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 14,800×10^6 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*.

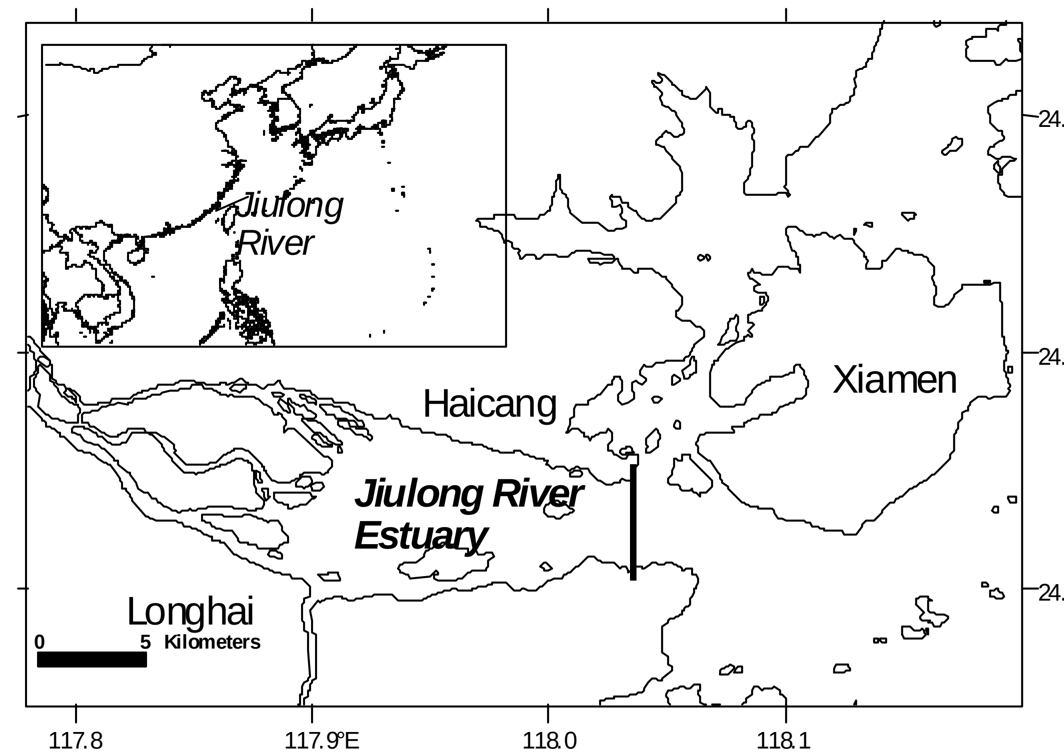

Figure 6.1. Map and location of the Jiulong River estuary. The line shows the boundary of the budgeted system.

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 $85x10^9$ 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 *DDIP* 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 *DDIP* 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.

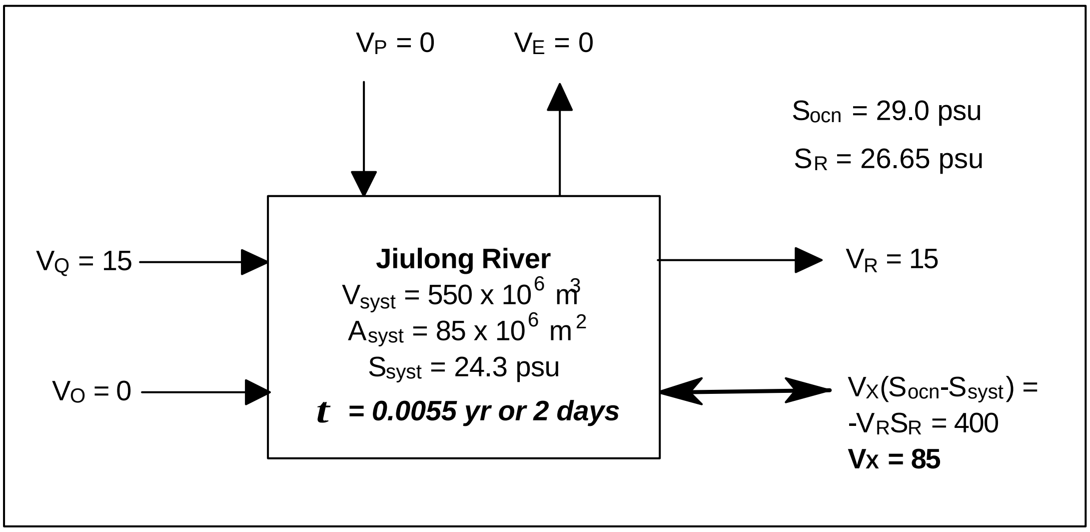

Figure 6.2. Water and salt budgets for the Jiulong River estuary system. Water flux in 10^9 m^3 yr^{-1} and salt flux 10^9 psu-m^3 yr^{-1}.

