2. BUDGETS FOR AUSTRALIAN ESTUARINE SYSTEMS

2.1 QUEENSLAND AND NEW SOUTH WALES TROPICAL AND SUB-TROPICAL SYSTEMS

The following two sections represent parts of a general comparison among estuaries in tropical and subtropical Australia, under the direction of Bradley Eyre. Most of these estuaries are very small. However, they typify the river mouths of many tropical and subtropical Australian rivers, and the collection of numerous sites relatively close to one another provides an unusual opportunity for detailed comparison. Therefore, rather than present each estuary individually, the sites are grouped into Tropical and Sub-tropical systems. The data are summarised, within these two groups, in tabular form.

2.1.1 Tropical Systems

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Study Area Descriptions

The four tropical estuaries (Site No. 2. Jardine [142.20E, 11.15S]; 3. Annan [145.27E, 15.53S]; 4. Daintree [145.43E, 16.28S]; and 5. Moresby [146.12E, 17.60S]) are in north Queensland, Australia (see Figure 1.1). This region experiences a wet and dry tropical climate, with a pronounced wet season between December and May (summer) and a dry season for the remainder of the year. These tropical estuaries do not receive sewage treatment plant (STP) inputs. The physical characteristics of each catchment and estuary are summarised in Table 2.1. Further details can be found in Eyre (1994) and Eyre and Balls (in press).

Table 2.1 General characteristics of the tropical estuarine systems and their catchments.

System	Catchment Area km^2	Ann. Rain mm	Runof Coeff.	Ann. Runoff $10^6\ m^3$	Length km	Area km^2	Mean depth m	Vol $10^6\ m^3$	% nat. veg.	% other veg.
Jardine	2900	1740	0.35	1769	9	5.6	1.4	7.8	100	0
Annan	750	1820	0.48	653	16	2.2	1.2	2.7	90	10
Daintree	2125	2020	0.57	2444	26	5.0	5.1	25.6	74	26
Moresby	125	3700	0.54	250	20	5.3	3.0	15.9	48	52

Methods

Although the general methodology used here generally accords with the LOICZ methodology (Gordon *et al.* 1996), the details differ as described in Section 2.1.2 Sub-tropical Systems (Eyre and Pepperell).

Results

Table 2.2 summarises the water exchange times in these systems, and Table 2.3 summarises the fluxes of dissolved inorganic and organic phosphorus and nitrogen. Most of the nonconservative TDP and TDN flux represents DIP and DIN. It should be noted that both the exchange times and the nonconservative fluxes are somewhat deceptive. Because of the way in which data for the budgets are collected, these represent samples between major runoff events, which rapidly flush the systems and wash particulate materials out of the systems. Even with this caveat, all of these systems tend to exhibit very short exchange times (1-3 weeks).

Table 2.2 Exchange time estimates for the tropical estuaries.

System	**Estuary Volume (10^6 m^3)**	**Exchange Time (Days)**
Jardine	7.8	8
Annan	2.7	15
Daintree	25.6	20
Moresby	15.9	13

The data summarised in Table 2.3 can be used according to the LOICZ Guidelines to calculate estimates of nitrogen fixation minus denitrification (*nfix-denit*) and primary production minus respiration (*p-r*). These estimates are summarised in Table 2.4. In the case of (*nfix-denit*), the calculations using total dissolved N and P are compared with calculations using only DIN and DIP.

Table 2.3 Inputs, oceanic exchange and nonconservative flux of dissolved inorganic and organic P and N for the tropical estuaries.

DIP							
Estuary	$F_{diffuse}$ kmol yr^{-1}	F_{atmos} kmol yr^{-1}	F_{urban} kmol yr^{-1}	F_{STP} kmol yr^{-1}	F_{ocean} kmol yr^{-1}	ΔDIP kmol yr^{-1}	ΔDIP mmol m^{-2} d^{-1}
Jardine	116	0	0	0	-296	180	0.09
Annan	38	0	0	0	-28	-10	-0.01
Daintree	93	0	0	0	-82	-11	-0.01
Moresby	65	6	0	0	11	-82	-0.04
DOP							
Estuary	$F_{diffuse}$ kmol yr^{-1}	F_{atmos} kmol yr^{-1}	F_{urban} kmol yr^{-1}	F_{STP} kmol yr^{-1}	F_{ocean} kmol yr^{-1}	ΔDOP kmol yr^{-1}	ΔDOP mmol m^{-2} d^{-1}
Jardine	139	0	0	0	13	-152	-0.08
Annan	16	0	0	0	-6	-10	-0.01
Daintree	121	0	0	0	-168	48	0.03
Moresby	0	0	0	0	0	0	0.00

