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Review

A Short-review: Semi-enclosed Coastal Seas in the Southeast Asia —From the Viewpoint of Water Mass Residence Time—

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Abstract—The concepts of remnant function and residence time are reviewd. Then, the characteristics of semi-enclosed coastal seas in the Southeast Asia such as Hurun Bay in Indonesia, the Banpakong estuary in Thailand, and the Sulu Sea in the Philippines are discussed based on the concept of water mass residence time. The concept of residence time is very useful to investigate the environmental problems such as eutrophication in the semi-enclosed coastal sea.

Key words: Southeast Asia, semi-enclosed coastal sea, residence time, remnant function, eutrophication

Introduction

The semi-enclosed coastal seas in the Southeast Asia such as Hurun Bay in Indonesia (A in Fig.1) and the Banpakong estuary in Thailand (B in Fig.1) have suffered from environmental problems such as eutrophication, red tide occurrence, hypoxia, anoxia and so on. The information on the average residence time of water mass in such semi-enclosed coastal seas is very useful to investigate such environmental problems.

The concepts of remnant function and average residence times are reviewed at first and the usefulness of information on water mass residence time in such semi-enclosed coastal seas in the Southeast Asia is discussed. The comparison of residence time and the water exchange time proposed by LOICZ (Gordon et al., 1996) is also done at last.

Concepts of remnant function and average residence time in a semi-enclosed coastal sea

Takeoka (1984) proposed a concept of residence time of coastal water, which is useful for describing the exchange and transport of water or material in a coastal sea. The residence time is defined as a time scale which will be taken for a particle or water mass to reach the outlet.

He considered a semi-enclosed sea A (Fig. 2) as a model of a simple coastal sea which has one river (R) and one mouth (B) to the ocean (S). If the water flux across the sea surface is negligibly small, five water masses can be defined in the basin as follows: V_T, the mass of the total water in the basin, which consists of V_R and V_S; V_R the mass of the water which originates from the river; V_S, the mass of the water which originates from the outer ocean; V_{QR}, the mass of the water which has newly entered the basin in a unit time from

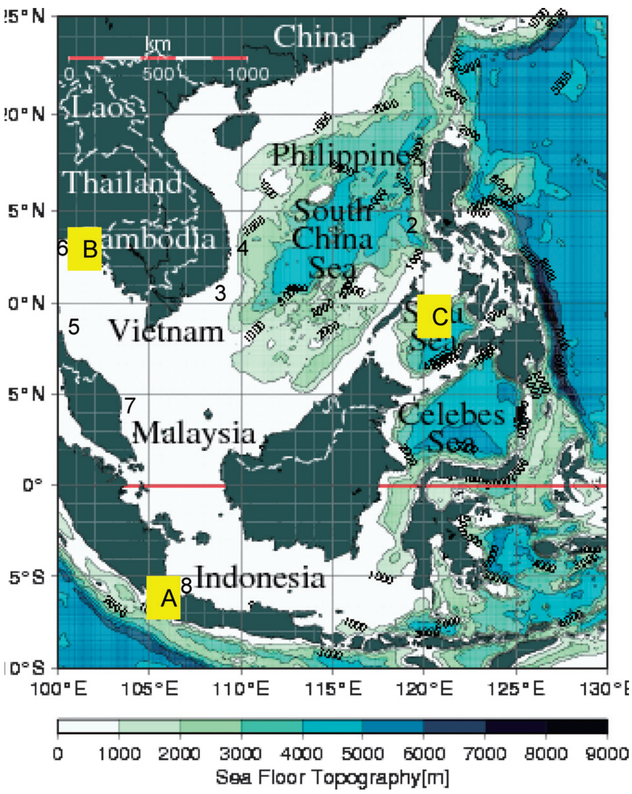

Fig. 1. Semi-enclosed coastal seas in the southeast Asia.

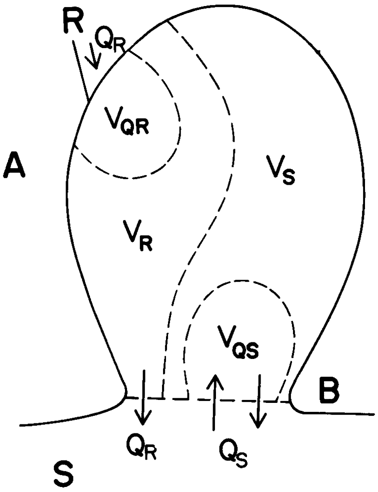

Fig. 2. Schematic distribution of the water masses in a simple model of a semi-enclosed coastal sea, which has one river R and on mouth B to the ocean S (Takeoka, 1984).

the river; and V_{QS}, the mass of the water which has newly entered the basin in a unit time from the outer ocean. V_{QR} and V_{QS} are parts of V_R and V_S, respectively. These notations also denote their amounts. Then, V_{QR} is the product of Q_R and the unit time and V_{QS} is the product of Q_S and unit time; here, Q_R is the water flux from the river, and Q_S is that from the ocean. The main part of Q_S is usually a flux by the tidal exchange in the case of the semi-enclosed coastal sea.