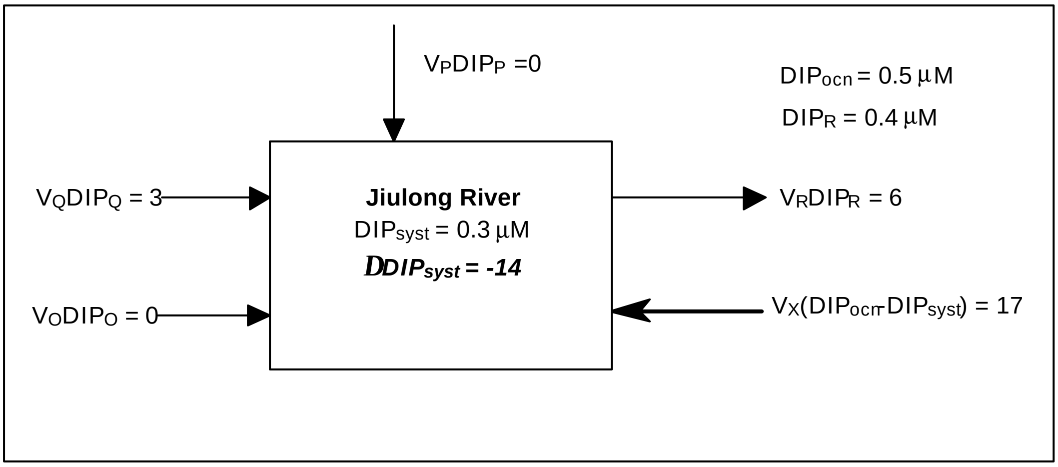

Figure 6.3. DIP budget for the Jiulong River estuary system. Flux in 10^6 mol yr^{-1}.

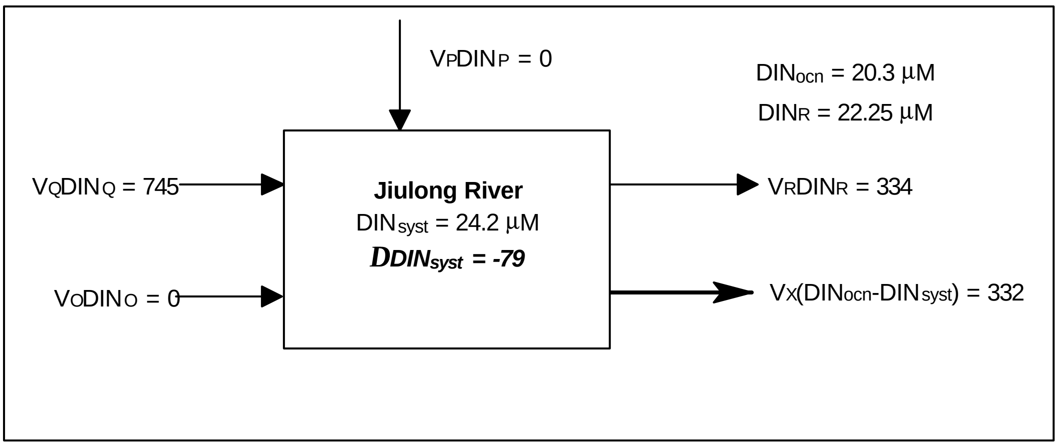

Figure 6.4. DIN budget for the Jiulong River estuary system. Flux in 10^6 mol yr^{-1}.

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).