DIN							
Estuary	$F_{diffuse}$ kmol yr^{-1}	F_{atmos} kmol yr^{-1}	F_{urban} kmol yr^{-1}	F_{STP} kmol yr^{-1}	F_{ocean} kmol yr^{-1}	ΔDIN kmol yr^{-1}	ΔDIN mmol m^{-2} d^{-1}
Jardine	3334	0	0	0	-1555	-1779	-0.9
Annan	781	0	0	0	-800	19	0.0
Daintree	4074	0	0	0	-3859	-215	-0.1
Moresby	8305	173	0	0	-6061	-2417	-1.2
DON							
Estuary	$F_{diffuse}$ kmol yr^{-1}	F_{atmos} kmol yr^{-1}	F_{urban} kmol yr^{-1}	F_{STP} kmol yr^{-1}	F_{ocean} kmol yr^{-1}	ΔDON kmol yr^{-1}	ΔDON mmol m^{-2} d^{-1}
Jardine	17 917	0	0	0	-12 650	-5268	-2.5
Annan	5558	0	0	0	-2478	-3081	-3.8
Daintree	11 322	0	0	0	-1852	-9469	-5.2
Moresby	0	0	0	0	0	0	0.0

Table 2.4 Calculations of (*nfix-denit*) and (*p-r*) for the tropical systems. [For (*nfix-denit*) calculations are based on both dissolved inorganic N and P and total dissolved N and P, assuming a Redfield N:P ratio of 16:1 for the reacting organic matter. For (*p-r*), calculations assume a Redfield C:P ratio of 106:1 for the reacting organic matter])

System	**(*nfix-denit*) inorganic N, P mmol m^{-2} d^{-1}**	**(*nfix-denit*) total dissolved N, P mmol m^{-2} d^{-1}**	**(*p-r*) mmol m^{-2} d^{-1}**
Jardine	-2.3	-3.7	-9.3
Annan	0.2	-3.4	1.3
Daintree	0.0	-5.6	0.6
Moresby	-0.6	-0.6	4.5
mean ± s. d.	-0.7±1.1	-3.3±2.1	-0.7±6.0
median	-0.3	-3.6	+1.0

There is a suggestion of weak net denitrification, whether dissolved inorganic nutrients or total dissolved nutrients are used for the calculation. The trend is somewhat more consistent with the total dissolved nutrients. Calculated (*p-r*) is near 0.

2.1.2 Sub-tropical Systems

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Study Area Descriptions

The twelve sub-tropical estuaries (Site No. 7. Caboolture [153.03E, 27.15S]; 8. Brisbane [153.17E, 27.37S]; 9. Logan [153.33E, 27.68S]; 10. Tweed [153.55E, 28.17S]; 11. Brunswick [153.55E, 28.53S]; 12. Richmond [153.58E, 28.88S]; 13. Clarence [153.35E, 29.43S]; 14. Bellinger [153.03E, 30.65S]; 15. Nambucca [153.02E, 30.65S]; 16. Macleay [153.05E, 30.90S]; 17. Hastings [152.87E, 31.42S]; 18. Manning [152.50E, 31.87S]) are in south-east Queensland and northern New South Wales, Australia. The locations of the sites are shown on Figure 1.1. This region experiences a wet and dry sub-tropical climate. During the summer months (October - April), moist unstable sub-tropical maritime airflows prevail, bringing heavy rainfalls and thunderstorms. During winter months (May - September) relatively stable anticyclonic air pressure systems with clear skies and light winds predominate. The physical characteristics of each catchment and estuary are summarised in Table 2.5, and further details can be found in Pont (1998).

Table 2.5 General characteristics of the sub-tropical estuarine systems and their catchments.