These five water masses have their own remnant function r_T, r_R, r_S, r_{QR}, and r_{QS}. Let consider a certain material in the basin, the amount of material at t=0 be R_0, and the amount of material which still remains in the basin at time t be R (t). A remnant function r (t) is defined as,

$$r(t)=R(t)/R_0. \tag{1}$$

The function r (t) denotes the decrease of the material or water mass considered, and the exchange of transport phenomenon of the material or water mass is directly described by this function. Hydraulic and numerical model experiments are useful to estimates the remnant function and one example using the numerical model will be introduced later in this paper.

The water masses in the bay also have their own average residence times; τ_T,

τ_R, τ_S, τ_{QR} and τ_{QS}. Average residence time (τ) is obtained by the time integration of r (t),

$$\tau = \int_0^\infty r(t)dt\,. \tag{2}$$

When the steady state is assumed, we can easily estimate the average residence time by

$$\tau=M_0/F_0, \tag{3}$$

where M_0 is the amount of material or water mass in the basin and F_0 inflow flux of material or water mass to the basin.

We know that $\tau_{QR}>\tau_R$, because most of V_{QR} is located near the head of the basin, where the material has the largest residence time. We also know that $\tau_R>\tau_T$ because V_R has a larger weight near the head of the basin than V_T has. Similarly,

$\tau_T>\tau_S$, and $\tau_S>\tau_{QS}$. As a result we have

$$\tau_{QR}>\tau_R>\tau_T>\tau_S>\tau_{QS}, \tag{4}$$

in the case where the river is located at the head of the basin. Some methods to estimate the average residence time will be also introduced later in this paper.

Hurun Bay

Hurun Bay is a semi-enclosed bay situated at the western coastal area of Lampung Bay, the southern coast of Sumatra and faces to the Sunda Strait (Fig. 3 a, A in Fig. 1). The fish culture and hatchery are popular in Hurun Bay and the eutrophication problems are occurring.

The environment within this area is strongly affected by the monsoonal wind system, that is, the dry season from December to March and the wet season from June to September. Intensive field observations were conducted at 8 stations shown in Fig. 3 (b) four times a year of 2004 (Suhendar et al., 2008). TOM (Total Organic Matter) concentration is low but DO (Dissolved Oxygen) concentration is high in the dry and wet seasons. However, TOM concentration is high but DO concentration is low during the transition seasons as shown in Fig. 4.

The average residence time of fresh water in the bay (τ_R) was estimated by the fresh water budget in the bay.

$$\tau_R=V_R/Q_R, \tag{5}$$

$$V_R=(So-Si)/So, \tag{6}$$

where V_R denotes the volume of the fresh water in the bay, Q_R the river discharge to the bay, So the representative salinity out of the bay (Sta.8 in Fig.3 b) and Si the average salinity in the bay (Sta. 1–Sta. 7 in Fig. 3 b).

From the analytical study based on the field observations, the reason of high TOM concentration and low DO concentration in the transition seasons and vice versa in the wet and dry seasons is that the long average residence time of fresh water in the bay during the transition seasons (18.6–3.3 days) and the short one during the dry and wet seasons (3.2–5.4 days), which is shown in Fig. 5. The long residence time in the transition seasons results in the accumulation of organic matter (TOM) in the bay, dissolved oxygen consumption and low DO.

The long average residence time of fresh water in Hurun Bay during the transition seasons is due to the weak monsoon wind, weak currents and small water exchange ratio across

