7. BUDGETS FOR ESTUARINE SYSTEMS IN TAIWAN

7.1 Chiku Lagoon

Jia-Jang Hung and Fancy Kuo

Study area description

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).

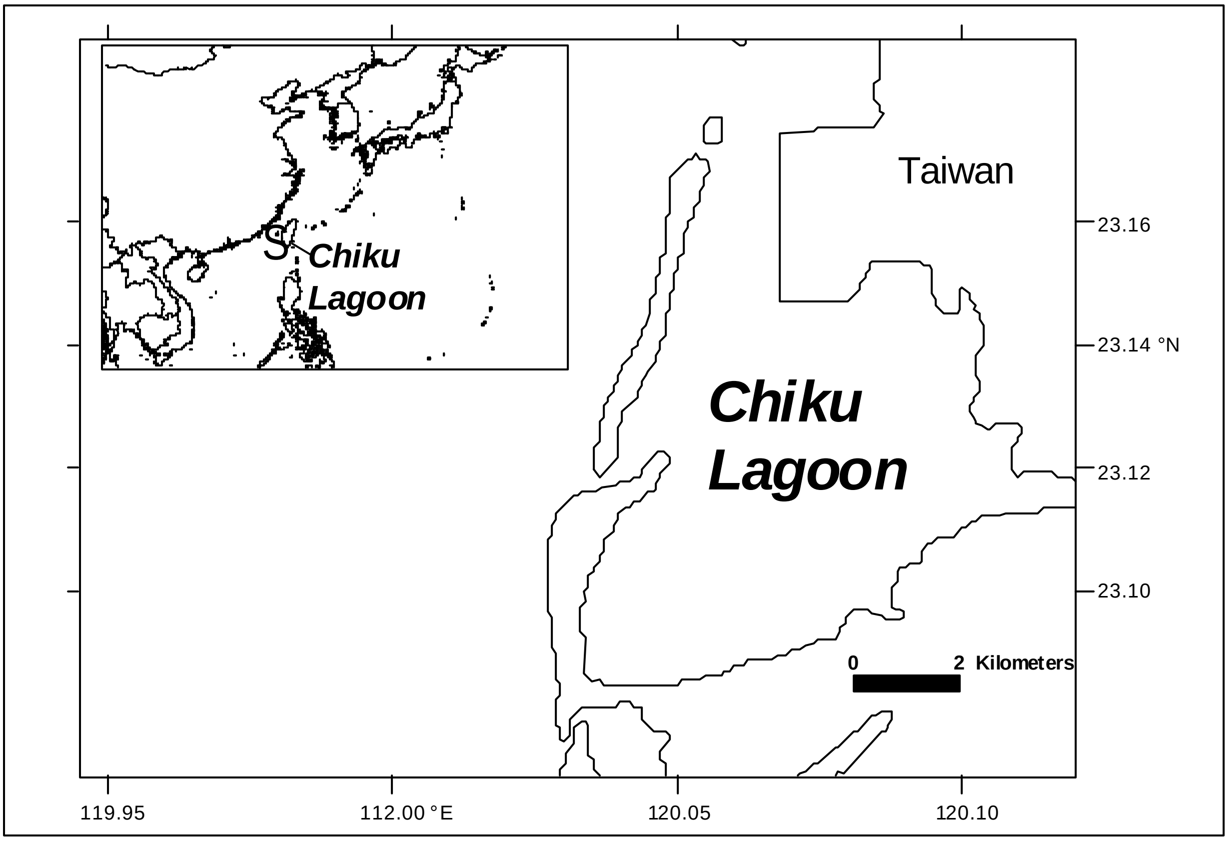

Figure 7.1. Map and location of Chiku Lagoon.

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.

Water and salt balance

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 simply derived from final means of various parameters.