System	Catch. Area km^2	Ann. Rain mm	Runoff Coeff.	Ann. Runoff $10^6\ m^3$	Length km	Area km^2	Mean depth m	Vol $10^6\ m^3$	% nat. veg.	% other veg.
Caboolture	401	1210	0.24	116	19	2.1	2.2	4.7	31	69
Brisbane	13 560	1152	0.09	1410	75	13.0	10.2	132.5	21	79
Logan	3540	1534	0.12	651	39	3.6	4.9	17.8	25	75
Tweed	1068	1716	0.29	532	33	6.3	3.4	21.6	30	70
Brunswick	213	1777	0.30	114	11	1.3	0.7	0.9	10	90
Richmond	6861	1849	0.23	2916	41	10.1	5.7	57.4	41	59
Clarence	22 446	1075	0.20	4826	62	26.2	6.1	158.7	55	45
Bellinger	1128	1471	0.26	431	17	1.8	2.6	4.7	54	46
Nambucca	1326	1354	0.25	450	29	4.6	2.6	11.8	25	75
Hastings	10 686	1217	0.26	3377	30	6.9	4.1	28.4	48	52
Macleay	3715	1310	0.14	680	30	4.9	4.1	20.1	55	45
Manning	8195	1276	0.26	2721	41	14.5	5.1	74.0	76	24

Methods

Nutrient delivery to the estuary was split into two categories, during floods and other times of the year, and these two categories were treated differently. During floods, the estuarine basins are completely flushed with freshwater or at least rapidly flushed and as such, dissolved nutrients behave conservatively and are most probably completely flushed through the estuarine basin to the continental shelf (see Eyre and Twigg 1997; Eyre 1998). The flood event intervals (I) were separated using the formula $I = A^{0.2}$ days after the peak of the hydrograph, where A is the area above the gauging stations.

A proportion of dissolved nutrients delivered during other times of the year (i.e. not in floods) are retained and transformed within the estuary with the remaining nutrients transported to the ocean. The transport, retention and transformation flux of nutrients was quantified as:

$$F_{diffuse} + F_{point} + F_{urban} + F_{atmosphere} + F_{input} + F_{removal} = F_{ocean}$$

where:

where:	$F_{diffuse}$	=	diffuse loading
	F_{point}	=	point source loading
	F_{urban}	=	urban loading
	$F_{atmosphere}$	=	atmospheric loading
	F_{input}	=	input flux within the estuary
	$F_{removal}$	=	removal flux within the estuary
	F_{ocean}	=	flux out of the estuary to the ocean

Each estuary was sub-divided into 15 to 30 boxes depending on the homogeneity of the estuarine sections. Water, salt and material budgets were calculated for each box using the LOICZ Biogeochemical Modelling Guidelines (Gordon *et al.* 1996). The salinity of each box was calculated from salinity profiles taken along the estuaries and the average material concentrations were obtained from a 4th order polynomial fitted to the material data (see below, Estuarine Sampling program) plotted as a function of salinity. The ($F_{input} + F_{removal}$) is equivalent to ΔY in Gordon *et al.* (1996) and is given as:

$$F_{input} + F_{removal} = F_{diffuse} + F_{point} + F_{urban} + F_{atmosphere} - F_{ocean}$$

F_{ocean} is equivalent to the sum $[V_R Y_R + V_X(Y_{ocn} - Y_{syst})]$ in Gordon *et al.* (1996). This term was calculated from the water, salt and material budgets.

Estuarine Sampling Program

Six sampling runs were undertaken in the sub-tropical estuaries (January, April/May, May, July/August, September and December) and two sampling runs were undertaken in the tropical estuaries (wet and dry seasons). Samples were collected at intervals of approximately 2 psu from seawater to freshwater along the axial salinity gradient in the estuary. Salinity profiles were also undertaken at each sample location.

Nutrient Loadings to the Estuary

Four major nutrient sources to the estuaries were quantified (diffuse source loading, point source loading as urban runoff and sewage effluent and atmospheric deposition).

Diffuse Source Loading ($F_{diffuse}$) to the estuary was calculated by integrating the product of flow-weighted concentrations and daily flows. The hydrographic response of floods in the catchments typically spans several days. Daily sampling was carried out during floods, with samples collected on rising and falling stages being considered sufficient to characterise loads. Fortnightly to monthly samples were collected during base flow conditions.

Point-Source Loading (F_{point}) of nutrients from sewage effluent discharges was calculated for the sewage treatment plants (STPs) discharging into each estuary by dividing annual STP loads by 365 (or 366) and multiplying by the number of days associated with each time period. The annual STP loads for these NSW estuaries had been previously estimated by Manly Hydraulics Laboratory (MHL) as part of a review of estuarine sewage outfalls in NSW (Phil Anderson, personal communication 1997). The annual STP loads for the sub-tropical south-east Queensland estuaries had been previously estimated as part of the Brisbane River and Moreton Bay Wastewater Management Study (Anonymous 1998). DIN and DIP loads were estimated by assuming that 75% of the TN and TP loads consisted of dissolved inorganic forms.

