1}	V_X = 1,200 x 10^6 m^3 d^{-1}
$V_Q = -V_R$ (10^6 $m^3 d^{-1}$)	1	1	1
$V_R S_R = -V_X(S_{ocn}-S_{sysr})$ (10^6 psu m^3 d^{-1})	-32	-32	-32
$(S_{ocn}-S_{syst})$ (psu)	0.32	0.11	0.03
τ (days)	10	3	1
terrigenous DIP load (kmol d^{-1})	+1	+1	+1
DIP_{syst} (μM)	0.08	0.08	0.08
DIP_{ocn} (μM)	0.09	0.09	0.09
$V_R DIP_R$ (kmol d^{-1})	-0	-0	-0
$V_X(DIP_{ocn}-DIP_{syst})$ (kmol d^{-1})	+1	+3	+12
ΔDIP (kmol d^{-1})	-2	-4	-13
ΔDIP (mmol m^{-2} d^{-1})	-0.01	-0.03	-0.09
terrigenous DIN load (kmol d^{-1})	+3	+3	+3
DIN_{syst} (μM)	0.03	0.03	0.03
DIN_{ocn} (μM)	0.32	0.32	0.32
$V_R DIN_R$ (kmol d^{-1})	-0	-0	-0
$V_X(DIN_{ocn}-DIN_{syst})$ (kmol d^{-1})	+29	+87	+348
ΔDIN (kmol d^{-1})	-32	-90	-351
ΔDIN (mmol m^{-2} d^{-1})	-0.2	-0.6	-2.3
(p-r) (mmol m^{-2} d^{-1})	+1.1	+3.2	+9.5
(nfix-denit) (mmol m^{-2} d^{-1})	-0.04	-0.12	-0.86

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APPENDICES

Appendix I. A simple method for estimating V_x from mixing equations in a 1-dimensional, steady-state system for LOICZ biogeochemical modelling.

Tetsuo Yanagi

For LOICZ biogeochemical modelling, it is important to estimate the mixing volume (V_X, in $m^3\ d^{-1}$) across the open boundary of the system (e.g., Gordon *et al*. 1996). Clearly this open-boundary transport is required to balance salt transport in estuaries. Less obviously, it can be an important source or sink for nutrient transport between estuaries and the coastal ocean. In the procedure recommended by the LOICZ guidelines, V_X is estimated from the water and salt budgets, where V_R is the residual volume transport associated with freshwater discharge, S_{syst} and S_{ocn} are the system and adjacent ocean salinity values, respectively; and S_R is the average of the ocean and system salinity:

$$V_X = \frac{-V_R S_R}{\left(S_{ocn} - S_{syst}\right)} \qquad (1)$$

Positive flux is into the system. Obviously this equation can be solved only if there is a quantifiable salinity difference between the system and the ocean, yet some systems lack a salinity gradient. V_X is still an important variable.

We offer an alternative way to estimate the mixing volume V_X without relying on a salinity difference between the system and the ocean. The water mixing across the open boundary of the system is governed by the dispersion process (Yanagi 2000), and the magnitude of the horizontal dispersion coefficient D_H ($m^2\ s^{-1}$) is estimated from the current shear and the diffusivity normal to the current shear by the following equations (from Taylor, 1953):

a) In the case of dominant vertical shear (narrow and deep estuarine system):

$$D_H = \frac{1}{120}\left(\frac{H^4}{K_V}\right)\left(\frac{U}{H}\right)^2 \qquad (2)$$

b) In the case of dominant horizontal shear (wide and shallow estuarine system):

$$D_H = \frac{1}{120}\left(\frac{W^4}{K_h}\right)\left(\frac{U}{W}\right)^2 \qquad (3)$$

where H (in m) is the average depth of the open boundary of the system; W (in m) is the length of the open boundary, that is the width of the system mouth, in m; U (in $m\ d^{-1}$) is the residual flow velocity at the surface layer of the open boundary (if this value is not independently known, it typically has a numerical value of about 0.1 $m\ s^{-1}$ or 8,640 $m\ d^{-1}$ (Yanagi 2000); K_V is the vertical diffusivity (typically ~ $10^{-4}\ m^2\ s^{-1}$ or 8.64 $m^2\ d^{-1}$ in the case of stratification and $10^{-3}\ m^2\ s^{-1}$ or 86.4 $m^2\ d^{-1}$ in the case of vertically well-mixed systems; we assume no stratification for the calculations here); and K_h is the horizontal diffusivity (also in $m^2\ s^{-1}$ or $m^2\ d^{-1}$; varies as a function of mixing scale [see below]).

The following criteria can be used to decide if a system should be treated as "narrow and deep" or "wide and shallow." The distance from the center of the system to its mouth is denoted L (m). A system is considered to be "narrow and deep" if L/W > 2 and W/H <500. A system is considered "wide and shallow" if L/W <2 and W/H >500.