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

Sampling period	**Freshwater input** ($10^3 m^3 d^{-1}$)			**Residual flow** ($10^3 m^3 d^{-1}$)	**Ocean salinity** (psu)	**Lagoon salinity** (psu)	**Exchange Volume** ($10^3 m^3 d^{-1}$)	**ô** (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 (ô) 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 (*ÄDIP*) and DOP (*ÄDOP*) 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 *ÄDIP* 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 *ÄDIP* 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 (*ÄDOP*) is negligible. The *ÄTDP* (*ÄDIP* +*ÄDOP*) 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 (*ÄDIN*) and DON (*ÄDON*) 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. *ÄDIN* is considerably greater than *ÄDON*.

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

Time	*ÄDIP* (10^3 mol d^{-1})	*ÄDOP* (10^3 mol d^{-1})	*ÄDIN* (10^3 mol d^{-1})	*ÄDON* (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	*ÄDIP* (mmol m^{-2}d^{-1})	*ÄDOP* (mmol m^{-2}d^{-1})	*ÄDIN* (mmol m^{-2}d^{-1})	*ÄDON* (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 *ÄDIP* 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-r) = -106 × *ÄDIP* = -106 × (-0.1 mol m^{-2} yr^{-1}) = +11 mol m^{-2} 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 *ÄTDN*. Expected *ÄTDN* is *ÄTDP* multiplied by N:P ratio of particulate organic matter. The particulate N:P ratio is assumed to be 16. Thus:

(*nfix-denit*) = -3 mol m^{-2} yr^{-1} – (-0.1×16) mol m^{-2} yr^{-1} = -1 mol m^{-2} 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 t** (day)	**(*p-r*)** (mol m^{-2} yr^{-1})	**(*nfix-denit*)** (mol m^{-2} yr^{-1})
Mean of modelled results from each sampling event	3,058×10^3	5	+11	-1
Modelling results from temporal means of various parameters	2,223×10^3	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.

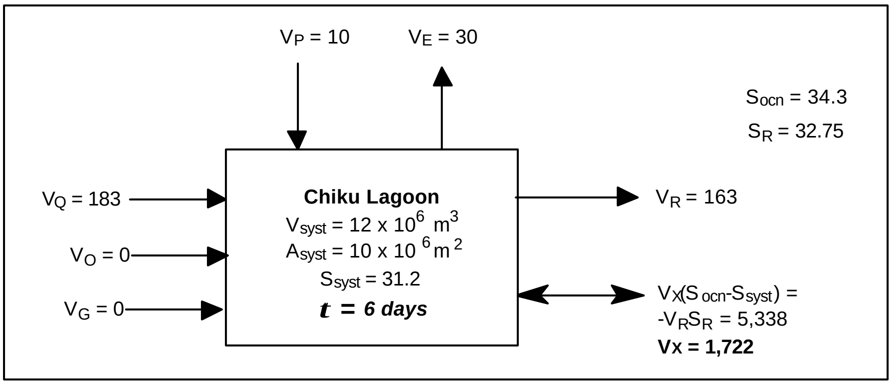

Figure 7.2. An example of water and salt budgets modelled from the first sampling event for the Chiku Lagoon. Water flux in 10^3 m^3 d^{-1} and salt flux in 10^3 psu-m^3 d^{-1}.

7.2 Tanshui River estuary

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Study area description

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).

