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ESTIMATION OF RESIDENCE TIME IN COASTAL WATERS OF VIETNAM: A COMPARISON OF RADIOACTIVITY, HYDRODYNAMICS, AND LOICZ APPROACH

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ESTIMATION OF RESIDENCE TIME IN COASTAL WATERS OF VIETNAM: A COMPARISON OF RADIOACTIVITY, HYDRODYNAMICS, AND LOICZ APPROACH

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Key words: water exchange, LOICZ, radioactivity method, numerical dynamic modeling.

ABSTRACT

Water exchange plays a vital role in controlling water quality and the assessment of environmental carrying capacity for marine spatial planning. Water exchange in water bodies is determined by residence time. A comparative study of the different residence times in the coastal waters of Vietnam by radioactivity, numerical dynamic modeling, and land–ocean interactions in the coastal zone (LOICZ) approaches is conducted. The residence time calculated using the radioactivity method was higher than that obtained through other approaches. The results of radioactivity and numerical dynamic modeling presented full images of water exchange in the study areas, whereas the LOICZ approach indicated water exchanges that occurred in the entire water body. Thus, a satisfactory agreement between calculated and measured water exchange was obtained for Cam Ranh Bay by integrating the radioactivity method within numerical modeling to improve the calculation of carrying capacity for marine spatial planning.

I. INTRODUCTION

Integrated coastal zone management is necessary for master planning of sustainable development. In such planning, the estimation of the environmental carrying capacity for coastal waters plays an important role to achieve environmental control and ecosystem improvement. Assessment of the coastal waters carrying capacity should be targeted as a national environmental criteria, including the status of the current environment, waste discharge and water exchange, and/or residence times of waters (GESAMP, 1986; Wackernagel, 1994; Zhiming et al., 2018).

Residence time is a measure of the average time a substance spends within a physical system; this substance could be any particle flowing with the water (Aikman and Lanerolle, 2004). In the case of the coastal waters, a measure of residence time can be extremely useful in determining transport and fate of contaminants and organisms in estuarine systems (Anderson et al., 2003; Lee et al., 2011). Several methods have been used to estimate residence time in coastal waters, including: direct measurements, box models, hydrodynamic models, residual velocity and salinity intrusion methods, and the dynamic systems approach (Takeoka, 1984; GESAMP, 1986; Wackernagel, 1994; Anderson et al., 2003; Lee et al., 2011; Rynne et al., 2016; Zhiming et al., 2018; Duong et al., 2019). Coastal waters in central Vietnam, in regions such as Cam Ranh Bay, are advantageously situated for integrated marine economic development. However, the environment of Cam Ranh Bay has been negatively impacted by waste from economic activities. Thom (2008) indicated that environmental quality deteriorated during 2002–2008, whereas Minh-Thu et al. (2013a) demonstrated that the environmental quality in the Thuy Trieu lagoon, the upper region of Cam Ranh Bay, while mostly unimpacted, had worsened slightly. Long et al. (2013) and Minh-Thu et al. (2013b) demonstrated that water exchange was involved in the self-purification of water bodies in the Cam Ranh Bay because of physical processes and hydrodynamics. Determination of residence time can assist with the estimation of the pollutant dilution capacity of the water bodies as well as the expansion of the environmental carrying capacity.