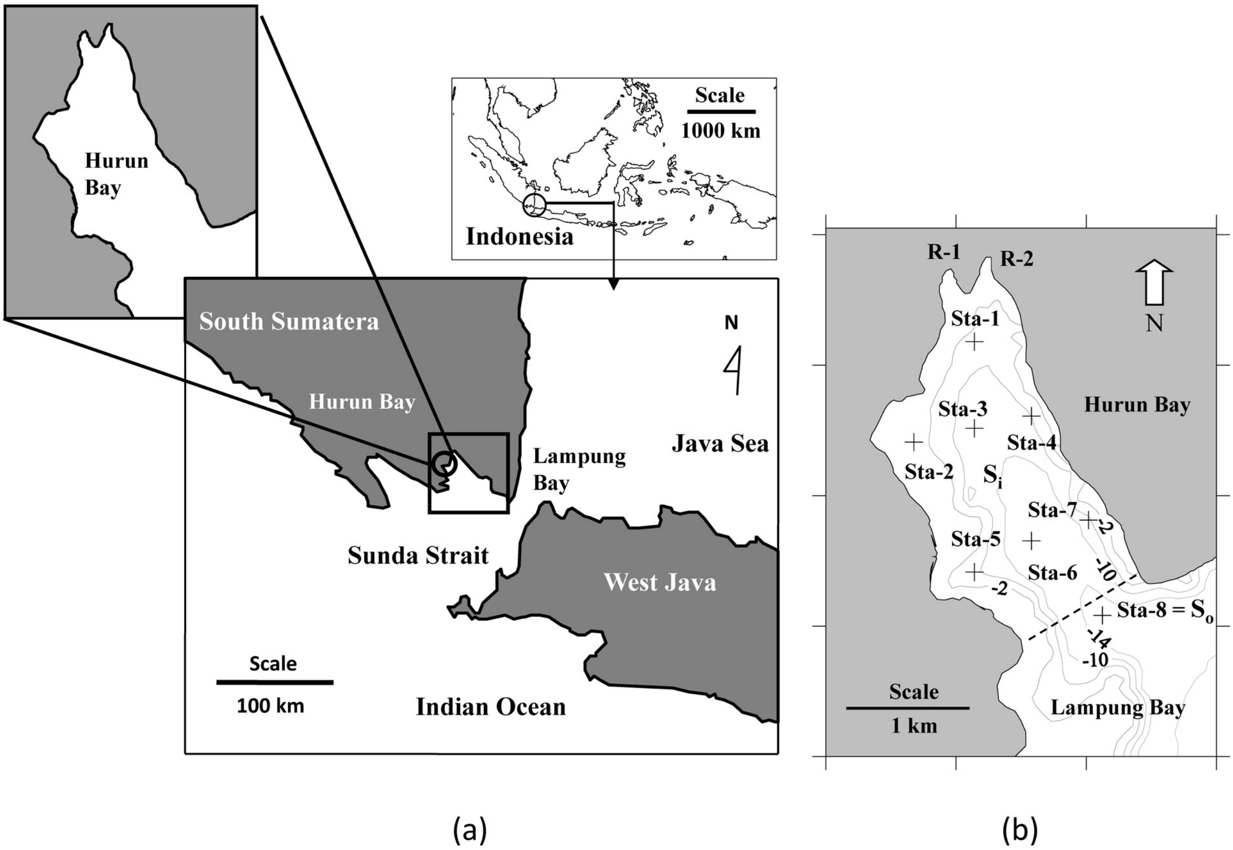

Fig. 3. Hurun Bay (a) and observation points (b). Numbers in (b) show the water depth in meters (Suhendar et al., 2008).

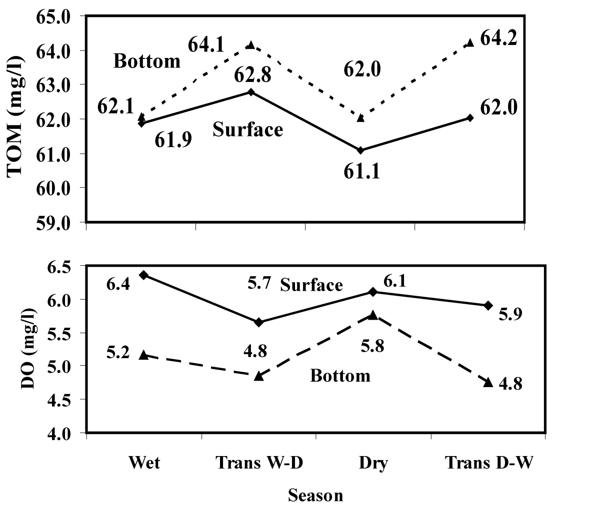

Fig. 4. Seasonal variations in TOM and DO at surface and bottom layers in Hurun Bay (Suhendar et al., 2008).

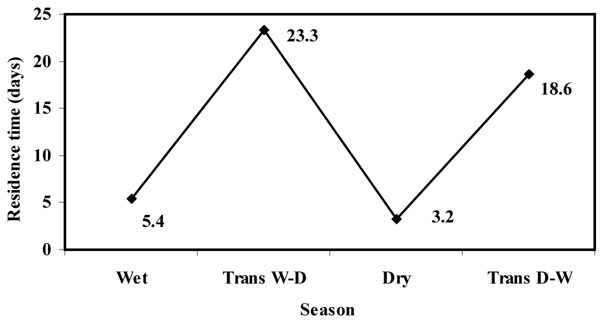

Fig. 5. Seasonal variation in average residence time of fresh water in Hurun Bay (Suhendar et al., 2008).

the bay mouth, and the short average residence time during the wet and dry seasons is due to the strong monsoon wind, strong currents and large water exchange ratio across the bay mouth (Suhendar et al., 2008).

Such results recommend that the aquaculture activity should be minimized in both transition seasons in order to reduce the risk of fish mortality caused by DO depletion due to the accumulation of organic matter in the bay.

Banpakong estuary

Seasonal variations in 3-dimensional circulation pattern in the Banpakong estuary, Thailand (Fig. 6, B in Fig. 1), were investigated using the Princeton Ocean Model (POM) by a diagnostic model technique (Yanagi, 1999) in Buranapratheprat and Yanagi (2003). Observed salinity and temperature at 22 stations shown in Fig.6, average wind velocity at Chonburi, river discharge from the Banpakong river in 2002, and calculated tidal elevation along the open boundary shown in Fig.6 were significant inputs for computation.