The LOICZ notation is more readily followed if U is rescaled to m d^{-1} (if not known it can be approximated as 10^5); and K_v is re-scaled to $m^2 d^{-1}$ (~ 10 in a vertically well-mixed system). D_H (in $m^2 d^{-1}$) according to equation (2) is then approximated in a narrow, deep estuarine system:

$$D_H \approx \frac{1}{1{,}000}\left(HU\right)^2 \qquad (2a)$$

To retain proper dimensionality, the coefficient 1,000 has the units $m^2 d^{-1}$, because this coefficient includes the estimated value for K_v. Note that, if K_v is explicitly known, equation (2a) should be modified accordingly.

Okubo (1971) gives data demonstrating the validity of a well-recognized relationship between the horizontal diffusion coefficient (K_h, in $cm^2 s^{-1}$) the horizontal scale of the diffusion (ℓ, in cm). The equation he offers to summarize that relationship is $K_h = 0.0103\, \ell^{1.15}$. It is assumed here that the diffusion scale for K_h in an estuary or embayment is given by the length of the open boundary (i.e., width of the system mouth, W). Expressing K_h in $m^2 d^{-1}$ and W (ℓ) in m, Okubo's equation becomes:

$$K_h = 18W^{1.15} \qquad (4)$$

Equations (3) and (4) can be combined for use with the LOICZ notation, expressing D_H in $m^2 d^{-1}$ in a wide, shallow estuarine system:

$$D_H = \frac{W^{0.85}U^2}{2{,}180} \qquad (3a)$$

D_H has the typical dimensions of diffusion (area/time), whereas the LOICZ notation is expressed as a volume exchange rate (volume/time). D_H derived from either equation (2a) or (3a) can then be used to approximate the mixing volume (V_X, in $m^3 d^{-1}$) as used in the LOICZ notation:

$$Vx = D_H\left(\frac{A}{F}\right) \qquad (5)$$

where A denotes the cross sectional area of the open boundary of the system (m^2) and F is the distance (m) between the geographic center of the system and the observation point for oceanic salinity (typically near the mouth of the system).

As detailed examples of the calculations, including explicit definition of U, D_H, and the K's, we apply these calculations to two systems in Japan: a narrow and deep bay (Dokai Bay) and a wide, shallow bay (Hakata Bay) (Table I.1). In the case of Dokai Bay, the salt balance method and the mixing equation method of estimating V_X agree within about 5%. In the case of Hakata Bay, the agreement is about a factor of two. Further examples should be explored to evaluate the general agreement between these two methods.

Table I.1. Sample calculations. U, the K's, and D_H are reported both in notation commonly given in the oceanographic literature and in the notation used here, in order to facilitate both comparison with that literature and calculations reported here.

VARIABLE/SYSTEM	Dokai Bay	Hakata Bay
L (m)	10,000	10,000
W (m)	1,200	6,000
H (m)	8.3	7
A (m^2)	10,000	42,000
L/W	8	2
W/H	145	857
Classification	narrow and deep	wide and shallow
U ($m\ s^{-1}$; $m\ d^{-1}$)	0.07; 6,000	0.05; 4,000
K_v, K_h ($cm^2\ s^{-1}$; $m^2\ d^{-1}$)	K_v = 1; 9 (assumed)	K_h = 45x10^3; 398x10^3 (from Okubo, 1971)
D_H ($cm^2\ s^{-1}$; $m^2\ d^{-1}$)	290x10^3; 2.5x10^6	1,440x10^3; 12x10^6
F (m)	6,000	12,000
V_X ($m^3\ d^{-1}$) — eq. (5)	4.2x10^6	42x10^6
V_X ($m^3\ d^{-1}$) — eq. (1)	4.0x10^6	90x10^6

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Appendix II. Possible modifications of the LOICZ two-layer box model in order to account for horizontal mixing

Tetsuo Yanagi, S. V. Smith, and V. Dupra

Introduction

When two-layer box model analysis is carried out according to the LOICZ biogeochemical budgeting guidelines (Gordon *et al.* 1996), the horizontal mixing volume (V_X) across the open boundary of the system is ignored. Of course this is not generally correct (see e.g., Dyer 1997). However, we cannot solve the salt and water balance, algebraically including the horizontal mixing term, because there are five unknowns, but only four equations (see Table II.1). It should be noted that the equations presented here are for the case of a 2-layer system with a single horizontal box. The equations in Gordon *et al*. (1996) could also be extended to include the case of boxes in series.

If we could estimate one unknown independently of the water and salt balances, then only four equations and four unknowns would remain. In the discussion here, it is proposed that the vertical mixing volume (V_Z) be estimated based on physical considerations independently of the salt balance. Then only four unknowns remain to balance the four water and salt equations. This is the situation in principle; it remains a challenge to develop a general formulation for V_Z that is at once consistent with physical oceanographic theory and direct observation.

In order both to illustrate the problem and to stimulate discussion, we present two theoretically based calculations, compare results derived from them with field estimates of V_Z, and discuss the two approaches in the context of the standard LOICZ box model. All terms used in the equations are defined in Table II.2. We refer to the first of the theoretical approaches, derived from Munk and Anderson (1948), as MA48. The second is derived from Yanagi (1999), or Y99.