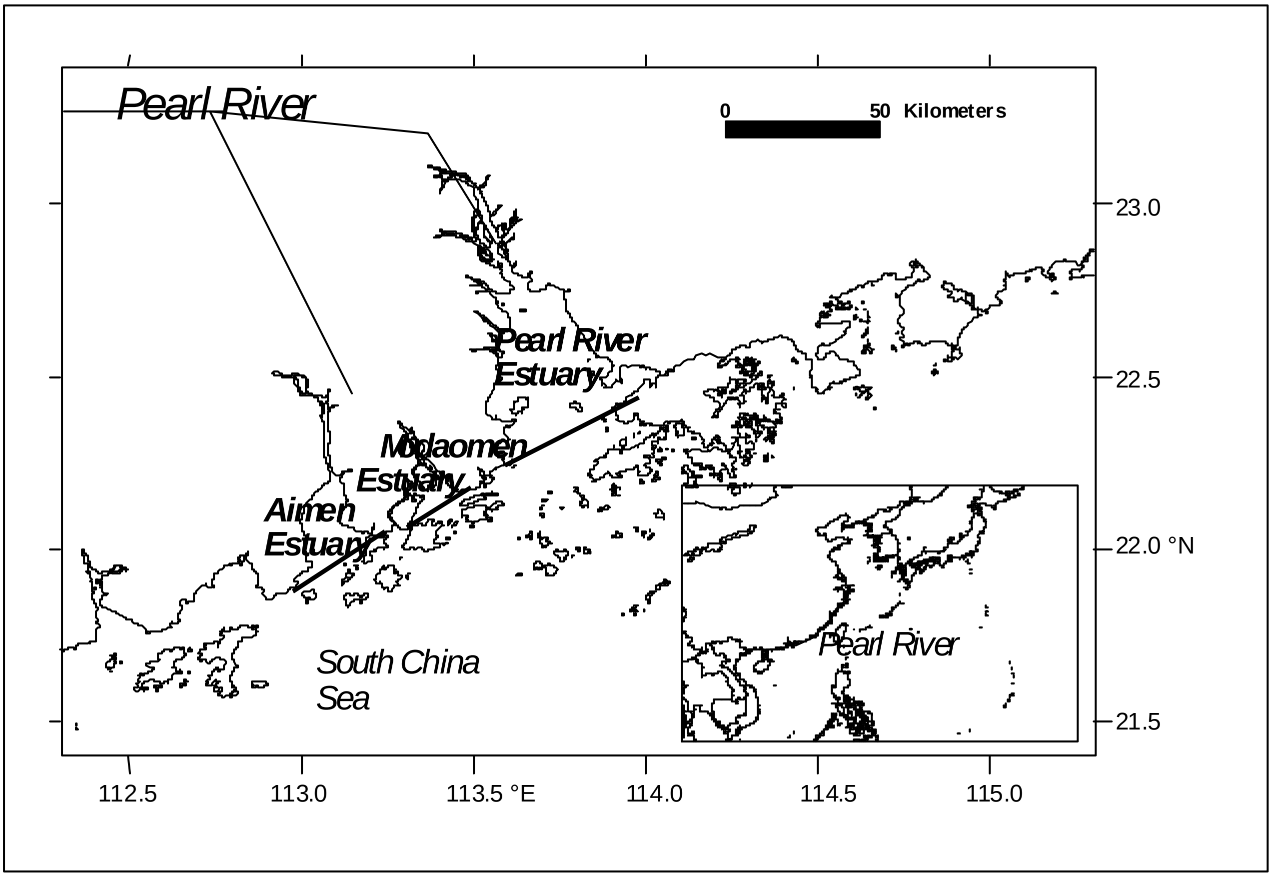

Figure 6.5. Studied estuaries in the Pearl River delta. Bars represent boundaries of the budgets.

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	Depth	Volume	***River inflow*** **(10^6 m^3 d^{-1})**	
	(10^6 m^2)	**(m)**	**(10^6 m^3)**	*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

Budgets of nonconservative materials
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 *DY*, 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 *DDIP* being from about -100 to -500x10^3 mol d^{-1} and *DDIN* 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 *DDIP* according to the relationship (Gordon *et al.* 1996):

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

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

$$(nfix\text{-}denit) = DDIN - DDIP \times (N:P)_{part} \qquad (4)$$

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***			
	DDIP	***DDIN***	**(*p-r*)**	**(*nfix-denit*)**	***DDIP***	***DDIN***	***(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).