The calculated results indicated that all driving forces interacted complicatedly to the seasonal variation of 3-dimensional circulation in the Banpakong estuary. Wind-driven

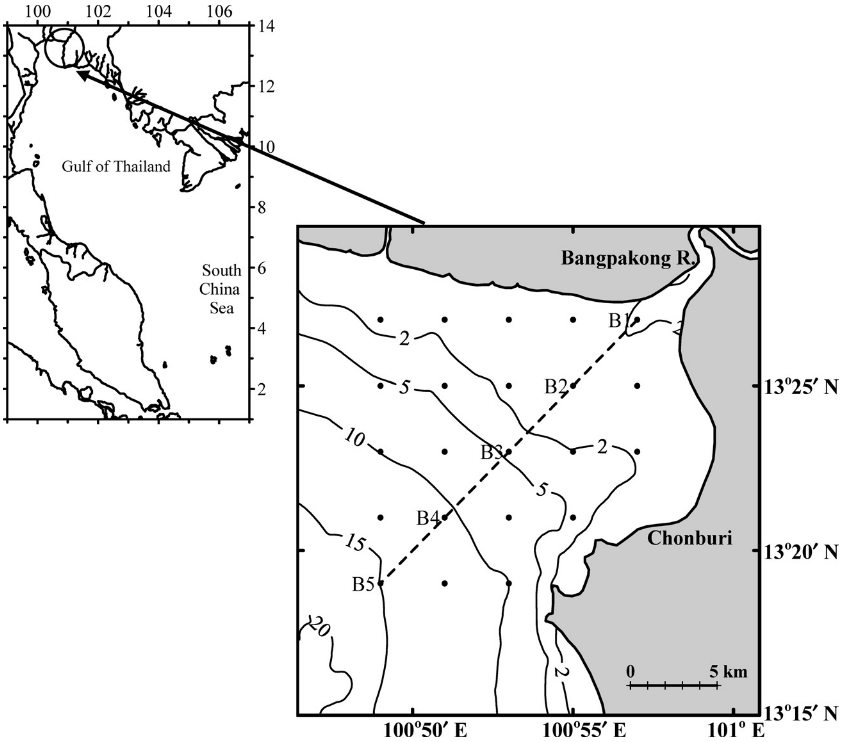

Fig. 6. Bangpakong River estuary. Dotts show the observation points of salinity and chlorophyll a. Numbers show the depth in meters (Buranatheprat and Yanagi, 2003).

current is predominant and its magnitude is large near the sea surface while tidal current prevalence is calculated throughout the water column. Influence of river discharges as an outflow and density-driven current are also calculated near the river mouth during the wet season (September).

The passive tracer experiment was conducted using the calculated 3-dimensional current field by the Euler-Lagrange method (Yanagi, 1999). The tracers of 3,600 particles were spread at the sea surface near the river mouth (black square in Fig. 7) and their movements were tracked until they all move out of a bounded area (screened area in Fig. 7) or the computational time is over 60 days. The position of tracer X_{n+1} (x_{n+1}, y_{n+1}, z_{n+1}) at time n+1, which was X_n (x_n, y_n, z_n) at time n, can be calculated by the following equation;

$$X_{n+1}=X_n+V\Delta t+1/2\,(\nabla V)V(\Delta t)^2, \qquad (7)$$

where V denotes the 3-diemnsional velocity vector of calculated flow, Δt is the time step, and ∇ is horizontal gradient.

The calculation results of particle distribution (Fig. 8) indicated that tidal current played important role to move particles out of the estuary in a short time scale and the seasonal variation in residence time of conservative and passive tracer depended on the variations in wind and river discharge. The average residence time of the passive tracer (τ_p) can be calculated by time integrating the results of the remnant function (rp (t) shown in Fig. 9) by using Equation (2).

Calculated average residence times (τ_p) from the longest to the shortest are 29.3 days, 20.4 days, 10.8 days and 6.0 days in April, June, December and September, respectively

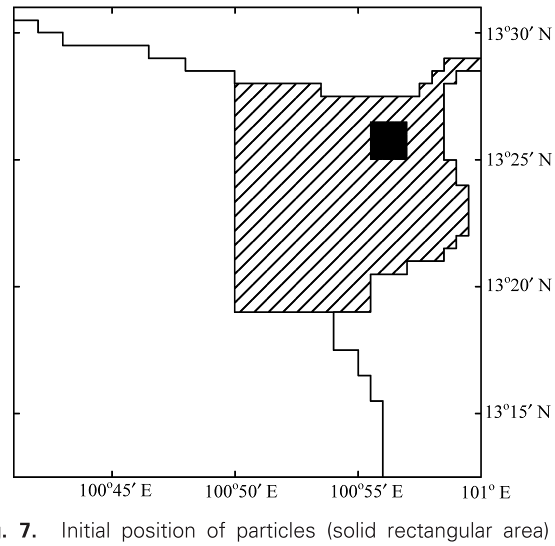

Fig. 7. Initial position of particles (solid rectangular area) and the boundary for the tracer experiment (screened area) (Buranatheprat and Yanagi, 2003).