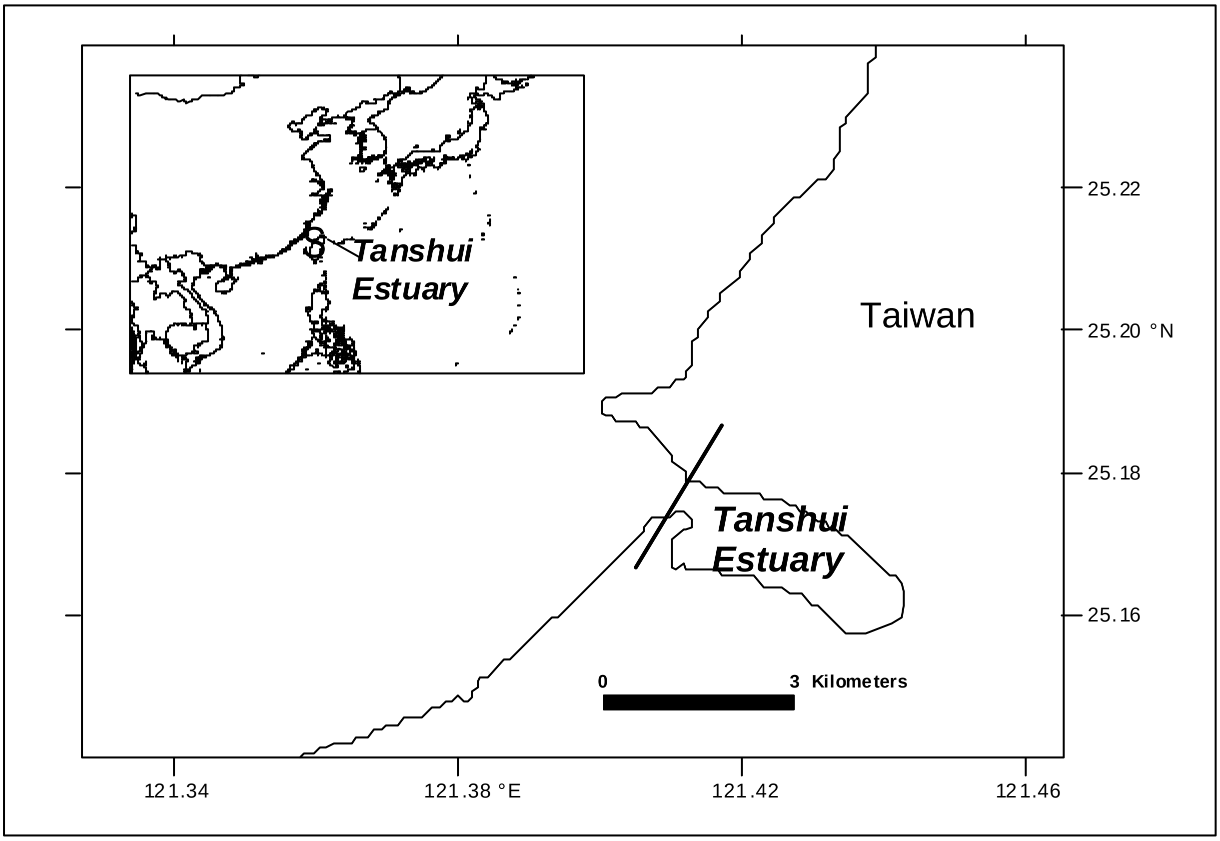

Figure 7.3. Map and location of Tanshui River estuary, Taiwan. The boundary of the budgeted area is marked.

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 6,730×10^3 m^3 d^{-1} in the dry season (March 1998) and about 8,670×10^3 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 (-9,976×10^3 m^3 d^{-1}) than for the dry season (-6,730×10^3 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 *ÄDIP* and *ÄDOP* 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 *ÄDIP* and -0.4 mmol m^{-2} d^{-1} (-0.1 mol m^{-2} yr^{-1}) for *ÄDOP* (Table 7.9). The magnitude is greater in the wet season than in the dry season. This *ÄDIP* 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 *ÄDIP* should be regarded as derived from biochemical processes (-0.06 mol m^{-2} yr^{-1}). Following such consideration, *DDOP* 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 *ÄDIN* and -14 mol m^{-2} yr^{-1} for *ÄDON*. 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 ÄDIP 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) = -ÄDIC$_o$ = 0.2 mol m^{-2} yr^{-1} x 106 = +21 mol m^{-2} yr^{-1}

If only 30% of the *DDIP* 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 ÄN, where the expected value is calculated from *ÄTDP* 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-denit) = -31 mol m^{-2} yr^{-1} – (-0.09 mol m^{-2} yr^{-1} x 16) = -26 mol m^{-2} 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.

