4. BUDGETS FOR ESTUARIES IN KOREA

4.1 Nakdong River estuary

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<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 $2{,}400\times10^3$ 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.

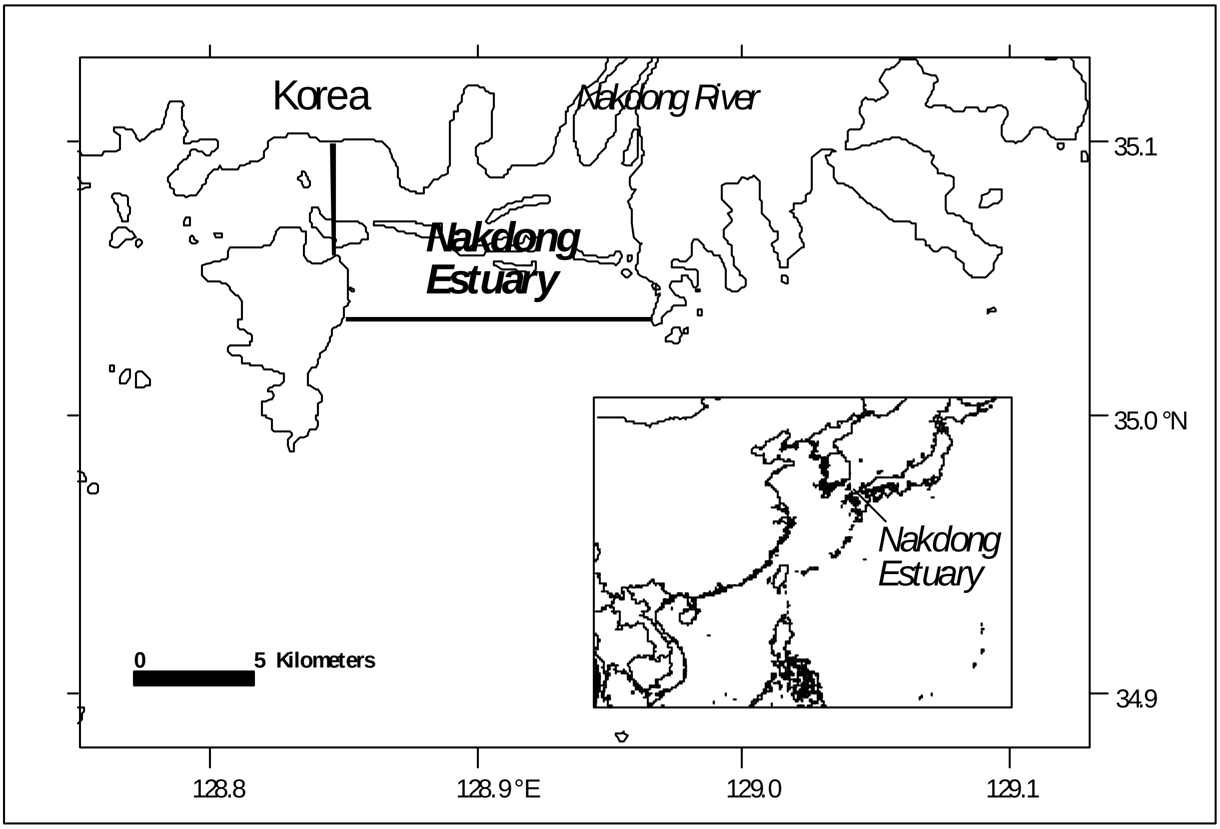

Figure 3.1. Map and location of the Nakdong River estuary. The boundaries of the budgeted area are indicated.

The average flow rate is 470 m^3 sec^{-1} or about $41{,}000\times10^3$ 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 $2{,}000\times10^3$ 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 = $1,300\times10^3$ 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
t (days)	12	5	7

$V_{syst} = 480\times10^6$ 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 (mM)	
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 (mM)	
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})
$V_P DIP_P$	0	0	0
$V_Q DIP_Q$	30	8	15
$V_G DIP_G$	68	18	35
$V_O DIP_O$	82	21	41
$V_R DIP_R$	48	1	17
$V_X(DIP_{OCN}-DIP_{SYST})$	42	17	25
DDIP	-90	-29	-49
$V_P DIN_P$	0	0	0
$V_Q DIN_Q$	4,000	6,000	5,000
$V_G DIN_G$	9,000	2,000	4,000
$V_O DIN_O$	11,000	3,000	6,000
$V_R DIN_R$	1,000	0	300
$V_X(DIN_{OCN}-DIN_{SYST})$	0	3,000	2,000
DDIN	-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