(Fig. 9), corresponding to τ_R based on Equation (5) using the same salinity and river discharge data and different boundary region (Buranapratheprat et al., 2002) (Fig. 10).

The average residence time of conservative and passive tracer (τ_p) and that of fresh water (τ_R) does not coincide necessarily because τ_p and τ_R consider different material. The seasonal variations in their residence times are nearly the same except in June, when the southwest monsoon with an opposite wind direction to the fresh water flow direction pre-

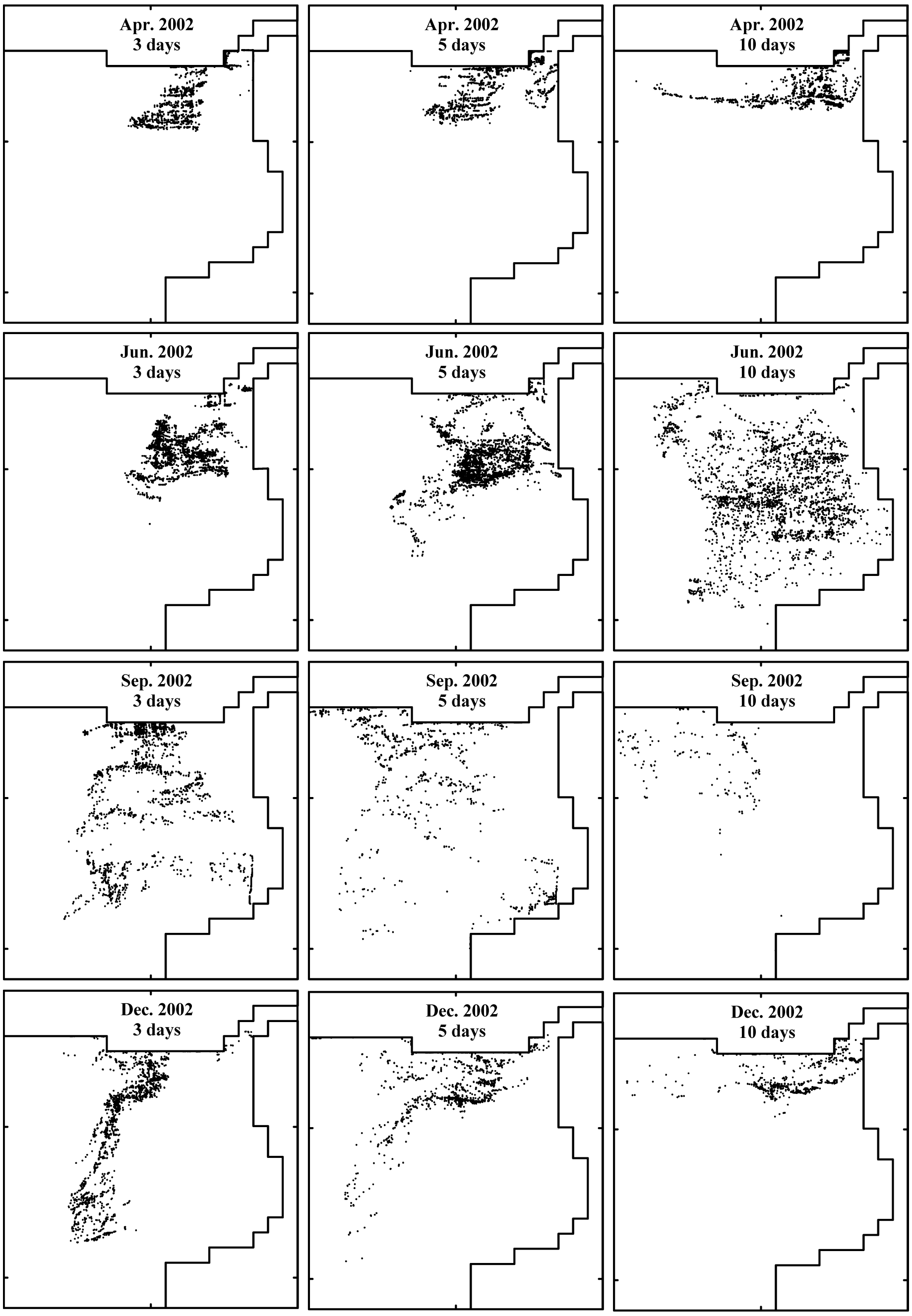

Fig. 8. Seasonal variation in tracer distributions 3 days, 5 days and 10 days after the injection (Buranatheprat and Yanagi, 2003).

vails, as shown in Fig. 10. Such results suggest that the density-driven current mainly governs the seasonal variation in current structure of the Bangpakong estuary, that is, the calculated tracer distribution, which was injected on the sea surface near the river mouth, nearly expresses the fresh water behavior originated from the river in the Banpakong estuary.