	DDIP	*DDOP*	*DDIN*	*DDON*	*(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						

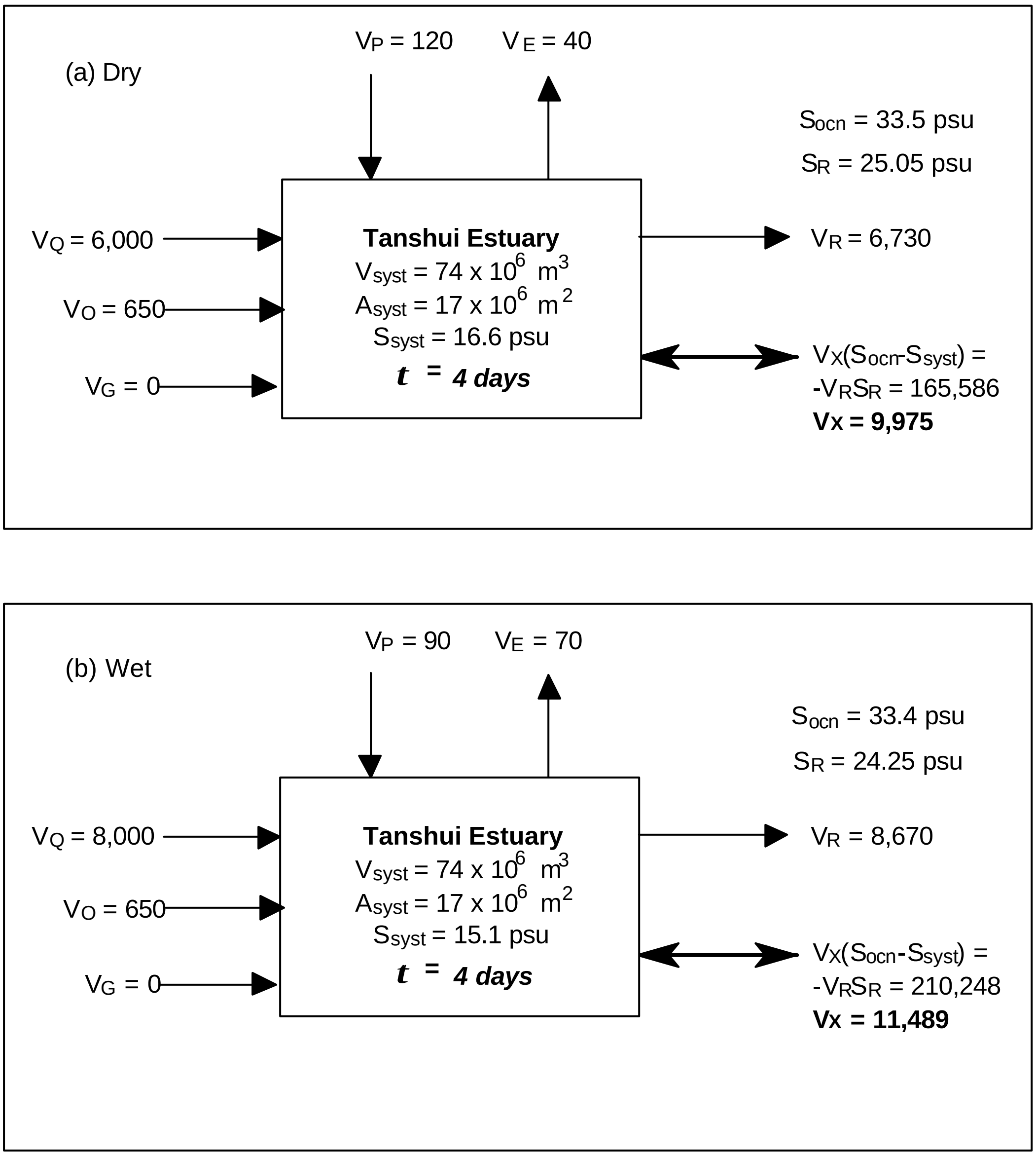

Figure 7.4. Water and salt budgets for the Tanshui River estuary during dry (a) and wet (b) seasons. Water flux in 10^3 m^3 d^{-1} and salt flux in 10^3 psu-m^3 d^{-1}.