Thus, it is important from an environmental management

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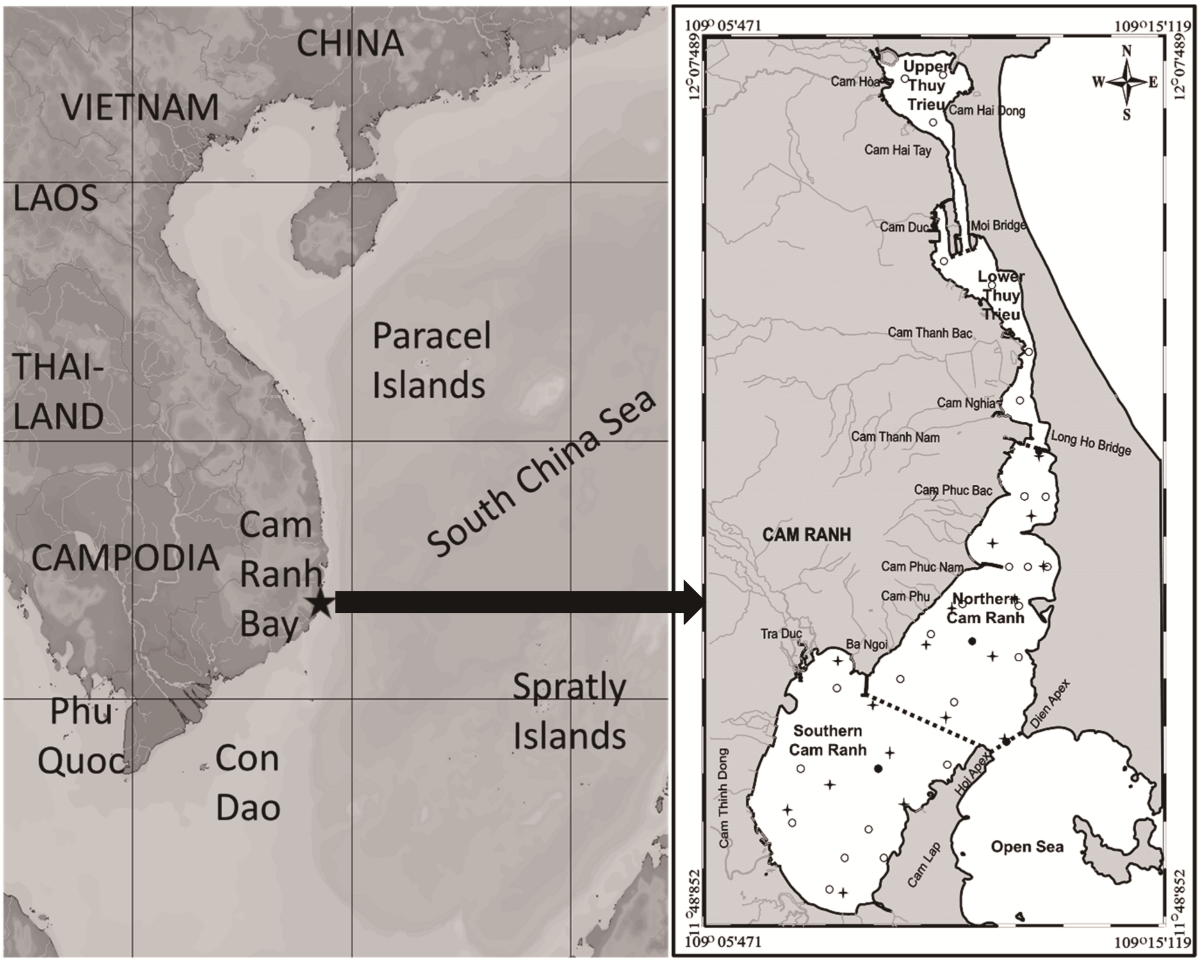

Fig. 1 Location of stations for collecting radioactivity data (✦); stations for measuring salinity, temperature and current profiles (O); 24-hour stations (●), (----) boundary of water bodies

standpoint to be able to accurately estimate water exchange or residence time. Through numerical hydrodynamic modeling, the land–ocean interactions in the coastal zone (LOICZ) approach and direct measurement by radioactivity, the water exchanges in Cam Ranh Bay were calculated.

II. METHODOLOGIES

1. Collecting and radioactivity analysis of water samples

The study was carried out in the Cam Ranh Bay during the period of 2002–2018 (Fig. 1).

Water samples being analyzed for radioactivity were collected at 17 stations (Fig. 1). At each station, 10 L of seawater was collected in plastic cans, including 5 L from the surface layer and 5 L from the bottom layer.

Salinity, temperature, and current profiles were measured at 23 normal stations and four 24-hour stations (Fig. 1). Current and CTD profiles were measured during the dry (southwest monsoon) and rainy (northeast monsoon) seasons.