	DDIP	***DDIN***	***(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

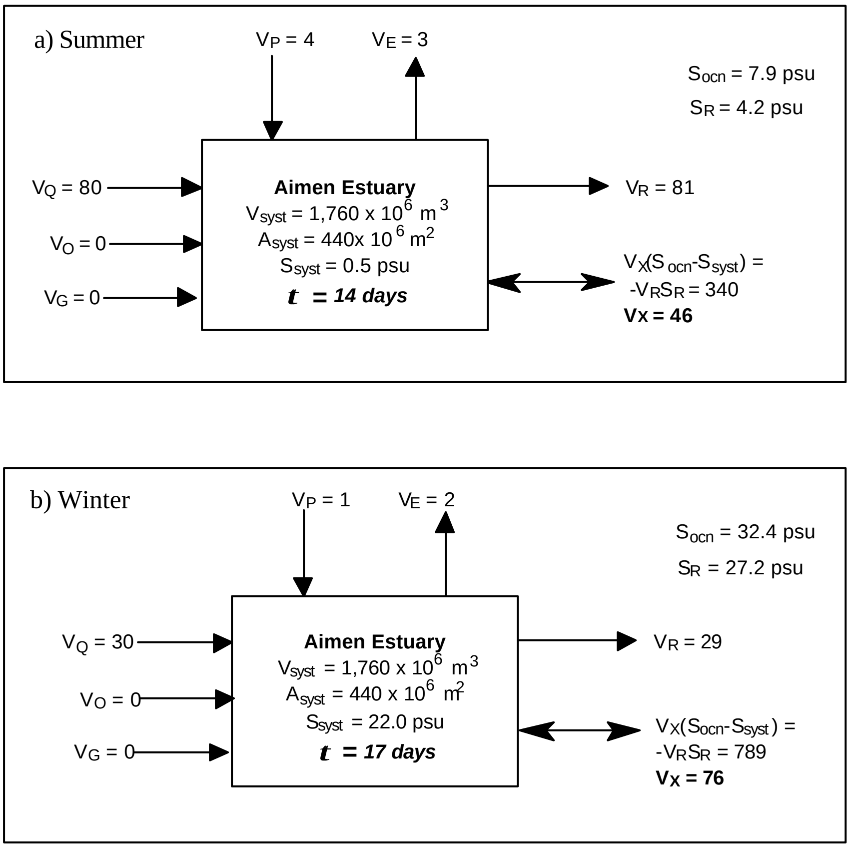

Figure 6.6. Water and salt budgets for the Aimen Estuary in summer and winter. **Water flux in 10^6 m^3 d^{-1} and salt flux in 10^6 psu-m^3 d^{-1}.**

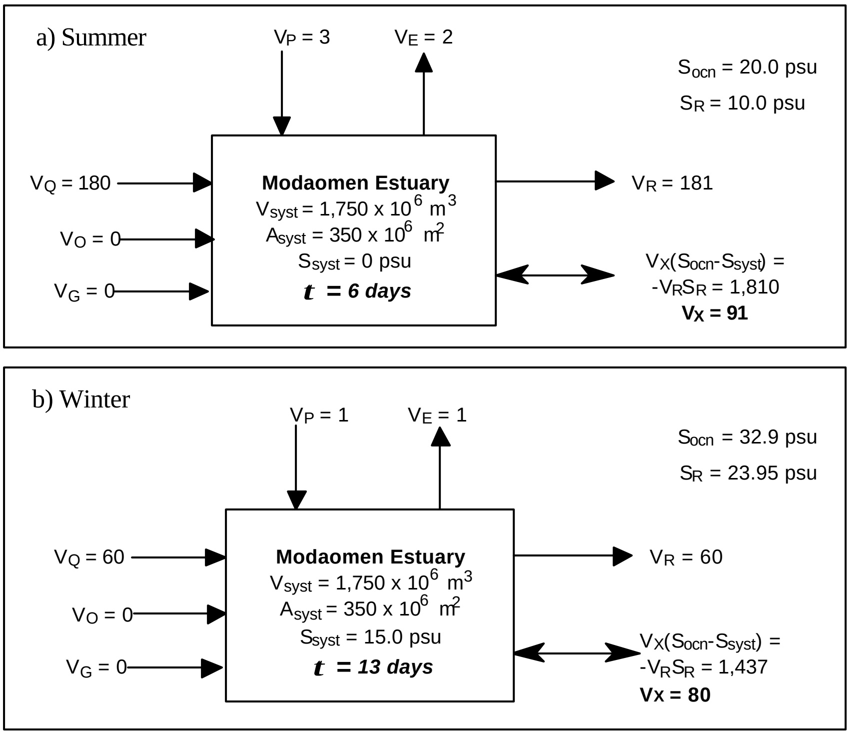

Figure 6.7. Water and salt budgets for the Modaomen Estuary in summer and winter. **Water flux in 10^6 m^3 d^{-1} and salt flux in 10^6 psu-m^3 d^{-1}.**