Theoretical approaches

MA48

The vertical mixing volume V_Z is governed by vertical diffusion from the physical viewpoint, and vertical diffusivity K_Z can be expressed by the following formulation (MA48):

$$K_Z = K_0\left((1+aR_i\right)^{-b} \quad (1)$$

$$R_i = -(g/\rho)(\partial\rho/\partial z)\left(\partial U/\partial z\right)^{-2} \quad (2)$$

Here K_0 denotes the vertical diffusivity in the case of no stratification (≈ 1 $cm^2\ sec^{-1}$), a = 3.33 and b = 1.5 are experimental constants; and R_i is the Richardson number. We use g = 980 cm sec^{-2}, ρ = 1.020 g cm^{-3}, ($\partial U/\partial z$)=6.0x10^{-2} sec^{-1}. The vertical density difference can be approximated as $0.0007\times(S_{syst-d}-S_{syst-s})$, where ($S_{syst-d} - S_{syst-s}$) denotes the salinity difference between the upper and lower boxes; h is the vertical distance (in cm) between the centers of the upper and lower boxes, so $(\partial\rho/\partial z)\approx 0.007\times\frac{\left(S_{syst-d}-S_{syst-s}\right)}{h}$. Substituting into Equation (2) the Richardson number, R_i, is approximated by the expression $187\times\left(\frac{S_{syst-d}-S_{syst-s}}{h}\right)$.

Because only salinity is being considered to account for the density gradient of the system, it is convenient to refer to the ratio $\left(\frac{S_{syst-d} - S_{syst-s}}{h}\right)$ as the "stratification parameter." When this ratio is large, the system is strongly stratified; when it approaches 0, the system is not stratified.

Equation (1) is then re-written as an approximation using this value for the Richardson number:

$$K_Z = K_0 \left\{1 + 620\left(\frac{S_{syst-d} - S_{syst-s}}{h}\right)\right\}^{-1.5} \quad (3)$$

Because K_0 is approximately 1 cm^2 sec^{-1}, equation (3) can be further simplified:

$$K_Z = \left\{1 + 620\left(\frac{S_{syst-d} - S_{syst-s}}{h}\right)\right\}^{-1.5} \quad (4)$$

If we consider Equation (4) in detail, we see that K_Z ranges between 0 and 1 cm^2 sec^{-1}. A value of <0.1 cm^2 sec^{-1} is obtained when the stratification parameter exceeds about 0.006, while the value is 1 cm^2 sec^{-1} if there is no vertical stratification.

Y99
In the case (Y99), the physically determined vertical diffusivity K_Z is expressed by the following equation using the vertical salinity gradient (from Yanagi 1999):

$$K_Z = K_b + \frac{\eta_0}{10^5\left(\frac{S_{syst-d} - S_{syst-s}}{h}\right)} \quad (5)$$

The stratification parameter remains the same. Here, K_b denotes a background vertical diffusivity (≈ 0.5 cm^2 sec^{-1}), and η_0 is a background vertical viscosity (≈ 5.0 cm^2 sec^{-1}). Other notation remains the same. It is convenient to re-state this equation:

$$K_Z = K_b + \left[\frac{20{,}000\left(S_{syst-d} - S_{syst-s}\right)}{h}\right]^{-1} \quad (6)$$

According to Equation (6) K_Z will never be less than K_b (here assumed to be 0.5 cm^2 sec^{-1}). K_Z will be no more than 0.1 cm sec^{-1} larger than K_b if the stratification parameter is greater than 0.0005. K_Z becomes large as the stratification parameter decreases below this value.

Comparisons with published values of K_Z

The two formulations (Equations [4] and [6]) each have, as a variable quantity, an inverse function of the stratification parameter. As a result (and as should be the case), K_Z becomes larger as stratification decreases. The MA48 formulation will assume some value between 0 and 1 cm^2 sec^{-1}, while Y99 remains near (but larger than) K_b unless stratification becomes very slight; the value is then unbounded. It is useful to compare the results with one another and with direct estimates of K_Z. The relationships between the two formulations of K_Z are summarized in Figure II.1. Between stratification parameter values of about 0.0001 and 0.001 (K_Z values slightly below 1 cm^2 sec^{-1} for both formulations), the two formulations agree fairly well; outside of those values, they do not.

Figure II.2 summarizes comparative information between the two methods presented here and observations given in Dyer (1997; D97). For this comparison, we assume that the "bed depth" reported by D97 is twice the value *h* in the above equations. Most of the points in MA48 roughly parallel the observations summarized in D97. However, the MA48 values are about an order of magnitude lower. Across the range of values given by D97, Y99 values show little variability. Consistent with Figure II.1, K_Z values for the two formulations slightly below 1 cm^2 sec^{-1} tend to agree; these values remain well below the observed values.

Additional insight is gained from a paper by Gargett (1984). He derived a formulation close to MA48, and then goes on to state that the constant multiplier (equivalent to K_0 in Equation [4]) "...will be site-specific, since they depend upon the actual amount of energy in a particular internal wave field, as well as the magnitude… [of a correlative term among the vertical and horizontal diffusivities [our words}]...". He then presents data from two experiments. One gives values of K_Z well within the range of Equation (4) (i.e., <1 cm^2 sec^{-1}). The second experiment gives values up to ~4 cm^2 sec^{-1}.