The longest average residence time of fresh water in June, shown in Fig. 10, well corresponds to the phytoplankton bloom (highest chlorophyll *a* concentration) season (Fig. 11) in the Bangpakong estuary (Buranatheprat et al., 2002).

Sulu Sea

The Sulu Sea (C in Fig. 1) is a semi-enclosed sea with a shallow sill of about 420 m deep and the deepest part of about 5,000 m as shown in Fig. 12. Though the scale of reservoir and the mechanism determining the residence time are completely different from the small scale estuary such as Hurun Bay and Banpakong estuary, the residence time of deep water and the estimation method are introduced in the followings.

The characteristics of the deep water in the Sulu Sea is very unique, that is, very warm (about 10°C) and low DO concentration (about 1 ml/l) compared to those in the South

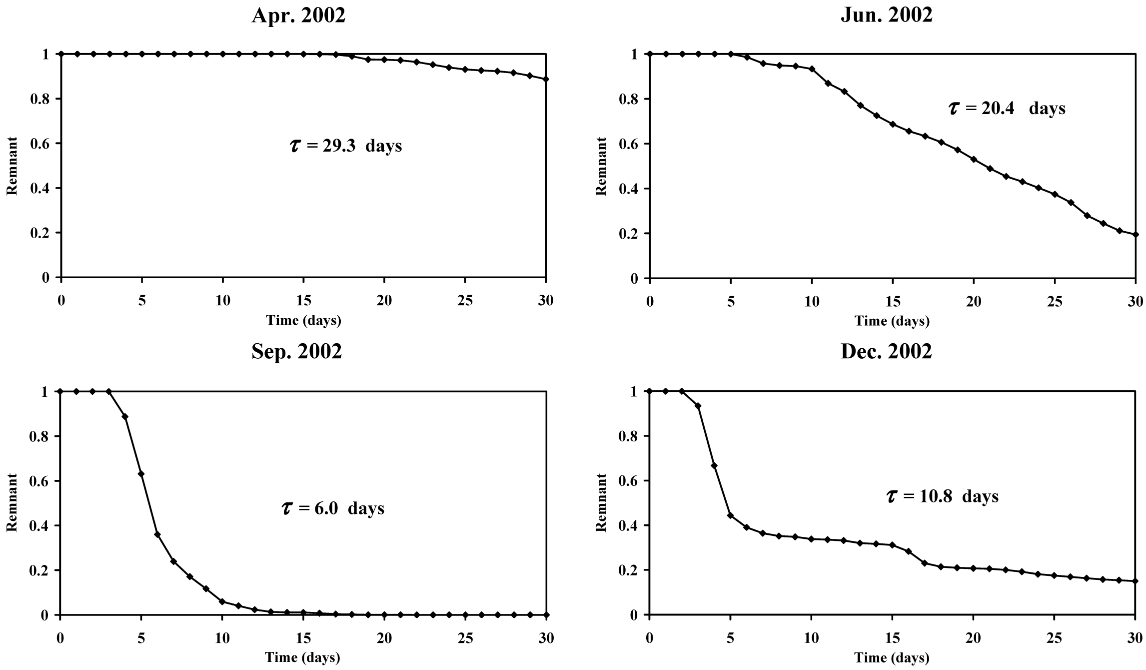

Fig. 9. Seasonal variations in remnant function of particles and residence time in the Banpakong estuary (Buranatheprat and Yanagi, 2003).

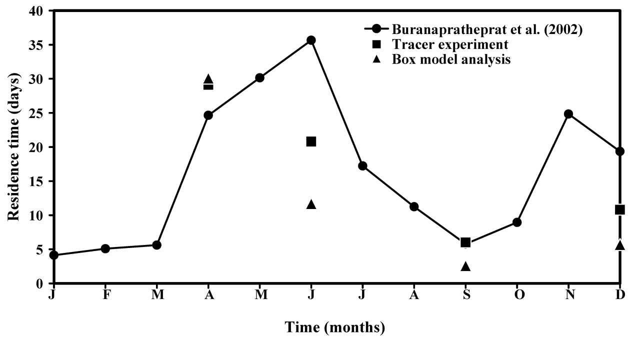

Fig. 10. Seasonal variations in average residence time of fresh water (black circle and triangle) and particles (black square) in the Bangpankong estuary. Circles and triangles show the different box scale, that is, circle is a box covering the whole observed area in Fig. 6 but triangle is a case with small scale shown by screened area in Fig. 7 (Buranatheprat and Yanagi, 2003).

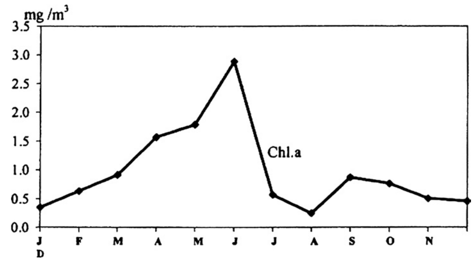

Fig. 11. Seasonal variation in chlorophyll a concentration in the Banpakong estuary (Buranatheprat et al., 2002).