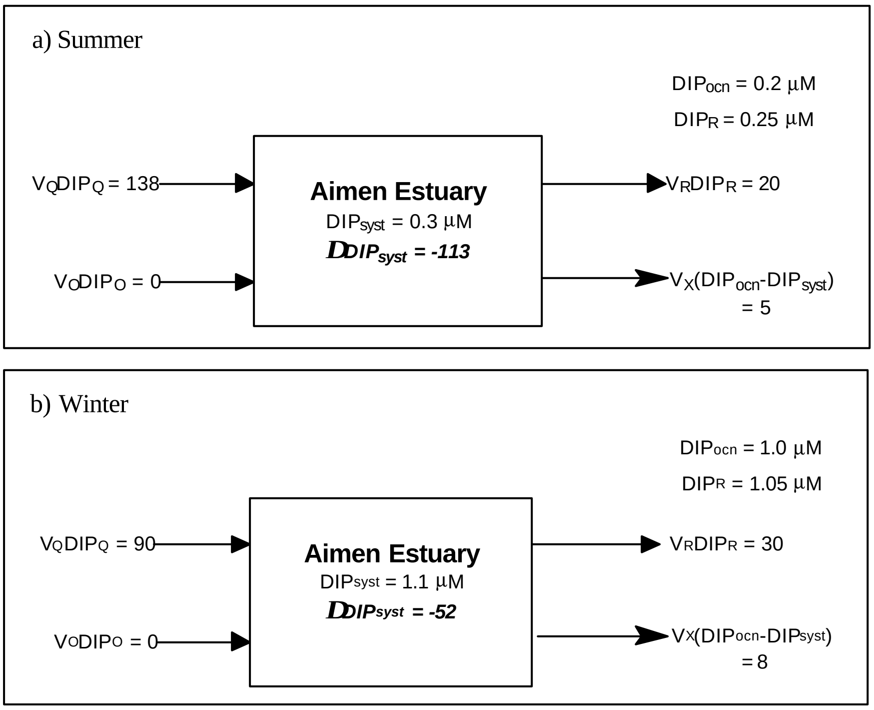

Figure 6.8. Dissolved inorganic phosphorus budget for the Aimen Estuary in summer and winter. Flux in 10^3 mol d^{-1}.

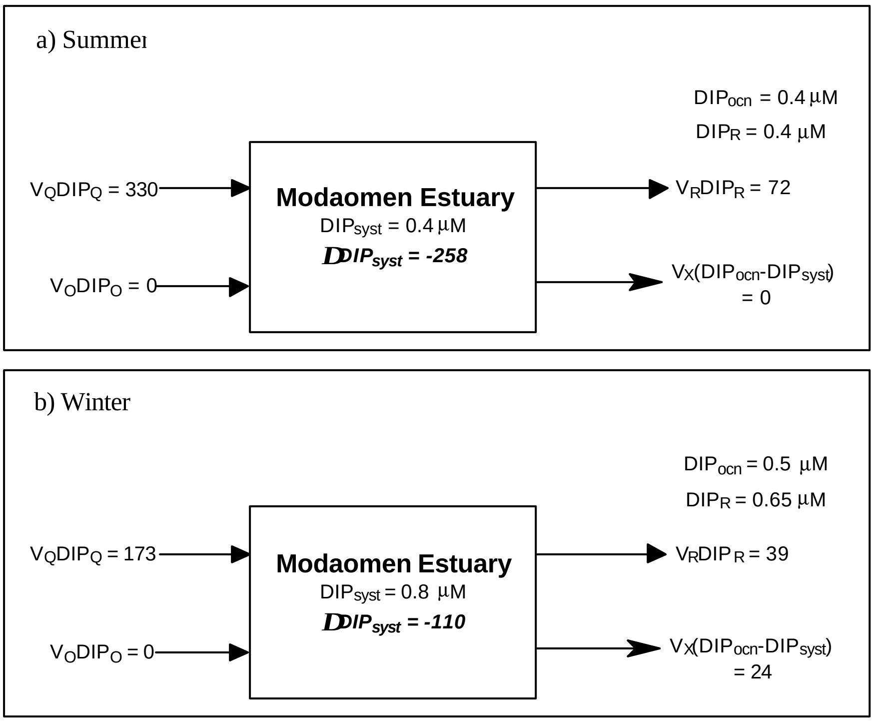

Figure 6.9. Dissolved inorganic phosphorus budget for the Modaomen Estuary in summer and winter. Flux in 10^3 mol d^{-1}.