We are forced to conclude that neither of the theoretical approaches is providing a good approximation of observations. These relationships might be improved if there were some independent estimate of either the multiplier (Equation [4]) or the additive term (Equation [6]).

Comparison of V_Z Calculated According to MA48, Y99, and LOICZ Formulations

It remains at least conceptually useful to consider how we would improve on the LOICZ formulation if we had an independent estimate of K_Z. We used the calculations for Manila Bay, the Philippines (Jacinto *et al.* 2000).

Table II.2 summarizes the relevant characteristics of that system. $S_{syst\text{-}d}$ = 33.0 psu, $S_{syst\text{-}s}$ = 32.0 psu, and *h* = 850 cm. The stratification parameter is thus 0.0012; this is approximately in the range where the two theoretical formulations should agree. According to MA48 (Equation [4]), K_Z becomes 0.44 cm^2 sec^{-1}. Y99 (Equation [7]) gives a value of 0.54 cm^2 sec^{-1}. As expected, in this system, the two physically-based estimates of K_Z agree relatively well.

K_Z can then be converted to a vertical mixing volume, V_Z, by the following equation:

$$V_Z = \frac{K_Z A_{syst}}{h} \qquad (7)$$

where A_{syst} is the cross sectional area between the upper and lower boxes (1.7x10^9 m^2 in Manila Bay).

The water and salt budgets for the steady-state vertically stratified model applied by LOICZ are expressed by the following equations slightly modified from Gordon *et al.* (1996). In that notation, fluxes into a box are positive.

$$V_{Q*} + V_{ent} = -V_{surf} \qquad (8)$$

In this notation V_{Q*} includes both runoff and the difference between rainfall and evaporation. Entrainment is defined to be positive with respect to the upper box:

$$V_{ent} = V_{deep} \qquad (9)$$

$$0 = V_{surf}S_{syst-s} + V_{Xsurf}\left(S_{ocn-s} - S_{syst-s}\right) + V_{ent}S_{syst-d} + V_Z\left(S_{syst-d} - S_{syst-s}\right) \qquad (10)$$

and

$$0 = V_{deep}S_{ocn-d} + V_{Xdeep}\left(S_{ocn-d} - S_{syst-d}\right) - V_{ent}S_{syst-d} - V_Z\left(S_{syst-d} - S_{syst-s}\right) \qquad (11)$$

See Table II.3 for the numerical values used in the sample calculations for Manila Bay.

V_{Xsurf} and V_{Xdeep}, the mixing volumes for the surface and deep layers, are expressed using the horizontal dispersion coefficient D_H (assumed the same for the surface and deep boxes) by the following equations:

$$V_{Xsurf} = \frac{D_H A_{surf}}{F} \quad (12)$$

$$V_{Xdeep} = \frac{D_H A_{deep}}{F} \quad (13)$$

Here A_{surf} denotes the cross sectional area of the upper box (= $220x10^3$ m^2 for Manila Bay), A_{deep} the cross sectional area of the lower box (= $150x10^3$ m^2); these are estimated as the layer depth multiplied by the layer thickness. F is the distance between the center of the box and the observation point of ocean salinity (≈ 40,000 m).

We can then solve these equations for the four unknowns: V_{surf}, V_{deep}, V_{ent}, and D_H., and subsequently for V_{Xsurf} and V_{Xdeep}. The equation for water exchange time for the system (τ), from Gordon *et al.* (1996) can be modified to allow for inclusion of the horizontal mixing:

$$\tau = \frac{V_{syst}}{(V_{Q*} + V_{deep} + V_{Xsurf} + V_{Xdeep})} \quad (14)$$

Comparison between the result without the horizontal mixing by Jacinto *et al.* (2000) and those with the two different formulations of horizontal mixing are presented in Table II.3. For the example presented here, vertical mixing, vertical advection and horizontal advection calculated by either of these methods are smaller than those by Jacinto *et al*. Part of the salt balance for the system results from horizontal mixing, so the inflow→entrainment→outflow of ocean water are smaller than calculated without the horizontal mixing term. At the same time, the estimated value for vertical mixing without the horizontal mixing term is not greatly different than vertical mixing with horizontal mixing. Water exchange time is about the same with and without the horizontal mixing terms.

These results underscore two points. There will be a difference in the salt and water budgets (hence, also in the nutrient budgets) calculated with and without horizontal mixing. Except in those systems for which independent external estimates of mixing can be made, there is presently no obvious, unambiguous way to calculate the "right" budgets. Until this problem can be resolved, we recommend that, at a minimum, biogeochemical budgeting be carried out without the horizontal mixing term; this at least provides an objective (if inaccurate) characterization of the system circulation and net biogeochemical reactions. A more detailed analysis might involve calculations by all three approaches: without horizontal mixing, and with the two formulations presented here. This would allow evaluation of the qualitative robustness of the calculations. If a generic and robust method were presented to improve the estimates of horizontal mixing, these calculations should be re-done.

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Table II.1. Equations and variables used in standard LOICZ analysis and the present analysis.