At the laboratory, 10-L seawater was evaporated at 50–60 °C until all the water had escaped. The residue was stored in well-sealed plastic boxes. All samples were measured using the well high purity germanium (HPGe) detector of the low-background gamma-ray spectrometry system (Canberra Industries, Inc, US) within 24 hours of sampling. Activities of ^{228}Ra (1,600 y) and ^{226}Ra (5.75 y) were determined by the ingrowth of ^{214}Pb (295 and 352 keV) and ^{228}Ac (338 and 911 keV), with γ counting after the radioactive equilibrium of ^{226}Ra and ^{214}Pb (about 3 weeks) was reached, whereas ^{228}Th activity was evaluated indirectly from that of ^{212}Pb (239 keV).

2. Estimation of water exchanges by radioactivity

Modeling of material transportation in coastal waters based on radioactivity (A) is shown in Equation (1)

$$\frac{dA_T}{dt} = K_h \frac{\partial^2 A_T}{\partial x^2} - \omega \frac{\partial A_R}{\partial x} \tag{1}$$

in which, A_R and A_T are the radioactive levels of ^{228}Ra and ^{228}Th in the water samples, respectively. In the offshore regions,

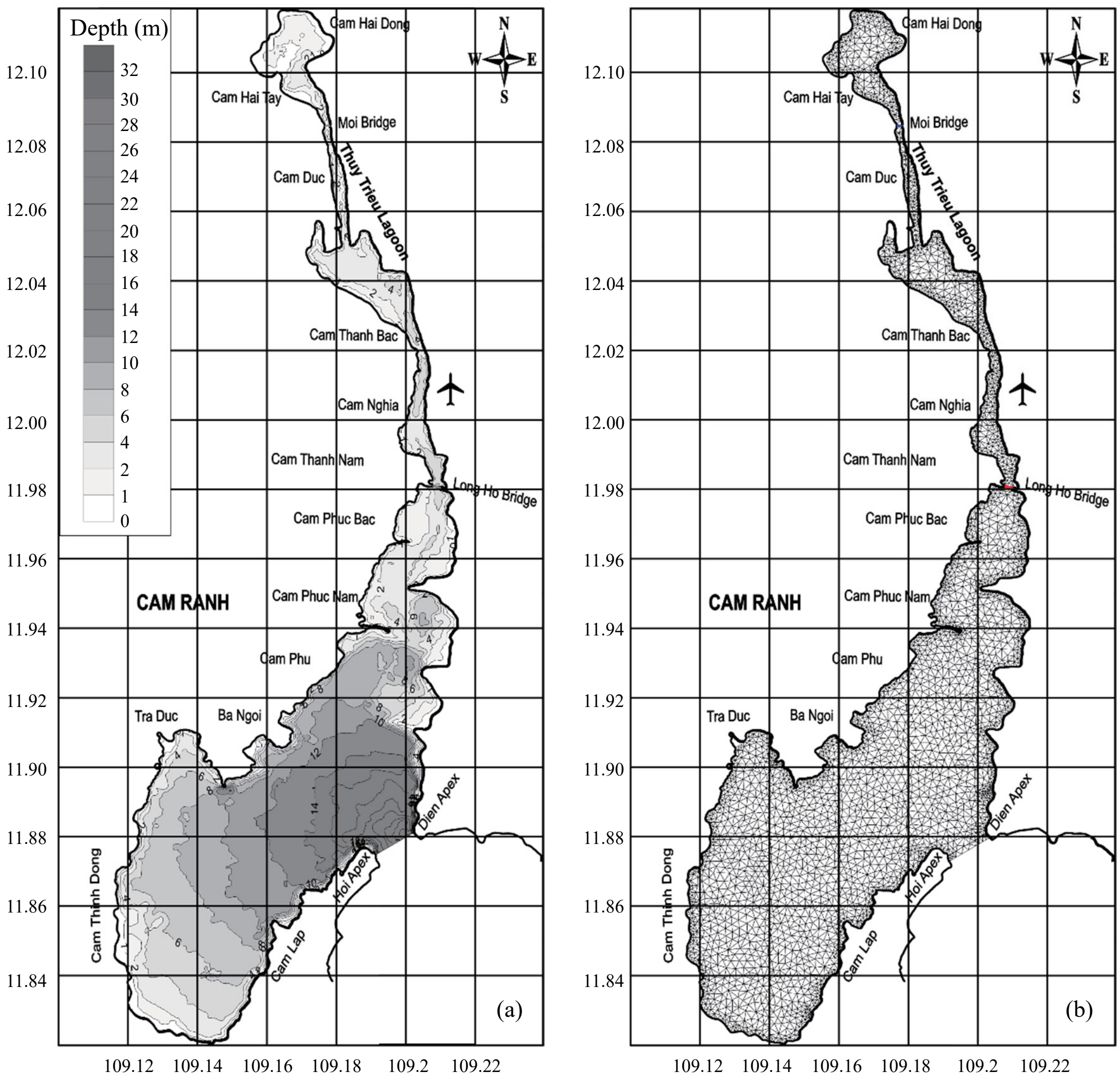

Fig. 2 Bathymetry data and triangular mesh in the study area

^{228}Ra can be determined via Equation (2) (Broecker et al., 1973; Kipp et al., 2018; Moore, 2000).

$$A_R = A_{R0} exp\left(-\sqrt{\frac{\lambda_R}{K_h}}x\right) \qquad \begin{matrix} A_R \to A_{R0} \text{ when } x \to 0 \\ A_R \to 0 \text{ when } x \to \infty \end{matrix} \tag{2}$$