7.3 Tapong Bay

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

Study area description

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.

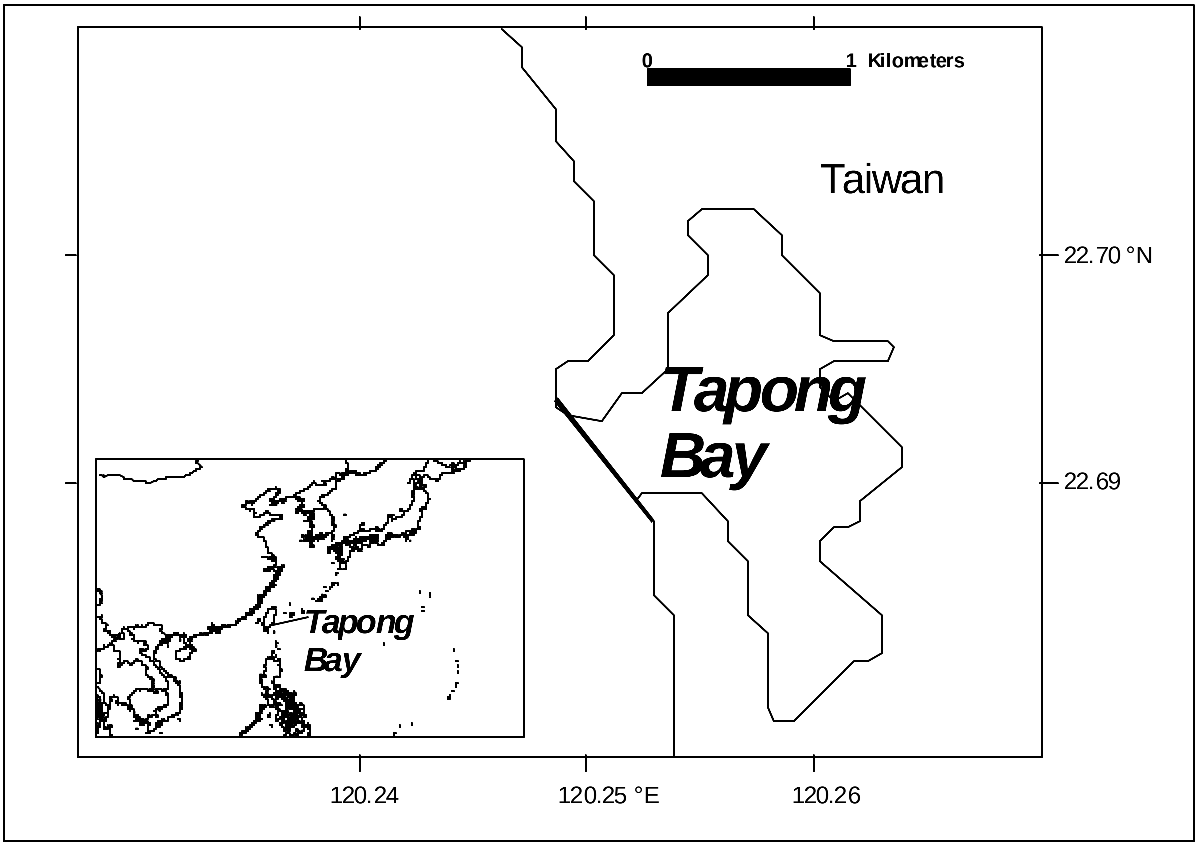

Figure 7.5. Map and location of Tapong Bay. The boundary of the budgeted area is indicated.