	Standard LOICZ?	**Present formulations?**
EQUATIONS		
Upper box water balance	Yes	Yes
Lower box water balance	Yes	Yes
Upper box salt balance	Yes	Yes
Lower box salt balance	Yes	Yes
Vertical mixing equation	No	Yes
UNKNOWNS		
surface box → ocean advection	Yes	Yes
ocean → deep box advection	Yes	Yes
deep box → surface box advection	Yes	Yes
deep box ⇔ surface box vertical mixing	Yes	Yes
system ⇔ ocean horizontal mixing	No	Yes

Table II.2. Constants or parameters used to solve for the two formulations of K_Z.

QUANTITY	**DEFINITION**	**VALUE**	
		MA48	*Y99*
K_0	vertical diffusivity without stratification	≈ 1 $cm^2\ sec^{-1}$	
a	experimental constant	3.33	
b	experimental constant	1.5	
R_i	Richardson number	Equation (2)	
g	gravitational acceleration	980 cm sec^{-2}	
ρ	nominal seawater density	1.02 g cm^{-3}	
$\partial U / \partial z$	nominal vertical velocity gradient	≈0.06 sec^{-1}	
K_b	Background vertical diffusivity.	---	≈0.5 $cm^2\ sec^{-1}$
η_0	Background vertical viscosity.	---	≈5 $cm^2\ sec^{-1}$

Table II.3. Comparisons among LOICZ, MA48, and Y99 calculations of water fluxes in Manila Bay (based on data in Jacinto *et al.* 2000).

QUANTITY	**Manila Bay** (Jacinto *et al*. 2000)	***LOICZ*** (10^9 m^3 yr^{-1}) [except as noted]	***MA48*** (10^9 m^3 yr^{-1}) [except as noted]	***Y99*** (10^9 m^3 yr^{-1}) [except as noted]
h	850 cm			
F	40,000 m			
S_{syst-d}	33.0 psu			
S_{syst-s}	32.0 psu			
S_{ocn-d}	34.4 psu			
S_{ocn-s}	34.4 psu			
Stratification parameter	0.0012			
V_{syst}	$30x10^9$ m^3			
A_{syst}	$1.7x10^9$ m^2			
A_{deep}	$150x10^3$ m^2			
A_{surf}	$220x10^3$ m^2			
V_{Q*}	$25x10^9$ m^3 yr^{--1}			
K_Z		0.74 cm^2 sec^{-1}	0.44 cm^2 sec^{-1}	0.54 cm^2 sec^{-1}
V_Z		466	278	340
D_H		---	9.7 x 10^6 cm^2 sec^{-1}	6.5 x 10^6 cm^2 sec^{-1}
V_{Xdeep}		---	115	77
V_{Xsurf}		---	169	114
V_{deep}		333	116	188
V_{surf}		-358	-141	-213
V_{ent}		333	116	188
τ		31 days	26 days	26 days

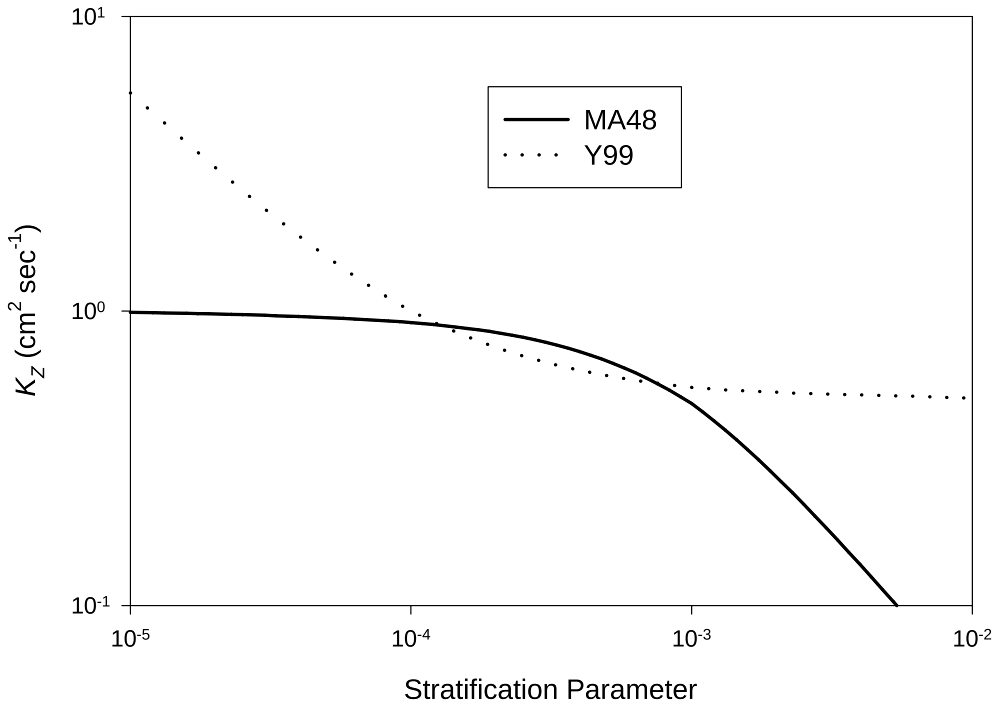

Figure II.1. Stratification parameter versus two estimates of K_Z as a function of that parameter (see text for definitions of terms).