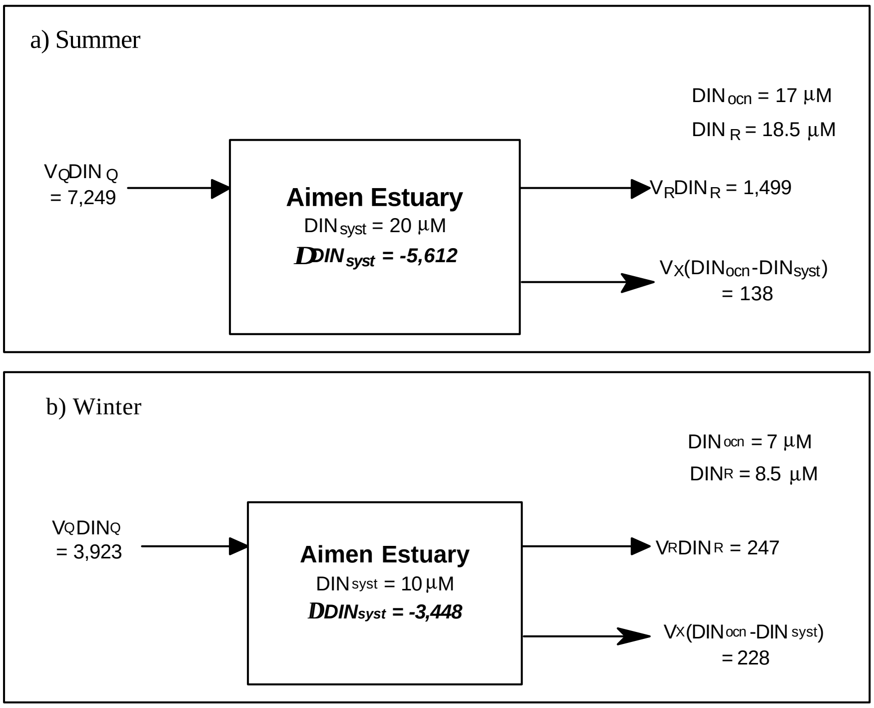

Figure 6.10. Dissolved inorganic nitrogen budget for the Aimen Estuary in summer and winter. Flux in 10^3 mol d^{-1}.

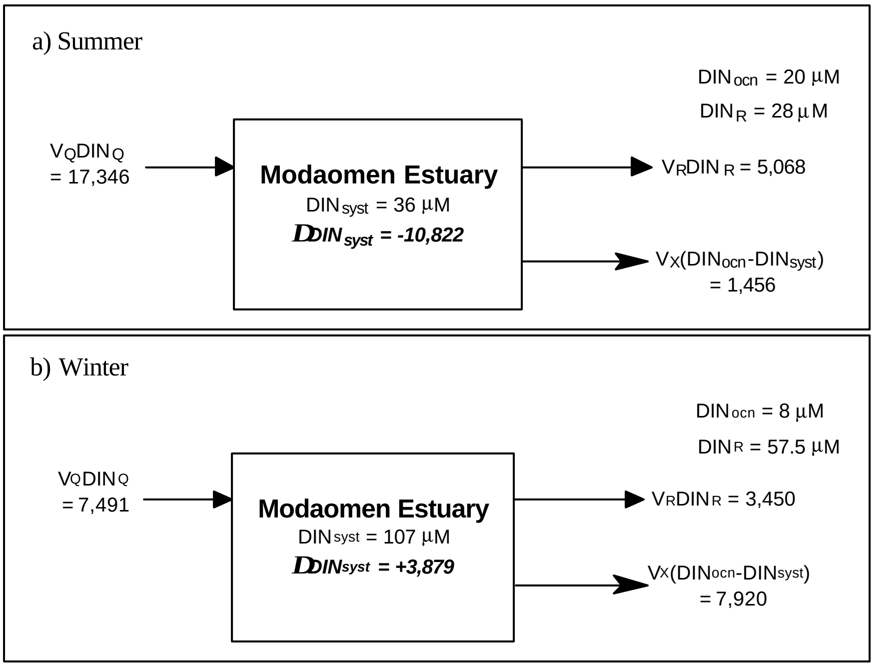

Figure 6.11. Dissolved inorganic nitrogen budget for the Modaomen Estuary in summer and winter. Flux in 10^3 mol d^{-1}.

6.3 Yalujiang River Estuary, China-North Korea

Christopher J. Crossland and Janet I. Marshall Crossland

<u>Study site description</u>

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.