Urban runoff (F_{urban}) was calculated as monthly nutrient loading to the nine northern NSW estuaries using the formula:

$$A_{ua}*R*X*C_{ur}$$

where: A_{ua} = the urban area ;
R = monthly rainfall;
X = an average runoff coefficient for urban areas of similar density,0.4;
C_{ur} = an average nutrient concentration (TN: 1.4 mg l^{-1}; TP: 0.4 mg l^{-1}; NO_3: 0.5 mg l^{-1}; NH_4: 0.6 mg l^{-1}) adapted from other relevant urban runoff studies.

Urban runoff concentrations were estimated for Lismore, Mullumbimby and the lower Tweed area, as they are adjacent regional urban centres with similar rainfall patterns, total impervious surfaces, and traffic and population densities similar to the study systems. The monthly nutrient loading to the three south-east Queensland estuaries from urban runoff was derived from Anonymous (1998).

Atmospheric Deposition ($F_{atmosphere}$) was calculated as monthly nutrient loading using the formula:

$$A_e*R*C_{ad}$$

where: A_e = the surface area of the estuary ;
R = rainfall;
C_{ad} = the average monthly nutrient concentrations in rainfall collected at Lismore.

The use of atmospheric concentrations for Lismore was considered appropriate because it is in the lower Richmond catchment, which has similar land uses, population densities and climatic variables to the study systems. Atmospheric loadings to the tropical estuaries were derived from Eyre (1995).

Results
Table 2.6 summarises the water exchange times in these systems, and Table 2.7 summarises the fluxes of total dissolved phosphorus and nitrogen. Note the cautionary remarks made in the previous section (2.1.1) about the nature of the data collection as well as exchange times and nonconservative flux calculations. The exchange times for these systems during low flow periods tend to be very long.

Table 2.6 Exchange time estimates for the sub-tropical estuaries.

System	Estuary Volume (10^6 m^3)	Exchange Time (Days)
Caboolture	4.7	410
Brisbane	132.5	295
Logan	17.8	412
Tweed	21.6	115
Brunswick	0.9	43
Richmond	57.4	85
Clarence	158.7	125
Bellinger	4.7	16
Nambucca	11.8	55
Hastings	28.4	41
Macleay	20.1	26
Manning	74.0	88

Table 2.7 Inputs, oceanic exchange and nonconservative flux of dissolved inorganic and organic P and N in the sub-tropical estuaries.

DIP							
Estuary	$F_{diffuse}$ kmol yr^{-1}	F_{atmos} kmol yr^{-1}	F_{urban} kmol yr^{-1}	F_{STP} kmol yr^{-1}	F_{ocean} kmol yr^{-1}	ΔDIP kmol yr^{-1}	ΔDIP mmol m^{-2} d^{-1}
Caboolture	203	1	0	218	-247	-175	-0.23
Brisbane	1858	3	1647	8548	-10 286	-1770	-0.37
Logan	1320	2	412	2475	-2318	-1891	-1.44
Tweed	499	2	19	523	-649	-394	-0.17
Brunswick	80	1	13	37	-71	-60	-0.13
Richmond	5050	6	177	130	-5103	-260	-0.07
Clarence	2847	11	35	232	-2422	-703	-0.07
Bellinger	526	1	7	41	-841	266	0.40
Nambucca	757	2	33	213	-564	-441	-0.26
Hastings	1035	2	8	547	-840	-752	-0.42
Macleay	2586	3	23	425	-3010	-27	-0.01
Manning	1199	6	75	415	-1115	-580	-0.11