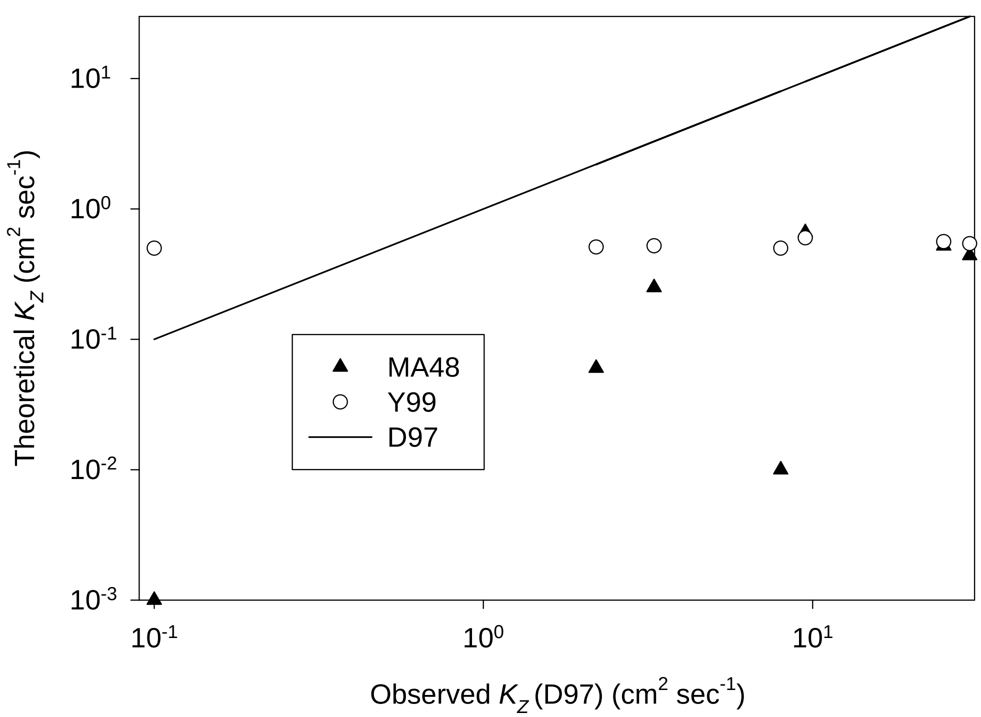

Figure II.2. Observed K_Z for 7 estuaries (from Dyer, 1997) versus K_Z calculated for those systems.

Appendix III Workshop Report

Welcome

Participants (Appendix IV) were welcomed to the workshop venue at the Hong Kong Baptist University, Kowloon, Hong Kong by the local host, Prof. Ming Wong. Support arrangements and the purpose of the workshop were outlined. The agenda (Appendix V) was introduced and working documents, diskettes and CD-ROMs of support and tutorial materials were distributed to participants.

Introduction and Tutorials

An introduction to the LOICZ Core Project of IGBP (Dr Chris Crossland) provided a context of goals and approaches being undertaken to describe global changes in materials fluxes in the coastal zone, and a framework for the workshop activities. A comprehensive description of the LOICZ biogeochemical budgeting approach by Prof. Stephen Smith, and the planned interpolation of local scaled information to global scales gave a foundation for the workshop enterprise. A detailed tutorial addressed key elements and tools available to researchers for the derivation of C-N-P budget models and estimation of net metabolism of coastal systems. These included:

- Biogeochemical budget construction and calculations (Vilma Dupra);
- Introduction and description of a new tool developed for use in site nutrient budget calculation – CABARET software (Dr Laura David). CD-ROM copies of the software were provided to all workshop participants;
- Waste load estimation and relationships for calculation were described (Dr Maria Lourdes San Diego McGlone) and copies of a recent publication in Marine Pollution Bulletin by McGlone and others were circulated;
- Alternative methods for estimating system exchange were addressed by Prof. Tetsuo Yanagi, and case examples were discussed.

Presentation of Site Biogeochemical Budgets

The preliminary budgets brought by the participants for regional sites were briefly presented and discussed. Key points included system settings, box arrays needed to encompass the sites, data availability and quality, and key features about the socio-economic settings and changes.

System sites included:

Japan
Dokai Bay (and comparison with an existing model for Hakata Bay)

China
Aimen Estuary, Pearl River delta
Modaomen Estuary, Pearl River delta
Jiulong River estuary

Korea
Nakdong River estuary
Sumjin River estuary

Regional Sea
Yellow Sea

Russia
Amursky Bay and Tavrichanka River estuary

Taiwan
Chiku Lagoon
Tapong Bay
Tsengwen River estuary
Tanshui River estuary

[Budgets recently developed for sites from the adjacent South China Sea region are also included, following on from efforts after the previous regional workshop: PhanThiet Bay, VanPhong Bay, Tien River estuary, ThuBon River estuary (Vietnam); and Teluk Banten (Indonesia). The Vietnam budgets were developed by Nguyen Huan as a result of his time in Hawaii on the South China Sea Regional Workshop Scholarship].