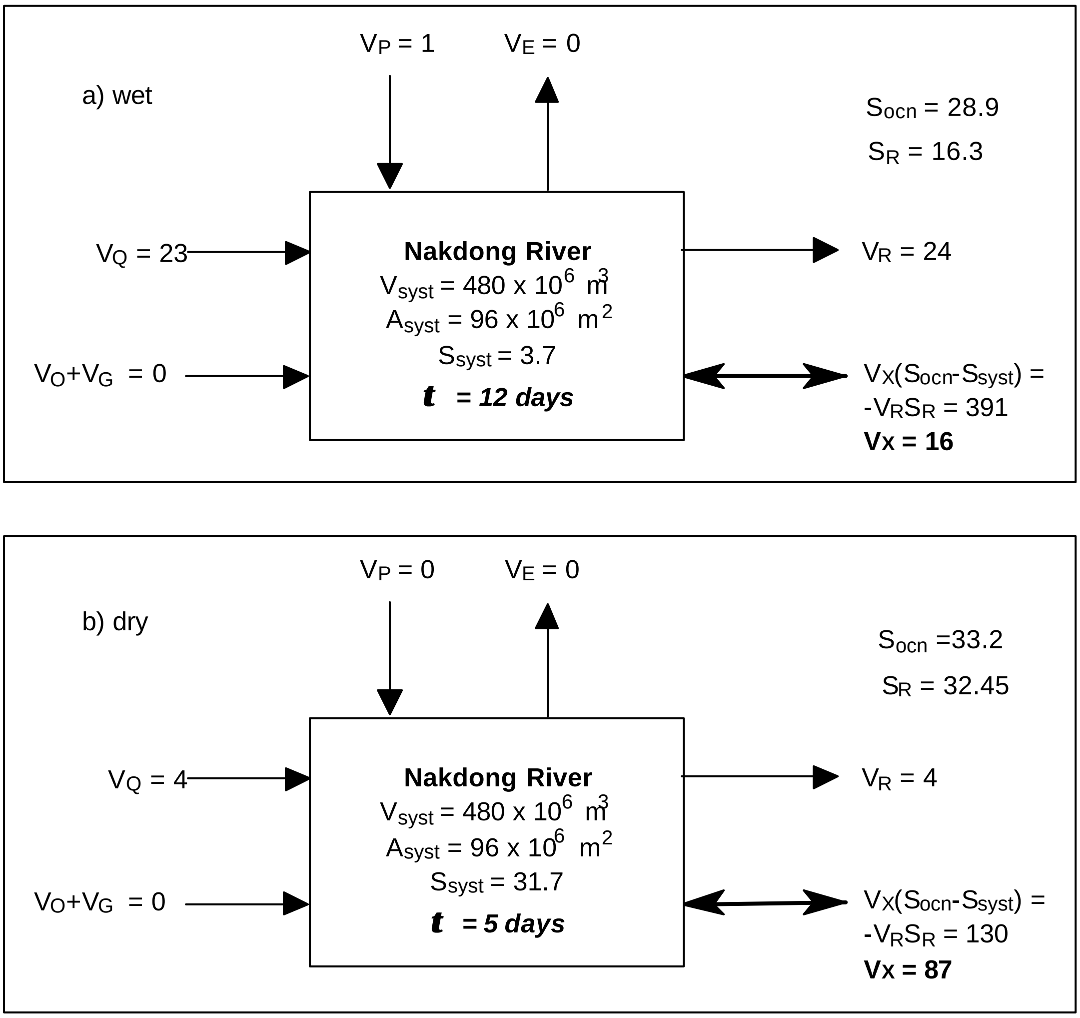

Figure 4.2. Salt and water budgets for the Nakdong River estuary in the wet (a) and dry (b) seasons. Water in 10^6 m^3 d^{-1} and salt flux in 10^6 psu-m^3 d^{-1}.