China and Celebes Seas. Moreover the characteristics of deep water in the Sulu Sea is very homogeneous compared to those in the South China and Celebes Seas. This is due to a large vertical diffusivity up to $10\,cm^2\,s^{-1}$ (Yanagi et al., 2007) in the deep layer of the Sulu Sea and such a large vertical diffusivity is resulted from the propagation of large internal tide wave energy from the upper layer in the Sulu Sea (Apel et al., 1985).

Nozaki et al. (1999) estimated the average residence time of the deep water in the Sulu Sea by using the chemical tracer. Dissolved oxygen in the deep water is consumed by decomposition of organic matter. The deep water in the Sulu Sea contains 1.23 ml/L of dissolved O_2 and may be compared with the values of 2.26 ml/L at 420 m in the South China Sea or 2.08 ml/L at the subsurface oxygen maximum at 500 m in the Sulu Sea (Nozaki et al., 1999). Nozaki et al. (1998), on the basis of the GEOSECS Pacific ^{14}C and dissolved O_2 data, have estimated an oxygen consumption rate to be 5.81 ml/L y^{-1} for the Pacific deep waters. If this rate is used in the Sulu Sea, the difference in the dissolved O_2 concentrations between the upper and deep layers in the Sulu Sea corresponds to 292 to 353 years. Based on such consideration and $\Delta\,^{14}C$ values in the deep water of the Sulu Sea, Nozaki et al. (1999) concluded that the average residence time of deep water in the Sulu Sea is 300 ± 150 years.

The ventilation of the deep water in the Sulu Sea might be resulted from the combination of 1) quasi-steady inflow of denser water from the South China Sea through the Mindro Strait (sill depth of about 420 m), 2) occasional inflow of denser intermediate water through the Mindro Strait from the South China Sea into the bottom layer of the Sulu Sea when the thermocline in the South China Sea is uplifted, and 3) formation of less dense bottom water by means of geother-

