9. BUDGETS FOR ESTUARIES IN INDONESIA

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

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Study area description

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

Biotic communities in the bay include coral reef and seagrass beds. The land adjacent to the bay, approximately 60 km west of Jakarta, is becoming rapidly industrialized. At present, however, domestic and agricultural wastes apparently dominate the discharge of nutrients into the system. Runoff into the system totals about 1-2x10^6 m^3 d^{-1}; we assume that this freshwater input dominates in the system, and we use the lower value for the analysis presented here. From regional data, we estimate that rainfall and evaporation each average < 10^6 m^3 d^{-1} across the bay area, approximately balancing one another in the water budget.

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

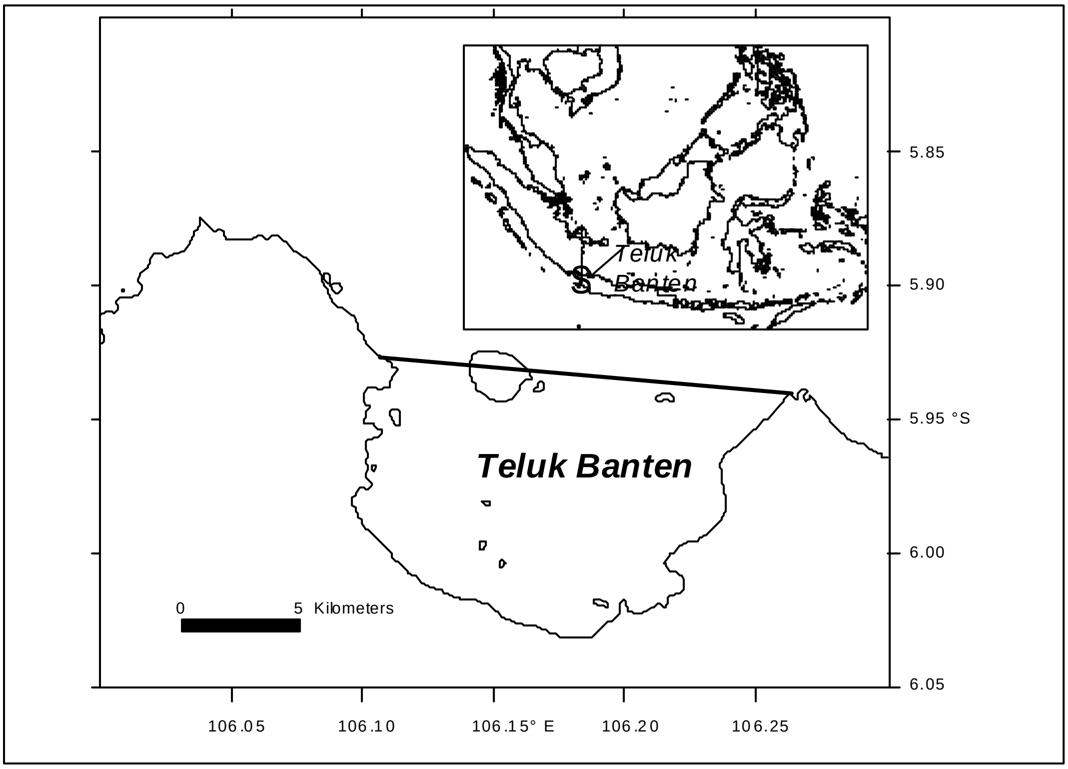

Figure 9.1. Map of Teluk Banten (Banten Bay). Solid bar shows the boundary of the budgeted area.

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

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

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

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

Salt flux associated with V_R is calculated as:

$$V_R S_R \approx -10^6 m^3 \_ d^{-1} \times 32 psu \approx -30 \times 10^6 psu \_ m^3 \_ d^{-1} \tag{2}$$

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

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

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

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

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

$$V_X \approx \frac{30 \times 10^6}{\left(\leq 0.1\right)} \geq 300 \times 10^6 \_ m^3 \_ d^{-1} \tag{3b}$$

Returning to equation (1), τ is $\leq$ 3 days.

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

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

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

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

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

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

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

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

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

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

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

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

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

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