in which K_h is the horizontal eddy diffusion coefficient of material at boundary conditions, and x is the offshore distance. K_h could be calculated from the slope (m) of a plot of ln(^{228}Ra) with the distance from stations to offshore, $K_h = m^2/\lambda$.

For solution (1) in the case of ^{228}Ra – ^{228}Th balance, Moore (2000) found that a residence time of semi-opened waters (τ) is expressed with Equation (3)

$$\tau = \frac{\lambda_R(\frac{A_T}{A_R})}{\frac{\lambda_T}{\lambda_T - \lambda_R} - \frac{A_T}{A_R}} \tag{3}$$

in which, λ_R and λ_T are the half-life of ^{228}Ra and ^{228}Th, respectively. For ^{228}Ra, λ_R = 1.9 y and ($\lambda_T/(\lambda_T-\lambda_R)$) = 1.49 (Rutgers van der Loeff et al., 2018).

3. Numerical hydrodynamic modeling

The finite element model for triangular meshes was applied to the hydrodynamic systems in Cam Ranh Bay with flowing components (Long and Chung, 2010; 2014):

- For horizontal direction (x, y), the dynamic equation is:

$$\begin{aligned} &\frac{d\vec{v}}{dt} + \vec{f} \times \vec{v} = g\nabla_{xy}\zeta - \frac{\partial}{\partial z}\left(N_m \frac{\partial \vec{v}}{\partial z}\right) = \\ &-\frac{g}{\rho_0}\int_z^{\zeta} \nabla_{xy}\rho dz + \vec{F}_m + \frac{\sigma}{\rho}\left(\vec{v}_\sigma - \vec{v}\right) \end{aligned} \tag{4}$$

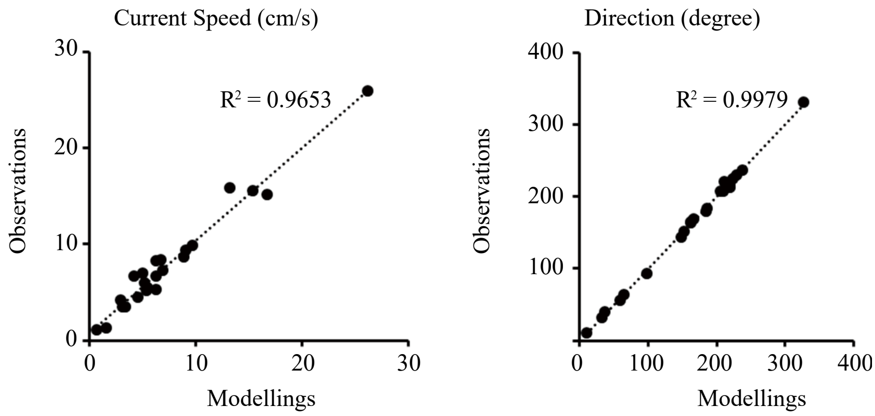

Fig. 3 Calibration of the hydrodynamic model in Cam Ranh Bay

- The function of conservation of salt and temperature:

$$\frac{dT}{dt}-\frac{\partial}{\partial z}\left(N_h\frac{\partial T}{\partial z}\right)=F_T+\frac{\sigma}{\rho}\left(T_\sigma-T\right) \quad (5)$$

$$\frac{dS}{dt}-\frac{\partial}{\partial z}\left(N_h\frac{\partial T}{\partial z}\right)=F_T+\frac{\sigma}{\rho}\left(S_\sigma-S\right) \quad (6)$$

- Other functions of dynamics:

$$\frac{dq^2}{dt}-\frac{\partial}{\partial z}\left(N_q\frac{\partial q^2}{\partial z}\right)=2\left[N_m\left(\left(\frac{\partial u}{\partial z}\right)^2+\left(\frac{\partial v}{\partial z}\right)^2\right)+\frac{g}{\rho_0}N_h\frac{\partial \rho}{\partial z}\right] -2\left[\frac{q^3}{B_1 l}\right]+\frac{\sigma}{\rho}\left(q_\sigma^2-q^2\right) \quad (7)$$

$$\frac{dq^2 l}{dt}-\frac{\partial}{\partial z}\left(N_q\frac{\partial q^2 l}{\partial z}\right) =lE_1\left[N_m\left(\left(\frac{\partial u}{\partial z}\right)^2+\left(\frac{\partial v}{\partial z}\right)^2\right)+\frac{g}{\rho_0}N_h\frac{\partial \rho}{\partial z}\right] -lW\left[\frac{q^3}{B_1 l}\right]+\frac{\sigma}{\rho}\left(q_\sigma^2 l_\sigma-q^2 l\right) \quad (8)$$

in which, E_1 and B_1 are the experimental coefficients (Mellor and Yamada, 1982) and W is a limiting function (Blumberg et al., 1992).

Input data:

- Wind input data for the model was derived from http://www.remss.com/windsat/windsat_browse.html. The data were simulated with in-situ data from wind stations in coastal regions such as Tuy Hoa, Nha Trang, Phu Quy and Vung Tau, from the period 1987–2014.
- Bathymetry maps were based on digital mapping (1/10,000) (Fig. 2).
- Boundary conditions: Monthly thermohaline data could be drawn from the NOAA database (http://www.nodc.noaa.gov/OC5/WOA01/5d_woa01.html) and Russia (http://nodc.meteo.ru/).
- Tidal data was collected at the Cau Da–tidal station based on the finite element model in Long and Chung (2014) and then simulated using the four 24-hour stations in Cam Ranh Bay.
- Grid: Total area of the marine regions was 92,386 km^2. The number of calculated nodes was 3,473 for the 5,903 of element triangles. The area of the triangles ranged 692 m^2 to 39,975 m^2, with an average: 15,651 m^2 (Fig. 2).

Calculation results: Grid data function in MATLAB was used for interpolation of in-situ data from all the nodes in the study regions, based on Delaunay triangulation. The calibration of the hydrodynamic modeling is shown in Fig. 3.

4. LOICZ approach for water exchanges

The LOICZ approach was developed based on the balance of materials in bodies of water (Gordon et al., 1996). This modeling has been applied in biogeochemistry as well as in estimation of ecological carrying capacity in coastal waters. Basically, a budget describes the rate of material delivery to the system ("inputs"), the rate of material removal from the system ("outputs"), and the rate of change in material mass within the system ("storage"). Some materials may undergo internal transformations of state, which lead to appearance or disappearance of these materials. In general case, the LOICZ is represented by Equation (9):

$$\frac{dM}{dt}=\sum inputs-\sum outputs+\sum\left[sources-sinks\right] \quad (9)$$