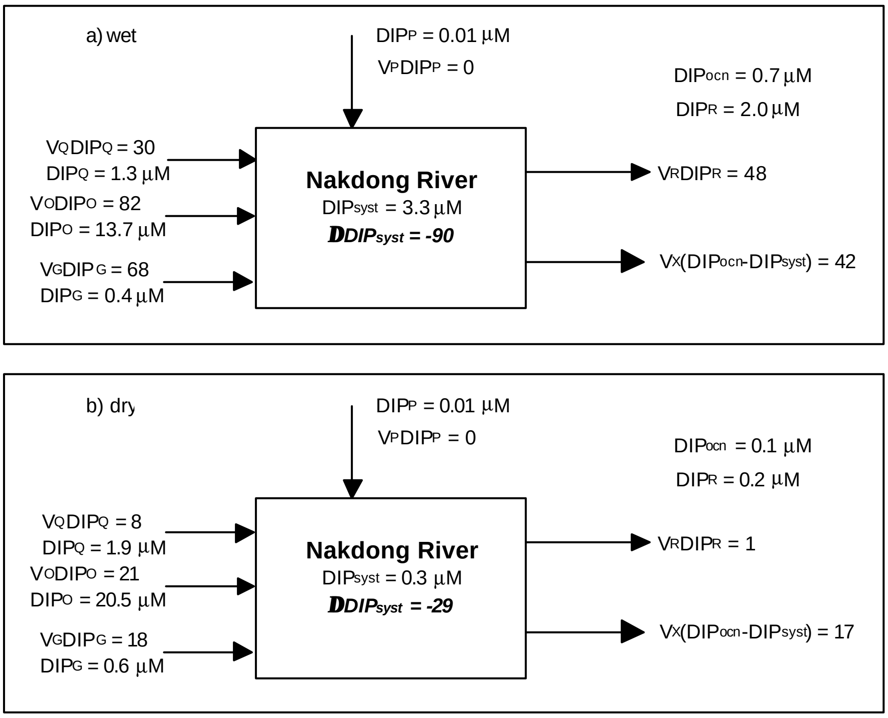

Figure 4.3. Dissolved inorganic phosphorus budget for the Nakdong River estuary in the wet (a) and dry (b) seasons. Flux in 10^3 mol d^{-1}.

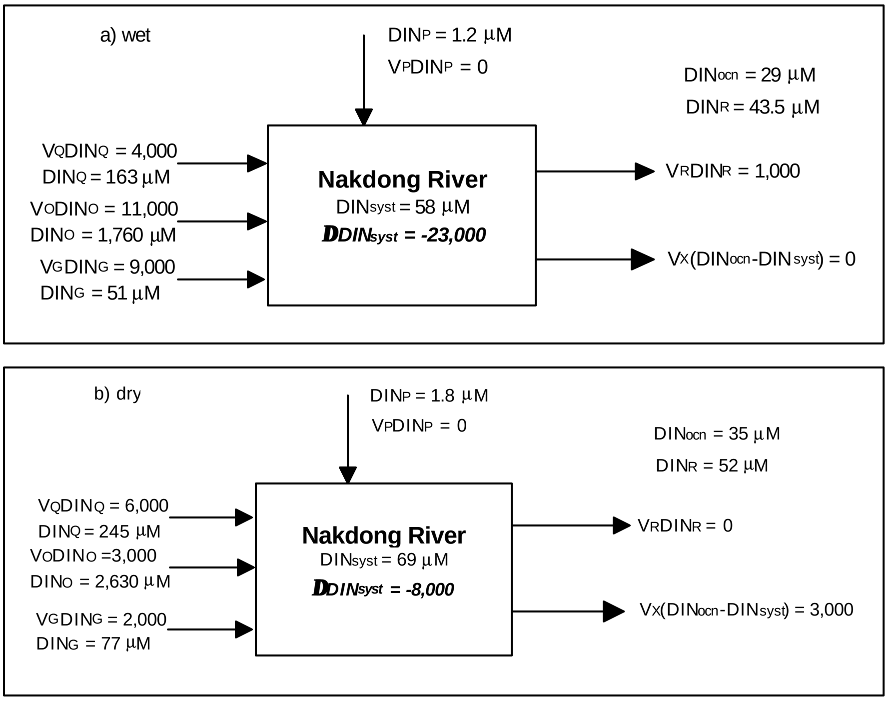

Figure 4.4. Dissolved inorganic nitrogen budgets for the Nakdong River estuary in the wet (a) and dry (b) seasons. Flux in 10^3 mol d^{-1}.

4.2 Sumjin River Estuary

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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 2×10^6 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: 58×10^3 m^3 d^{-1} from domestic sewage, 100×10^3 m^3 d^{-1} from industrial wastes, and 9×10^3 m^3 d^{-1} from domestic animals.