Budgets Development

Break-out groups worked interactively on the development of these systems, supplemented with methodological and site/issue tutorials and discussions. Estimates for sites and evolution of assessment approaches were made and budget refinements emerged from resolution of techniques, application of derivative data, and assessment of estuarine mixing/exchange and watershed information.

Participants identified further sites which could be the subject of additional budget developments including : Amur River estuary, Amursky Bay (Russia); addition of allied systems such as Xiamen Arm to the Jiulong River estuary (China); estuaries on eastern side of Yellow Sea (Korea) and Yalujiang River estuary (China/North Korea)

Outcomes and Wrap-up

Budgets for all systems were developed to interim draft stage of completion during the workshop; text additions and checks on data sources were required for completion of most budgets. A schedule for contribution of final documents, report and publication, along with the process for review and editing was agreed, noting that hard-copy reports, web-posting and CD-ROM products are planned.

Members of the Project steering committee met informally during the workshop to plan content and programs for further workshops, and to review and finalise arrangements for preparation and publication of tutorial materials.

The participants joined with LOICZ in expressing thanks to Prof. Ming Wong, Dr K.C. Cheung and Ms Doris Ng, Department of Biology and Institute of Waste Management, Hong Kong Baptist University, for the excellent support and hosting of the workshop in Hong Kong. The financial support of the Global Environment Facility was gratefully acknowledged.

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Appendix V Workshop Agenda

LOICZ/UNEP Workshop on
Estuarine Systems of the East Asia Region
Hong Kong Baptist University
Hong Kong
13-15 June 2000

Tuesday, June 13:

0900-0915	Welcome, introduction and housekeeping (Stephen Smith, Ming Wong, Chris Crossland)
0915-0930	Overview of LOICZ (Chris Crossland)
0930-1020	Technical overview: LOICZ budgeting and interpolation (Stephen Smith)
1020	Coffee and discussion
1040-1100	Tutorial: details of LOICZ budgeting (Vilma Dupra)
1100-1120	Tutorial: tools for calculations (CABARET software), run off algorithm (Laura David)
1120-1140	Tutorial: waste load estimates (Maria Lourdes McGlone)
1140-1200	Example: “non-budget” approach to estimating exchange (Tetsuo Yanagi)
1200	Lunch and discussions
1300	Case studies overview
1300-1320	Dokai Bay, Japan (Tetsuo Yanagi)
1320-1340	Pearl River delta (Ming Wong and KC Cheung)
1340-1400	Amursky Bay/Tavichanka estuary (Anatoly Mozherovsky)
1400-1420	Yellow Sea (Chang Soo Chung)
1420-1440	Nakdong River estuary (Sung RyullYang)
1440-1500	Jiulong River estuary (Hua-sheng Hong and Wenzhi Cao)
1500	Coffee and discussion
1520-1540	Chiku Lagoon (Jia-Jang Hung)
1540-1600	Tapong Bay (Jia-Jang Hung)
1600-1700	Discussion of ongoing workshop structure: What mix of tutorial, formal presentations and/or plenary discussions will fit the needs of the workshop participants.

Wednesday June 14:

0900-0915	Brief reminder of working arrangements
0915-1200	Breakout groups/individuals refining budgets
1200	Lunch
1300-1630	Breakout groups or plenary, as required to refine and present developed budgets
1630-1700	Plenary to present or discuss budgets

Thursday June 15:

0900-0915	Brief review of program and working arrangements
0915-1200	Breakout groups, plenary to discuss budgets and start preliminary regional synthesis
1200	Lunch
1300-1500	Plenary wrap-up discussion
1445-1500	Closing announcements
1500+	Informal discussions

LOICZ/UNEP Workshop on
Estuarine Systems of the East Asia Region
Hong Kong Baptist University
Hong Kong
13-15 June 2000

Primary Goals:
To work with researchers dealing with estuarine systems of the East Asia region, in order to extract C,N,P budgetary information from as many systems as feasible from existing data. The East Asian systems include one of the major coastal regions of the world oceans and are heavily influenced by anthropogenic activity. The workshop provides the opportunity to characterize terrigenous inputs to the estuaries of the region, and outputs from the estuaries - hence the net role of the estuarine zone of this region as a source or sink for carbon, nitrogen, and phosphorus.

This workshop will complement earlier workshops, held in
- Ensenada, Mexico (June 1997);
- Canberra, Australia (October 1998);
- Merida, Mexico (January 1999);
- Manila, Philippines (July 1999);
- Bahia Blanca, Argentina (November 1999); and
- Goa, India (February 2000).

It is hoped that each workshop participant will be able to bring the available data for at least two budgets: one from one of the "pollution hot spot" regions within their country, and one for a physiographically fairly similar region which is apparently subjected to less pollution. By this strategy, we hope to compile a set of sites that will represent a relatively wide range of human pressures in the East Asia region.

Anticipated Products:
1. Develop budgets for as many systems as feasible during the workshop.
2. Examine additional data, brought by the researchers, or provided in advance, to scope out how many other systems can be budgeted over an additional two months.
3. Prepare a LOICZ technical report and a CD-ROM summarizing this information.
4. Contribution of these sites to 1-2 papers to be published in the refereed scientific literature.
5. It is anticipated that one participant from the workshop will be offered the opportunity to spend up to two months in Hawaii or Manila, getting further experience and developing additional budgets for the region.