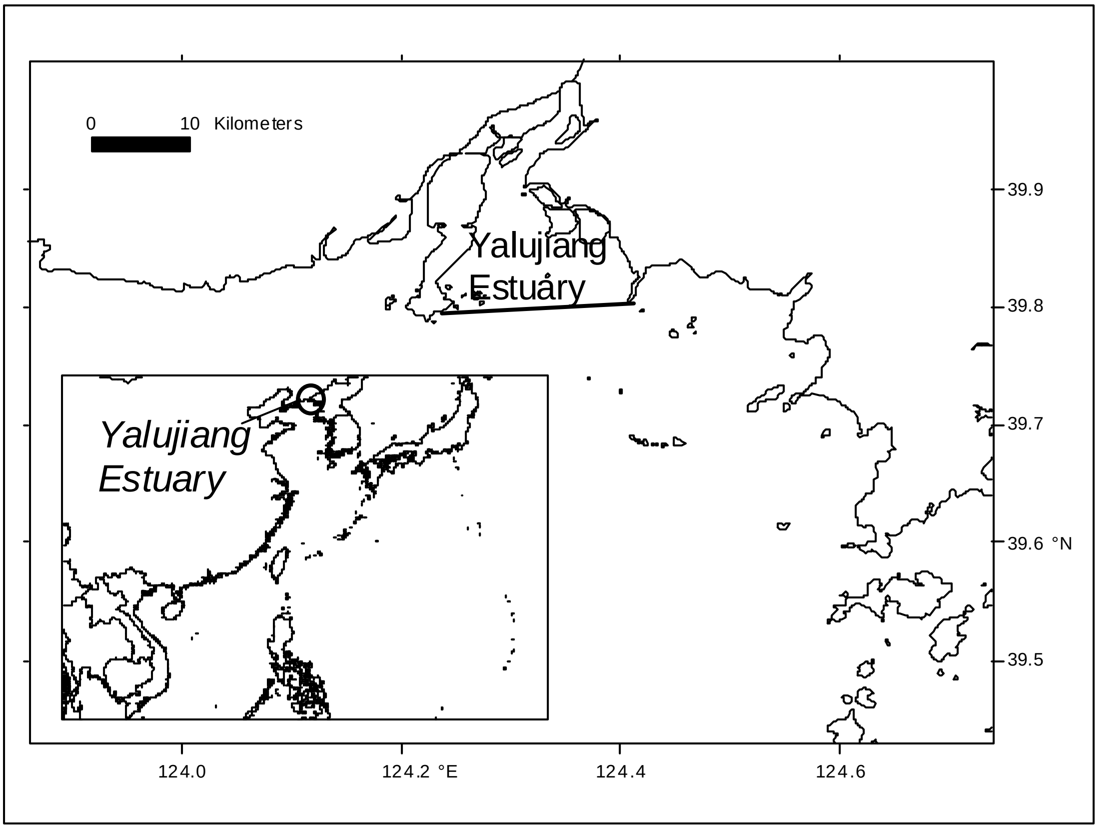

Figure 6.12. Map and location of the Yalujiang River estuary.

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: $+76 \times 10^3$ mol d^{-1} (or +0.4 mmol m^{-2} d^{-1}).
Dry season: ΔDIP for the system: $+13 \times 10^3$ 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: -46×10^6 mol d^{-1} (or -271 mmol m^{-2} d^{-1}).
Dry season: ΔDIN for the system: $+1 \times 10^6$ 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 8 µM 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.

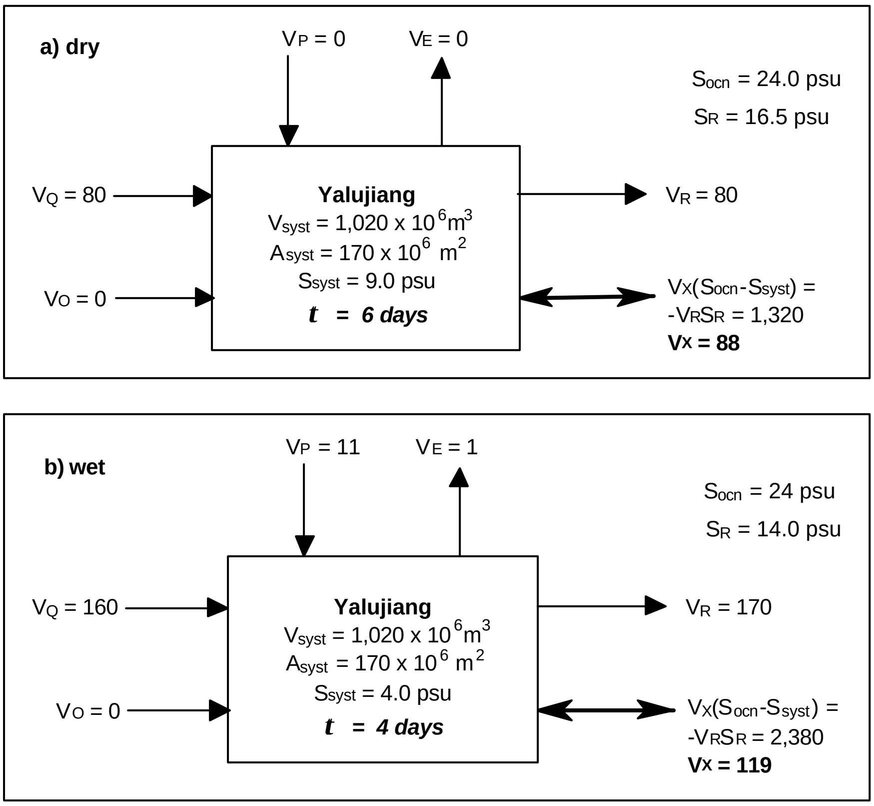

Figure 6.13. Water and salt budgets for Yalujiang River estuary, during dry (a) and wet (b) seasons. Water fluxes in 10^6 m^3 d^{-1}; salt fluxes in 10^6 psu m^3 d^{-1}.