Water residence time in LOICZ was calculated using Equation (10):

$$\tau=\frac{V_{syst}}{\left(V_X+\left|V_R\right|\right)} \quad (10)$$

Table 1 Th and Ra isotopes (mBq/L) in waters of Cam Ranh Bay

Value	^{228}Th	^{228}Ra	^{226}Ra	Salinity in surface (ppt)	Salinity in bottom (ppt)	^{228}Th/^{228}Ra	Residence time (day)
Min	0.65	9.99	3.66	31.30	31.30	0.03	15.38
Max	3.95	82.75	20.10	33.00	34.50	0.13	66.88
Average	1.54	27.60	11.47	32.27	33.10	0.06	30.88
±SD	0.75	17.00	5.51	0.54	1.02	0.03	14.40

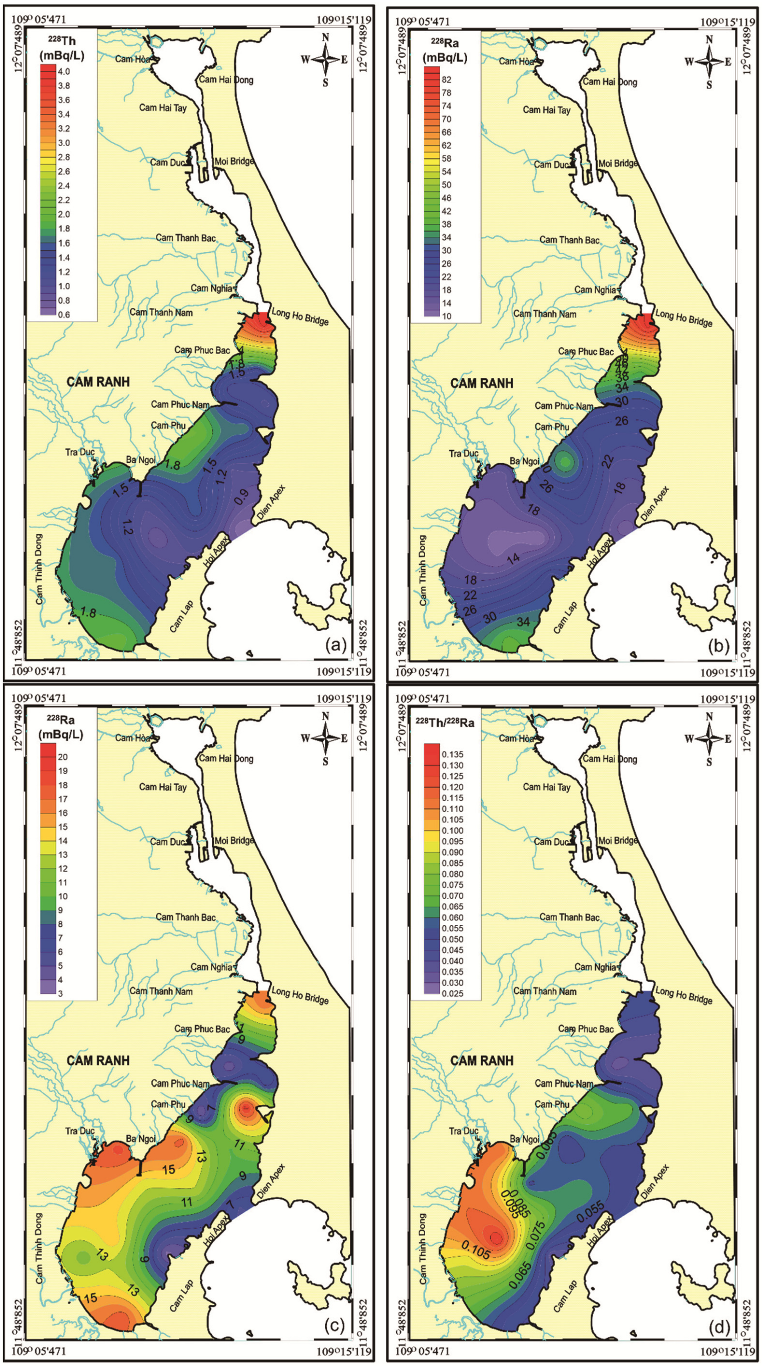

Fig. 4 Distribution of ^{228}Th (a), ^{228}Ra (b), ^{226}Ra (c), and ^{228}Th/^{228}Ra (d) in Cam Ranh Bay