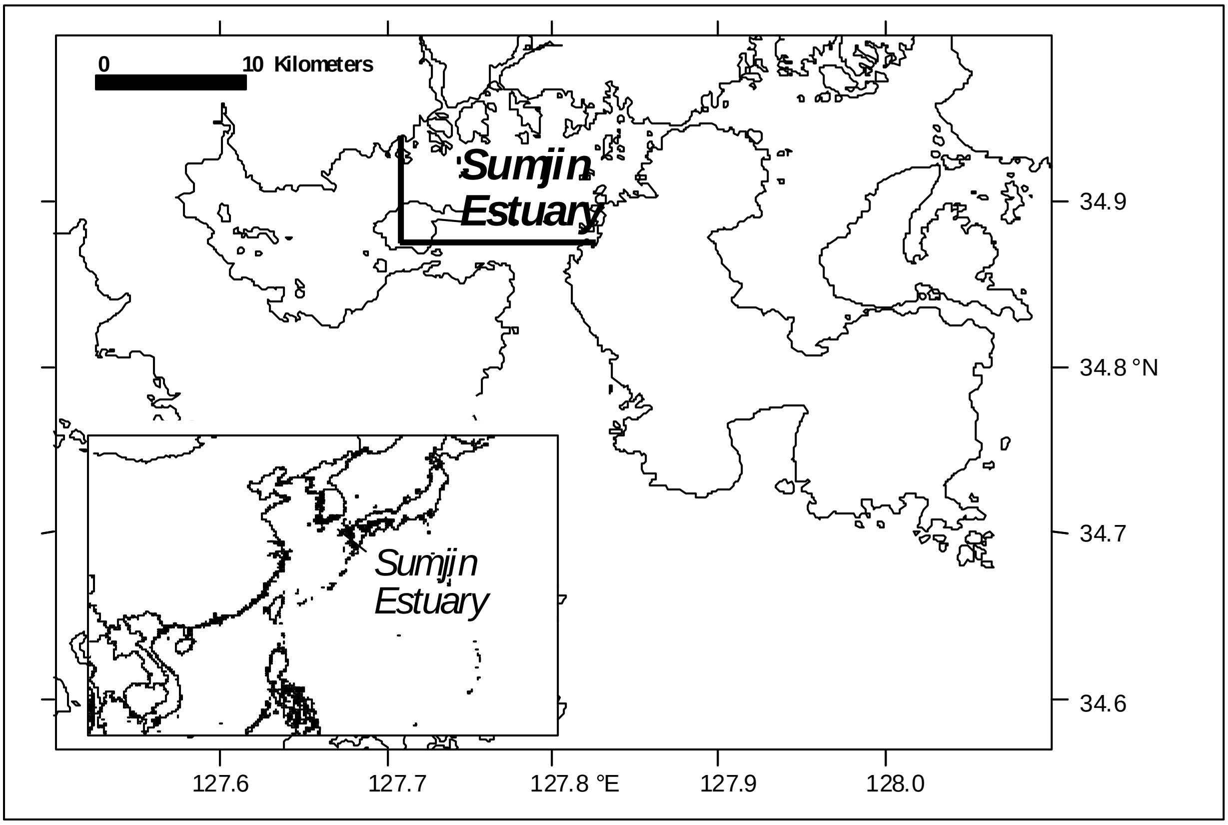

Figure 4.5. Map and location of the Sumjin River estuary.

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
t (day)	109	171	156

V_{syst} = 1,100x10^6 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 (mM)		
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 (mM)		
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
DDIP	-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
DDIN	-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 $+530\times10^3$ mol C d^{-1} or +10 mmol C m^{-2} d^{-1} in the wet season and $+424\times10^3$ 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.