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 overpumping 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** ($10^3m^3d^{-1}$)			**Residual flow** ($10^3m^3d^{-1}$)	**Waste salinity** (psu)	**Ocean salinity** (psu)	**Lagoon salinity** (psu)	**Exchange volume** ($10^3m^3d^{-1}$)	**ô** (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^{3}mol d^{-1})	4.1	2.3	17	6	0.3	0.2	1	3	3.1	1.5	14	18
Mean (10^{6}mol 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 (*ÄDIP*) is a mean value of time-weighed *ÄDIP* from the dry season (August 1999) and the wet season (October 1999, December 1999 and February 2000). The *ÄDIP* 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 (*ÄDIP +ÄDOP*) 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	*ÄDIP* (10^3 mol d^{-1})	*ÄDOP* (10^3 mol d^{-1})	*ÄDIN* (10^3 mol d^{-1})	*ÄDON* (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 (*ÄDIN*) are estimated by a similar method as for *ÄDIP*, except that data for DIN in rainwater is available and included in *ÄDIN* calculations. *ÄDIN* 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, *ÄDON* 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 *ÄDIP* 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:

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

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	***ÄDIP*** (mmol $m^{-2}d^{-1}$)	***ÄDOP*** (mmol $m^{-2}d^{-1}$)	***ÄDIN*** (mmol $m^{-2}d^{-1}$)	***ÄDON*** (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: 12x10^6 m^3						

Net nitrogen fixation or denitrification (*nfix- denit*) is calculated from the difference between observed and expected *ÄN*. The expected *ÄN* is *ÄP* 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).

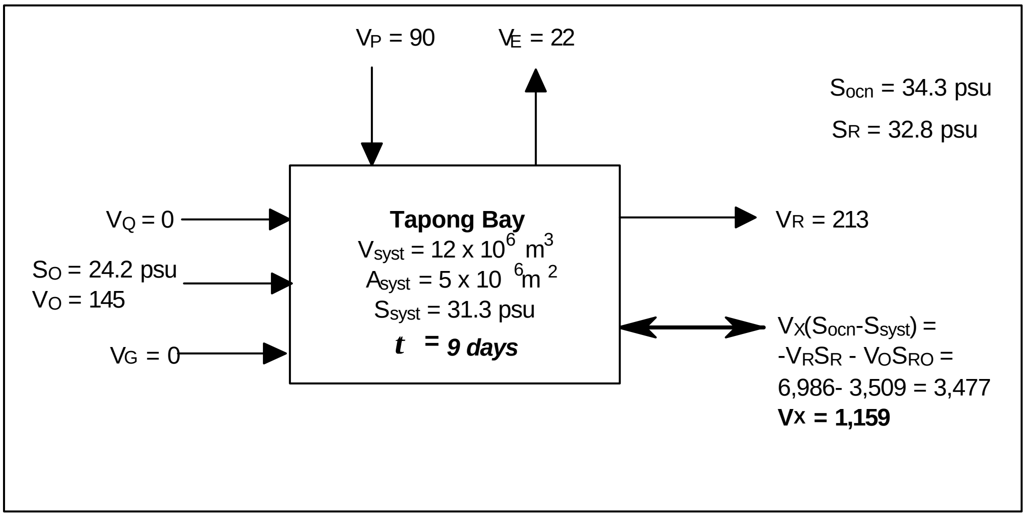

Figure 7.6. Water and salt balance for Tapong Bay during August 1999. Water flux in 10^3 m^3 d^{-1} and salt flux in 10^3 psu-m^3 d^{-1}.

7.4 Tsengwen River estuary

Jia-Jang Hung

Study area description

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.