Participation:
The number of participants will be limited to fewer than 18 persons, to allow the active involvement of all participants. Nominees include:
- Three to five resource persons (regional and external);
- Up to 13 researchers from the region (see below).

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 budgets and tutorials presented on the LOICZ Modelling web page (http://data.ecology.su.se/MNODE/), and arriving with preliminary budgets, electronic maps, and 1-3 page write-ups from “their” sites. In order to be included in the workshop report, the budgets should conform as well as possible to the budgeting protocol laid out in the above documentation. Guidelines for budget preparation and write-ups and a

tutorial package entitled CABARET can (and should) be downloaded from the LOICZ Modelling website.

Further Details:
At an absolute minimum, each participant is expected to arrive at the workshop (or send us in advance) the following materials:

1. A 1-3 page description of the area (see materials posted on the Web and in the various workshop reports) and a map of the site. These should be in electronic format.
2. Within the context of needs for the overall LOICZ project, some estimate of water exchange (most commonly via water and salt budgets) and budgets for the dissolved inorganic nutrients, nitrogen and phosphorus, constitute the minimum useful derivations from the biogeochemical budgeting. Budgets of other materials, while potentially interesting for other purposes, do not satisfy this minimum requirement. The minimum data requirements are as follows:
    a. The primary seasonal pattern of the region is at least one wet season and one dry season per annum. Ideally, a budget for each season should be developed. If a system is vertically stratified, then a 2-layer budget is preferred over a single-layer budget. If a system has a strong land-to-sea salinity gradient, then it is preferable to break the system along its length into several boxes.
    b. Data requirements to construct a satisfactory water and salt budget include: salinity of the system and the immediately adjacent ocean, runoff, rainfall, evaporation, and (if likely to be important) inputs from other freshwater sources such as groundwater or sewage. Preferably, the salinity and freshwater inflow data are for the same time period (for example, freshwater inflow data for a month or so immediately prior to the period of salinity measurement). In the absence of direct runoff estimates for small catchments, estimations can be made from a knowledge of catchment area and monthly rainfall and air temperature for the catchment. See materials on the LOICZ biogeochemical modelling web site.
    c. Data requirements for the nutrient budgets are: concentrations of dissolved nutrients (phosphate, nitrate, ammonium and, if available, dissolved organic N and P) for the system and the adjacent ocean, concentrations of nutrients in inflowing river water (and, if important, in groundwater), some estimate of nutrient (or at least BOD) loading from sewage or other waste discharges. If atmospheric deposition (particularly of N) is likely to be important, an estimate of this is also useful. If direct waste load measurements are not available, estimations can be made from a knowledge of the activities contributing to the waste loads and the magnitudes of those activities. See the materials on the website.

Workshop Schedule (All participants are expected to stay for the entire workshop):

June 12: Arrival
June 13: General introduction to the budgeting procedure and related issues; presentation of preliminary budgets (no details, simply a quick summary to see who has what.)
Breakout groups to revise and refine budgets. This will vary, as needed, from tutorial, through detailed help, to procedural discussions.
June 14: Continue breakouts; afternoon plenary to evaluate progress.
June 15: Breakouts/plenary as required to develop synthesis.
June 16: Departure.

Background Documents:

1. Gordon, D.C., Boudreau, P.R., Mann, K.H., Ong, J.-E., Silvert, W., Smith, S.V., Wattayakorn, G., Wulff, F. and Yanagi, T. 1996 LOICZ Biogeochemical Modelling Guidelines. *LOICZ Reports and Studies* **5**, 96 pages.
2. 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**, 84 pages.
3. LOICZ Modelling web page, for everyone with www access: (http://data.ecology.su.se/MNODE/).

- The LOICZ web pages, including the guidelines, are frequently updated. Recent additions to the site include several PowerPoint presentations designed to familiarize participants further with the budgeting procedures and with an overview of the LOICZ budgeting efforts.
- A CD-ROM with the current web page will be available during the workshop.
- CABARET (Computer Assisted Budget Analysis, Research, Education, and Training). A version of this software and a PowerPoint demonstration of its use are available on the web site and update version will be provided at the workshop.

Appendix VII Glossary of Abbreviations

NH_4	Ammonium
NO_3	Nitrate
DIN	Dissolved inorganic nitrogen
DON	Dissolved organic nitrogen
DIP	Dissolved inorganic phosphorus
DOP	Dissolved organic phosphorus
POP	Particulate organic phosphorus
PON	Particulate organic nitrogen
PTN	Particulate total nitrogen
PTP	Particulate total phosphorus
ON	Organic nitrogen
OP	Organic phosphorus
TN	Total nitrogen
TP	Total phosphorus
DOC	Dissolved organic carbon
DIC	Dissolved inorganic carbon
POC	Particulate organic carbon
OC	Organic carbon
SiO_4	Silicate
nfix	Nitrogen fixation
denit	Denitrification
p	Primary production
r	Respiration
TDN	Total dissolved nitrogen
TDP	Total dissolved phosphorus
CTD	Conductivity Temperature Depth