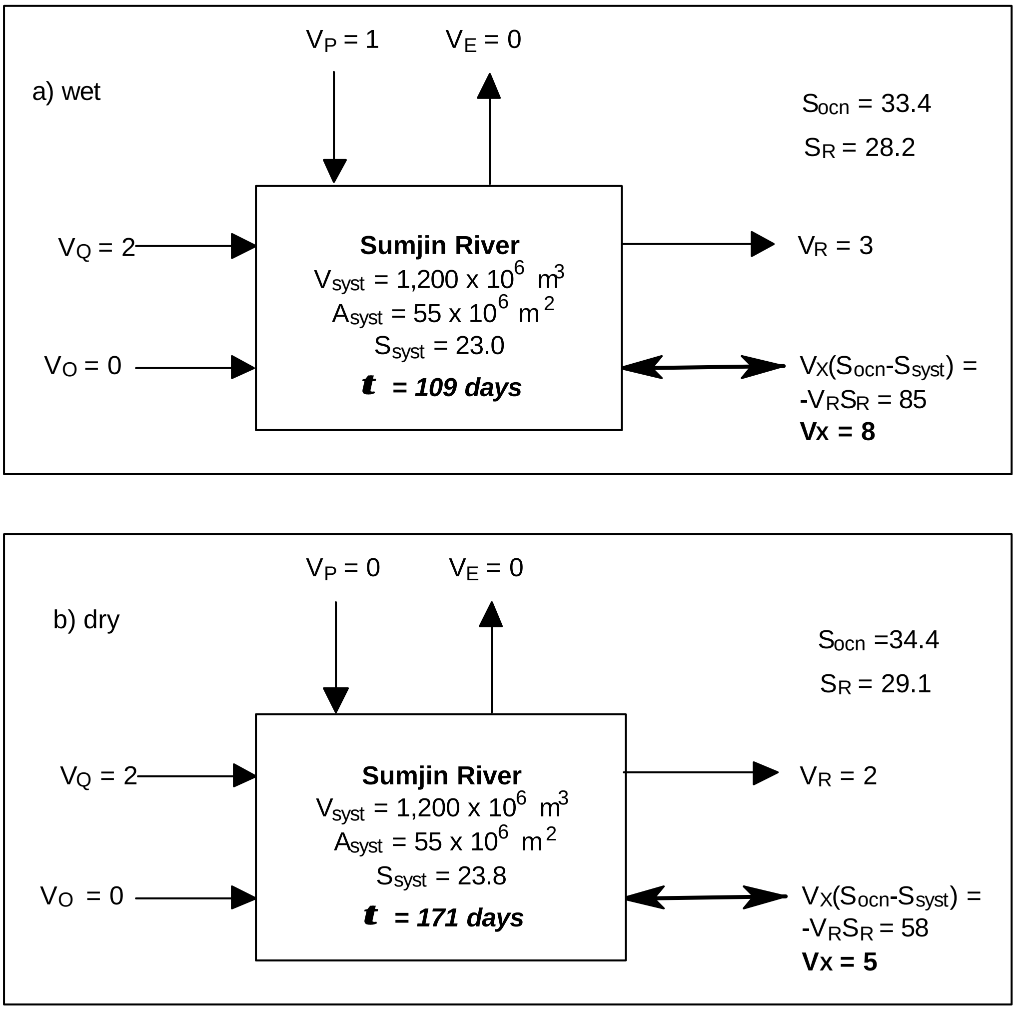

Figure 4.6. Salt and water budgets for the Sumjin River estuary in the wet (a) and dry (b) seasons. Water flux in 10^6 m^3 d^{-1} and salt flux in 10^6 psu-m^3 d^{-1}.