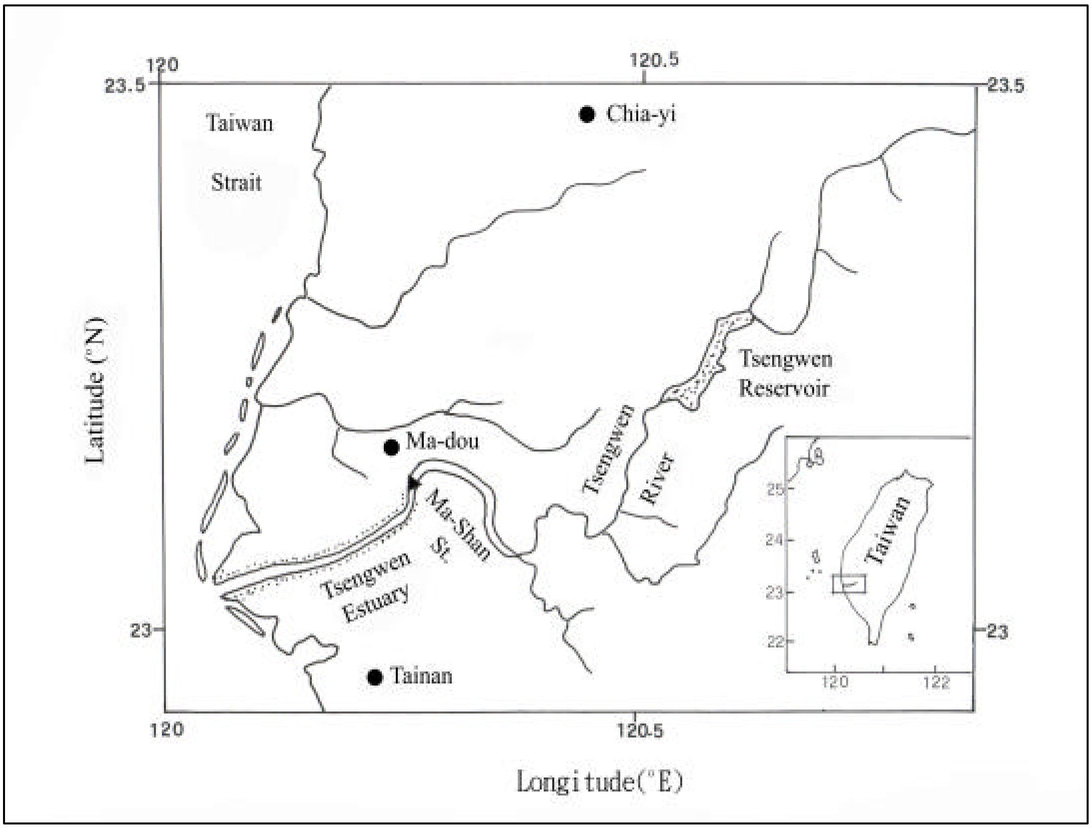

Figure 7.7. Map and location of Tsengwen River estuary.

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 14×10^3 m^3 d^{-1} for the dry season, 411×10^3 m^3 d^{-1} for the wet season and $1{,}957 \times 10^3$ m^3 d^{-1} for the flood season. The exchange flows are proportional to the total freshwater inputs (residual flows), and are about 24×10^3 m^3 d^{-1} for the dry season, 668×10^3 m^3 d^{-1} for the wet season and $2{,}526 \times 10^3$ 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
DDIP (mmol m^{-2} d^{-1})	-0.002	-0.9	-0.1
DDOP (mmol m^{-2} d^{-1})	-0.006	+0.2	-0.1
DDIN (mmol m^{-2} d^{-1})	+0.4	-31	-2.7
DDON (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 (*DDIP*) 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 *DDIP* and *DDOP* in the flood period because both *DDIP* and *DDOP* 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})
DDIP (1995)	-0.01
DDOP (1995)	-0.01
DDIP (1996)	-0.06
DDOP (1996)	-0.03
(*p-r*)$_{1995}$ (particulate C/P=106)	+1
(*p-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 *DDIP* and *DDOP*, nonconservative fluxes of DIN (*DDIN*) and DON (*DDON*) 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,

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

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 *DN*. Expected *DN* is *DP* 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).