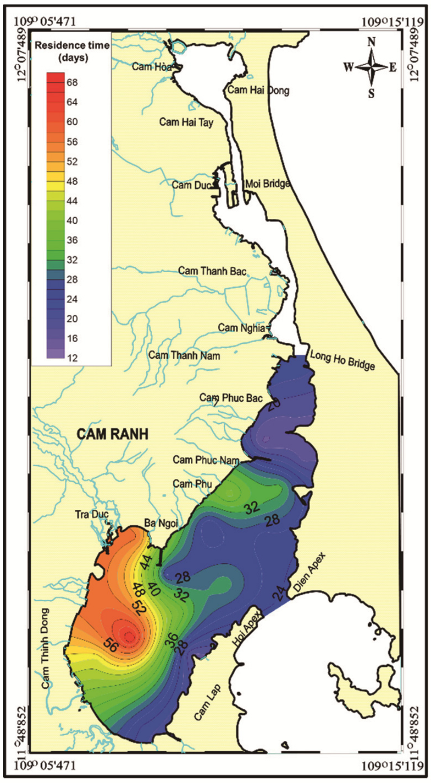

Fig. 5 Residence time in Cam Ranh Bay based on the radioactivity approach

III. RESULTS

1. Water exchange in Cam Ranh Bay determined by the distribution of Ra and Th isotopes

The activity of ^{229}Th, ^{228}Ra, and ^{226}Ra ranged from 0.65–3.95 mBq/L; 9.99–82.75 mBq/L; and 3.66–20.10 mBq/L, respectively (Table 1). The distribution of these activities of Th and Ra isotope is shown in Fig. 4. The ^{226}Ra levels near the coastline, as well as in the regions affected by freshwater and low current, were higher than that in seawater (Fig. 4c). In the Long Ho Bridge area, due to high total suspended sediments (TSS), the Th and Ra isotope activity was the highest. The ratio of ^{228}Th/^{228}Ra indicated the presence of sources of freshwater and seawater in the Bay (Fig. 4d).

Kaufman et al. (1981) found that due to the fact that ^{228}Ra decays to ^{228}Th, the ratio of ^{228}Th/^{228}Ra < 0.05 indicates the boundary of coastal water mass and seawater mass. Fig. 4d shows that most of Cam Ranh Bay was contributed to by seawater in its eastern part. The western part of the bay was not taken into account due to high TSS and freshwater levels and low currents.

Results of water exchange in Cam Ranh Bay were estimated very slowly. The residence time ranged from 15.38 – 66.88 days, average 30.88 ± 14.40 days (Table 1 and Fig. 5). Fig. 5 shows that Cam Ranh Bay was divided into two parts. The first part was in the western part of Cam Ranh Bay, which had a lower water exchange; the residence time was higher than 40 days. Another part had a higher water exchange rate with a residence time of less than 30 days. A waterfront exited in between these parts.

2. Modeling of hydrodynamic systems in Cam Ranh Bay

The calculated results are presented in Fig. 6–7.

Currents at flood tide: The vertical velocity could reach the maximum value with the direction of 274.9° - 336.5°. The maximum current speed was 57.9 cm/s, and a direction of 299.0° and was located at 109.20194°E; 11,87954°N with a water depth of 4.2 m (Fig. 6b). The modeling estimation was similar to the natural dynamic systems in these areas. To avoid an unnecessary repeat, we used the following phrases for the current speeds in Cam Ranh Bay:

- current speed $|\vec{v}| < 10(cm/s)$: weak current
- current speed $10(cm/s) \le |\vec{v}| < 20(cm/s)$: a moderate current
- current speed $20(cm/s) \le |\vec{v}| < 30(cm/s)$: a quite strong current
- current speed $|\vec{v}| \ge 30(cm/s)$: strong current

Quite strong and strong currents were often observed in a narrow slit at Long Ho Bridge, where they caused sediment bed erosion with high TSS. In the flood tide cycle phase, the frequency of the weak current was about 88%, and that of moderate current was 10.5%, whereas the frequencies of the quite strong and strong currents were low (total of 1,5%).