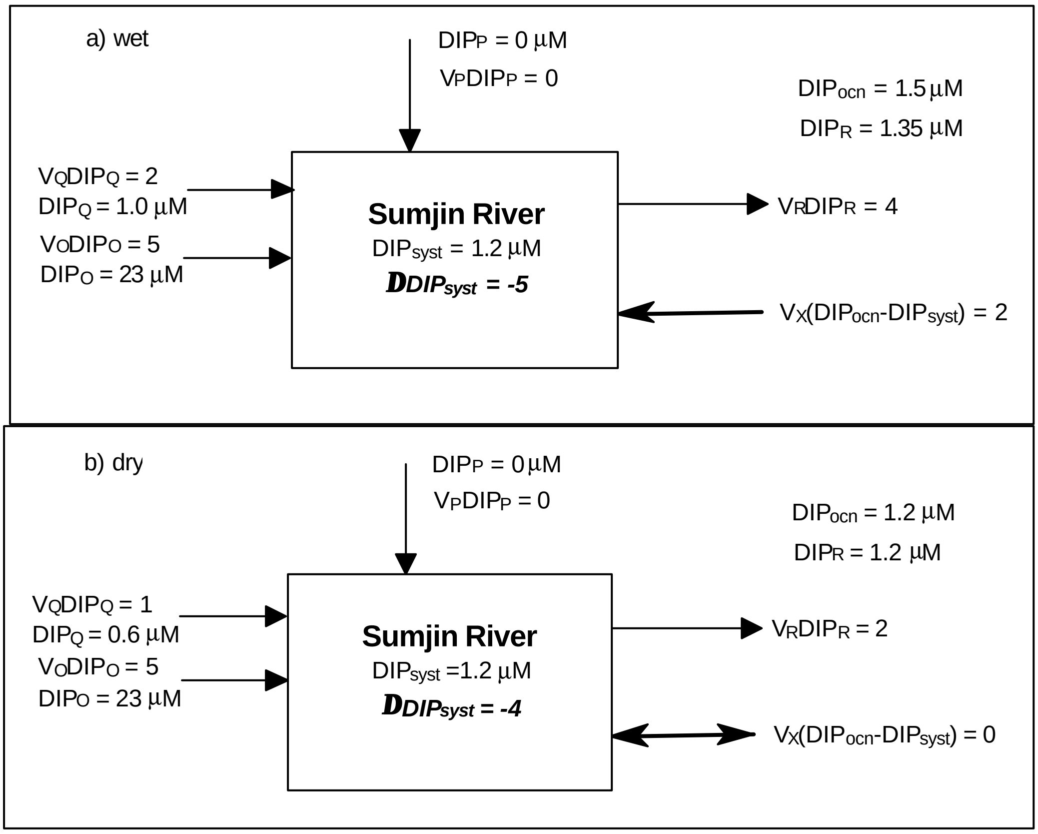

Figure 4.7. Dissolved inorganic phosphorus budget for the Sumjin River estuary in the wet (a) and dry (b) seasons. Flux in 10^3 mol d^{-1}.

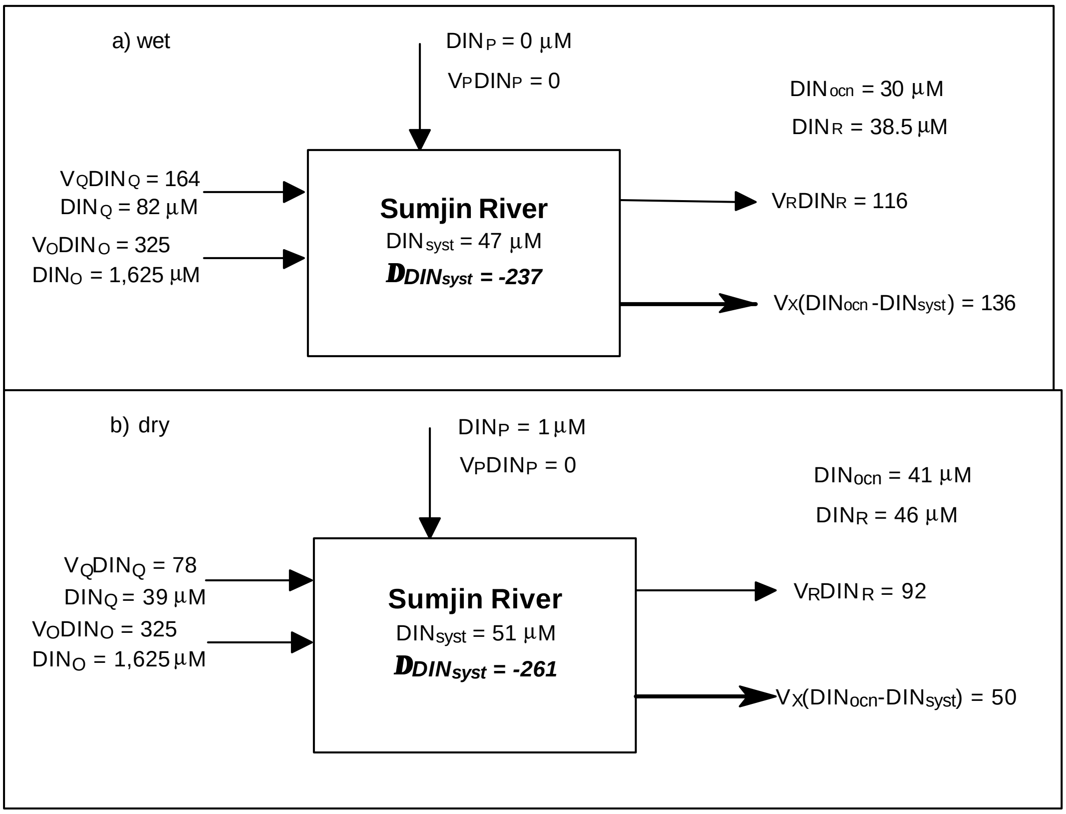

Figure 4.8. Dissolved inorganic nitrogen budgets for the Sumjin River estuary in the wet (a) and dry (b) seasons. Flux in 10^3 mol d^{-1}.