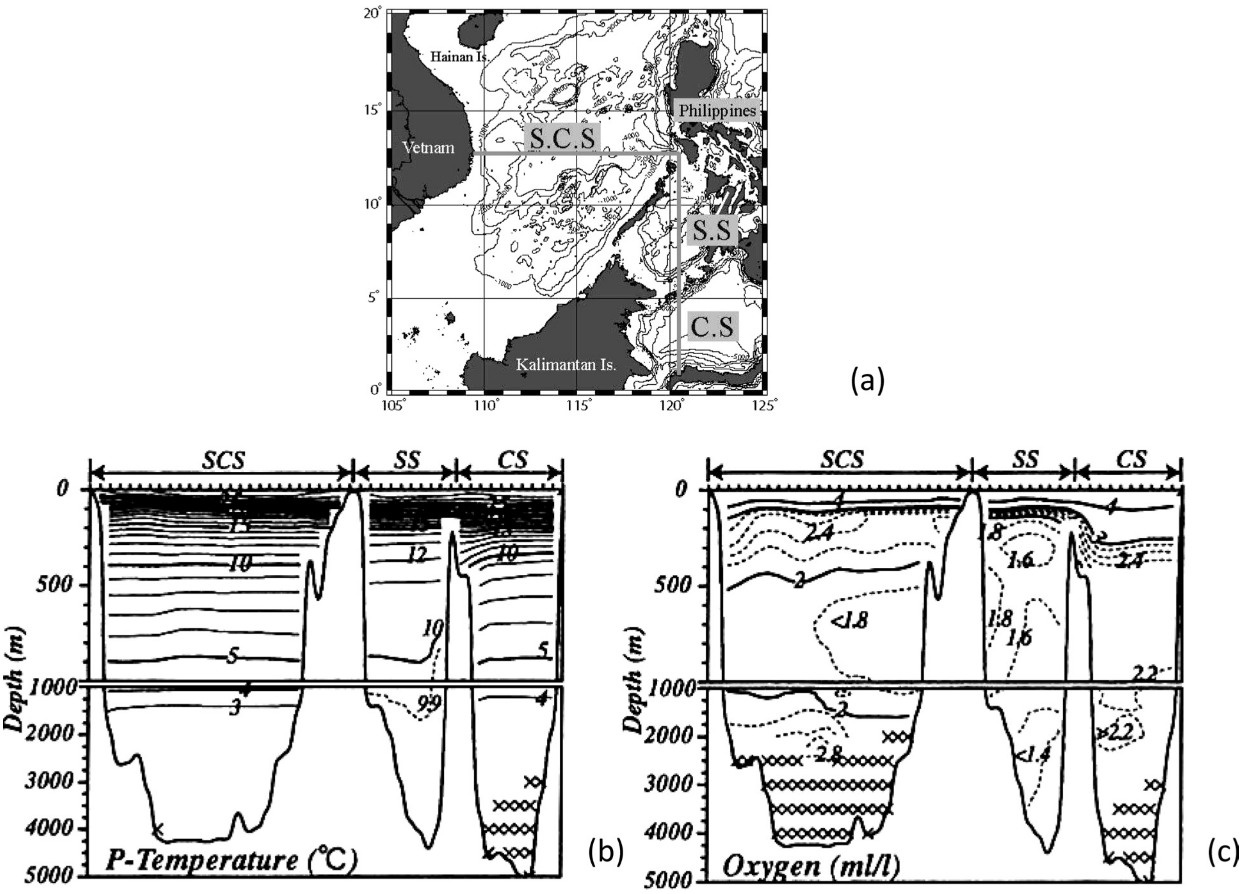

Fig. 12. Sulu Sea (a), vertical section of potential water temperature (b) and that of dissolved oxygen (c) from World Ocean Database CD-ROM Ver 1.2 (Yanagi et al., 2007).

Table 1. Water exchange times in some semi-enclosed costal seas in the southeast Asia (LOICZ, 2000 a, b)

Nation	Name	Area (km^2)	Average depth (m)	τ_X (days)	$\tau_{X'}$ (days)	Fig. 1
Philippines	Linguang Gulf	2,100	46	32	31	1
	Manila Bay	1,700	17	31	28	2
	Sulu Sea	200,000	5,000	1.1×10^5	C	
Vietnam	PhamThiet Bay	370	15	6–55	6–55	3
	NhaTrang Bay	410	17	37–67	35–65	4
Thailand	Bandan Bay	480	3	80	53	5
	ChaoPhraya estuary	38	10	4–5	3–4	6
	Banpakong estuary	100	5	4–37	B	
Malaysia	Kuala Terengganu estuary	8	6	<1	<1	7
Indonesia	Bantan Bay	150	7	1–10	1–10	8
	Hurun Bay	3	10	3–23	A	

mal heating, which in turn causes overturning of the Sulu Sea bottom water below a depth of 3,000 m (Gamo et al., 2007).

Such a long average residence time of the deep water in the Sulu Sea results in the unique biogeochemical properties and ecosystem there (Nishida and Gamo, 2007).

Water exchange time

LOICZ (2000 a, b) summarized the water exchange time proposed by Gordon et al. (1996) in the semi-enclosed coastal seas in the southeast Asia (Table 1). Water exchange time (τ_X) is defined by

$$\tau_X = V_T/V_x, \quad (8)$$

$$V_x = V_Q \cdot Si/(So - Si), \quad (9)$$

$$V_Q = Q_R + Q_P - Q_E, \quad (10)$$

where V_T (m^3) denotes the volume of bay water, V_x ($m^3\ s^{-1}$) the exchange rate across the bay mouth which corresponds to Q_S in Fig. 2, V_Q the residual water flux from the bay to the open ocean which corresponds to Q_R in Fig. 2, Q_R river discharge, Q_P precipitation and Q_E the evaporation. Such water exchange time corresponds to the average residence time of total water mass in the bay (τ_T) by Takeoka (1984) but τ_X and τ_T are not the same because τ_T is defined by

$$\tau_T = V_T/(Q_R + Q_S). \quad (11)$$

The definition of Equation (8) has no meaning from the physical viewpoint because V_T is consisted by V_R and V_S. As the definition of V_T/Q_R has no meaning, V_T/V_x or V_T/Q_S has no meaning. The time for exchange of total bay water must be expressed by Equation (11) and the definition of Equation (8) must be changed as

$$\tau_{X'} = V_T/(V_x + V_Q) \quad (12)$$

$\tau_{X'}$ in some representative semi-enclosed coastal seas in the southeast Asia are also summarized in Table 1 with τ_X of Hurun Bay, Banpakong estuary and Sulu Sea (LOICZ, 2000 a, b). The difference between τ_X and $\tau_{X'}$ is not large except Bandan Bay in Thailand because the water mass exchange effect across the bay mouth is larger than the flushing effect by the river discharge in these semi-enclosed coastal seas.

Water exchange time in each bay (water mass exchange effect across the bay mouth) is determined by the current system there, which is composed of the tidal current, the wind-driven current and the density-driven current, and the effect of density-driven current is usually large. For example, the short water exchange times in PhamTiet, NhaTrang and Bantan Bays are obtained in the wet season, when the density-driven current (estuarine circulation) develops, and the long ones in the dry season, when the density-driven current is weakened. The long water exchange time in Bandon Bay in Thailand is obtained in the dry season (April).

Conclusion

The concept of average residence time of water mass is very important and useful especially in the semi-enclosed coastal sea because we can understand the reason of eutrophication and its temporal change by applying this concept. We have to develop multi-disciplinary study by the physical, chemical and biological oceanographers in the semi-enclosed coastal seas of the southeast Asia in order to solve the environmental problems such as red tide, hypoxia and anoxia there.

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