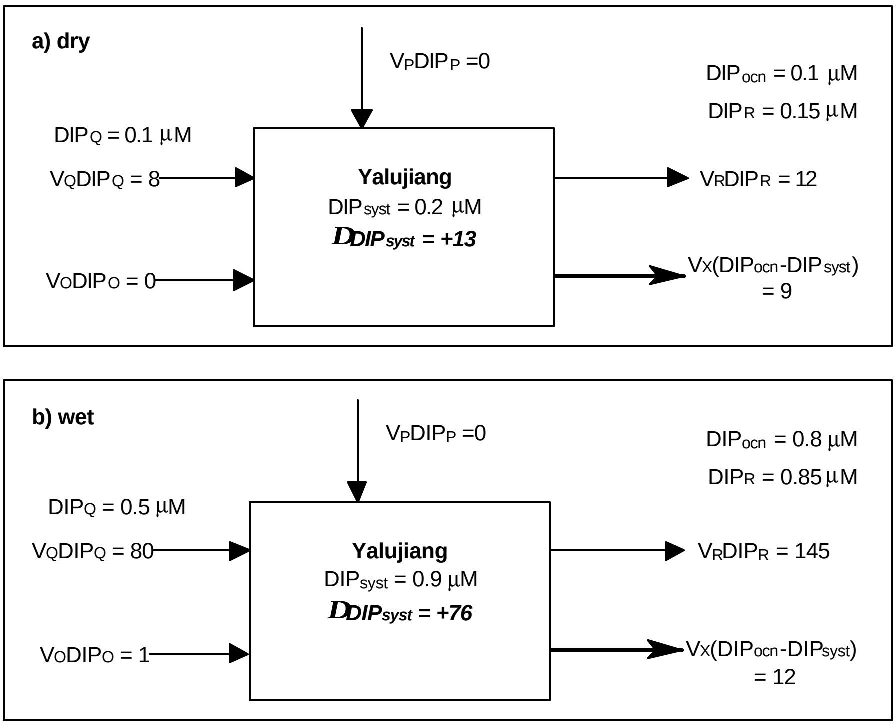

Figure 6.14. DIP budgets for the Yalujiang River estuary during dry and wet seasons. Fluxes in 10^3 mol d^{-1}.

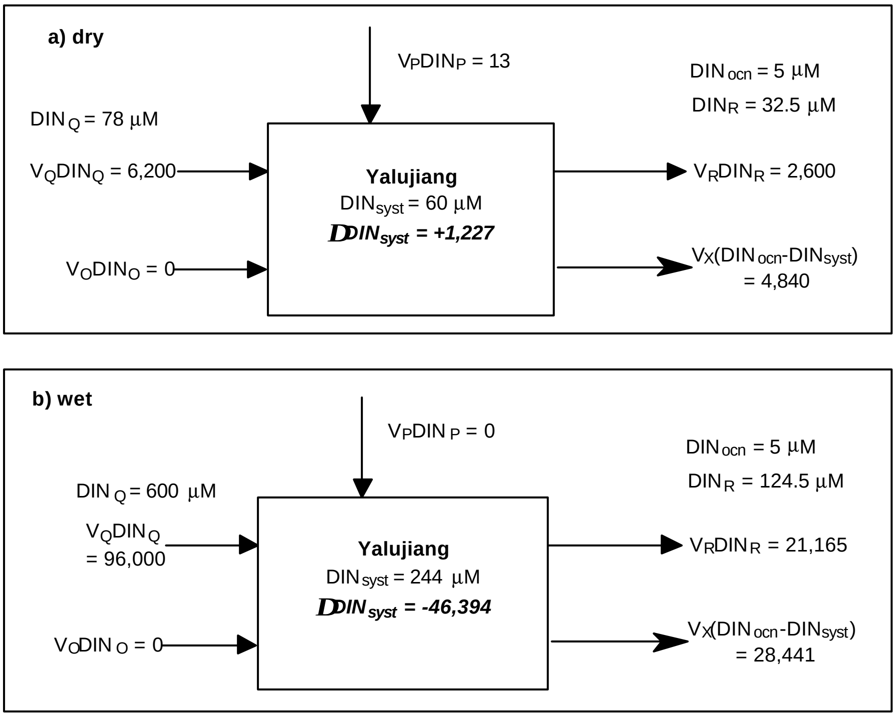

Figure 6.15. DIN budgets for the Yalujiang River during dry and flood seasons. Fluxes in 10^3 mol d^{-1}.