DOP							
Estuary	$F_{diffuse}$ kmol yr^{-1}	F_{atmos} kmol yr^{-1}	F_{urban} kmol yr^{-1}	F_{STP} kmol yr^{-1}	F_{ocean} kmol yr^{-1}	ΔDOP kmol yr^{-1}	ΔTDOP mmol m^{-2} d^{-1}
Caboolture	274	0	0	0	-303	30	0.04
Brisbane	5758	1	0	0	-4986	-772	-0.17
Logan	2820	1	0	0	-2551	-270	-0.20
Tweed	3054	1	-2	0	-2988	-64	-0.03
Brunswick	58	0	2	0	-21	-39	-0.08
Richmond	2684	2	25	0	-1896	-817	-0.22
Clarence	8963	3	5	0	-8096	-875	-0.10
Bellinger	296	0	1	0	-381	84	0.13
Nambucca	2195	0	5	0	-1414	-786	-0.47
Hastings	1917	0	1	0	-1678	-241	-0.14
Macleay	4425	1	3	0	-3215	-1213	-0.48
Manning	2258	1	10	0	-2142	-127	-0.02
DIN							
Estuary	$F_{diffuse}$ kmol yr^{-1}	F_{atmos} kmol yr^{-1}	F_{urban} kmol yr^{-1}	F_{STP} kmol yr^{-1}	F_{ocean} kmol yr^{-1}	ΔDIN kmol yr^{-1}	ΔDIN mmol m^{-2} d^{-1}
Caboolture	3621	44	0	696	-5129	769	1.0
Brisbane	36 547	325	18 098	48 673	-115 629	11 986	2.5
Logan	11 251	99	4498	4886	-16 681	-4053	-3.1
Tweed	3922	182	254	129	-11 648	7161	3.1
Brunswick	1575	39	182	299	-1803	-292	-0.6
Richmond	30 992	420	2391	739	-22 483	-12 059	-3.3
Clarence	60 592	655	468	1065	-61 788	-992	-0.1
Bellinger	6118	50	93	441	-8569	1868	+2.8
Nambucca	14 373	115	203	740	-12 965	-2466	-1.5
Hastings	35 725	265	110	2007	-30 701	-7406	-4.1
Macleay	47 639	178	304	940	-51 281	2220	0.9
Manning	14 117	351	457	1315	-13 904	-2336	-0.4
DON							
Estuary	$F_{diffuse}$ kmol yr^{-1}	F_{atmos} kmol yr^{-1}	F_{urban} kmol yr^{-1}	F_{STP} kmol yr^{-1}	F_{ocean} kmol yr^{-1}	ΔDON kmol yr^{-1}	ΔDON mmol m^{-2} d^{-1}
Caboolture	14 215	10	0	0	-15 228	1303	1.7
Brisbane	65 467	75	0	0	-55 723	-9819	-2.0
Logan	50 143	22	0	0	-50 188	23	0.0
Tweed	38 826	39	65	0	-39 385	454	0.2
Brunswick	1717	10	46	0	-1753	-19	-0.1
Richmond	86 647	107	611	0	-96 573	9208	2.5
Clarence	265 665	-73	120	0	-260 773	-4938	-0.5
Bellinger	14 081	10	24	0	-18 183	4068	6.2
Nambucca	17 051	26	52	0	-15 270	-1858	-1.1
Hastings	55 410	62	28	0	-47 060	-8440	-4.8
Macleay	145 052	39	78	0	-141 947	-3223	-1.3
Manning	39 820	70	117	0	-38 043	-1963	-0.4

The data summarised in Table 2.7 can be used according to the LOICZ Guidelines to calculate estimates of nitrogen fixation minus denitrification (*nfix-denit*) and primary production minus respiration (*p-r*). These estimates are summarised in Table 2.8. In the case of (*nfix-denit*), the calculations using total dissolved N and P are compared with calculations using only DIN and DIP.

These estimates indicate that most of the systems are slight net nitrogen fixers and net autotrophic. Additional inter-annual estimates for the Richmond River are given in Appendix IVA, using a non-LOICZ (but adapted) approach.

Table 2.8 Calculations of (*nfix-denit*) and (*p-r*) for the subtropical systems. [For (*nfix-denit*), calculations are based on both dissolved inorganic N and P and total dissolved N and P, assuming a Redfield N:P ratio of 16:1 for the reacting organic matter. For (*p-r*) calculations assume a Redfield C:P ratio of 106:1 for the reacting organic matter.]

System	**(*nfix-denit*) inorganic N, P mmol m^{-2} d^{-1}**	**(*nfix-denit*) total dissolved N, P mmol m^{-2} d^{-1}**	**(*p-r*) mmol m^{-2} d^{-1}**
Caboolture	4.7	5.7	24.2
Brisbane	8.5	9.0	39.5
Logan	19.9	23.2	152.5
Tweed	5.9	6.5	18.2
Brunswick	1.4	2.7	13.4
Richmond	-2.1	3.9	7.5
Clarence	1.1	2.0	7.8
Bellinger	-3.6	0.5	-42.9
Nambucca	2.7	9.1	27.8
Hastings	2.6	0.0	44.6
Macleay	1.1	7.5	1.1
Manning	1.3	1.3	11.6
mean ± s.d.	+3.6±6.1	+6.0±6.3	+25.4±45.7
median	+2.0	+4.8	+19.7