Currents at ebb tide: The maximum vertical velocity could be found when the current direction was 95.6°–169.1° (Fig. 6a). The maximum vertical velocity reached 81.6 cm/s with the direction of 99.4°, and was often located at 109.20091°E; 11.87900°N with a water depth of 1.2 m. The ebb tide velocity was higher than that in flood tide cycles. The statistical value of current was the distribution of 73.3% weak current, 15.7% moderate current, 7.6% quite strong current, and 3.7% strong current.

In the term of seasonal changes, in the northeast monsoon, surface current distributed in 70.4% weak current, 27.8% moderate current and 1.8% quite strong current, without a strong current (Fig. 7a). Contracting, in the southwest monsoon, Fig. 7b showed 85.9% weak current, 12.5 % moderate current, 0.8 % quite strong current, and 0.8% strong current.

In addition, the water mass exchange at a transect of the gate in Cam Ranh Bay indicated the residence time was about 15 – 25 days (Long et al., 2013) which depended mainly on tidal cycles and inland runoff.

3. Estimation of water exchanges using LOICZ modeling

By applying the LOICZ approach, exchange capacity of water masses in Cam Ranh Bay was strongly variable. Depending on the topographical systems, residence times of water masses ranged from 5.29 – 24.61 days during the dry season and 2.39 – 14.11 days during the rainy season (Fig. 8). In general, for the whole water system, the residence time in the dry season was 18.90 days and in the rainy season was 16.02 days (Minh-Thu et al., 2013b)

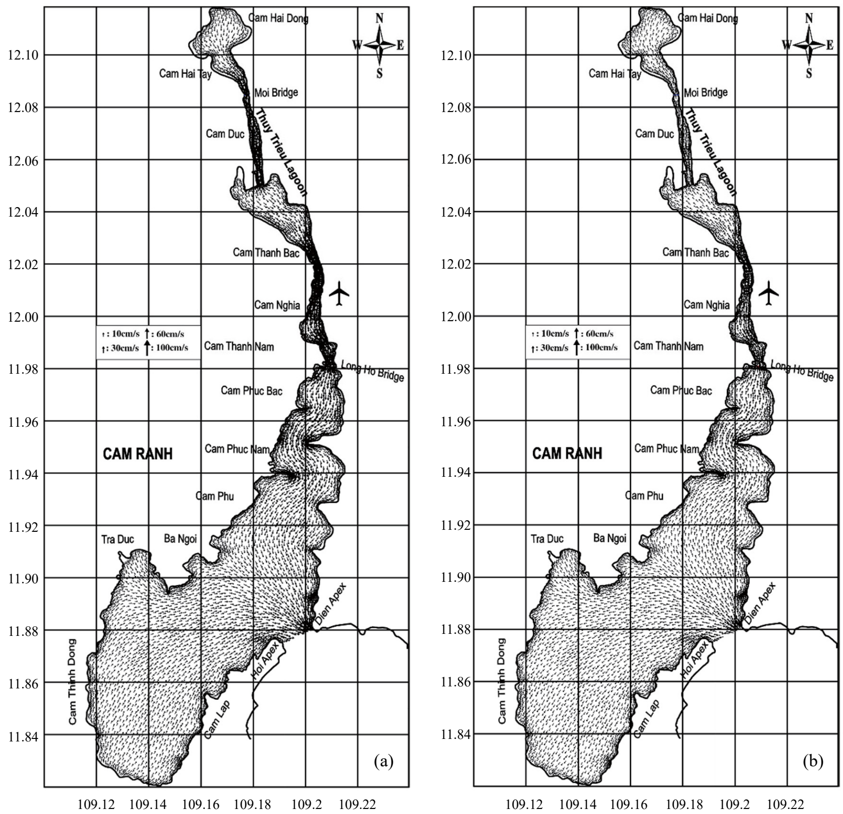

Fig. 6 Current distribution in Cam Ranh Bay at ebb tide (a) and flood tide (b).

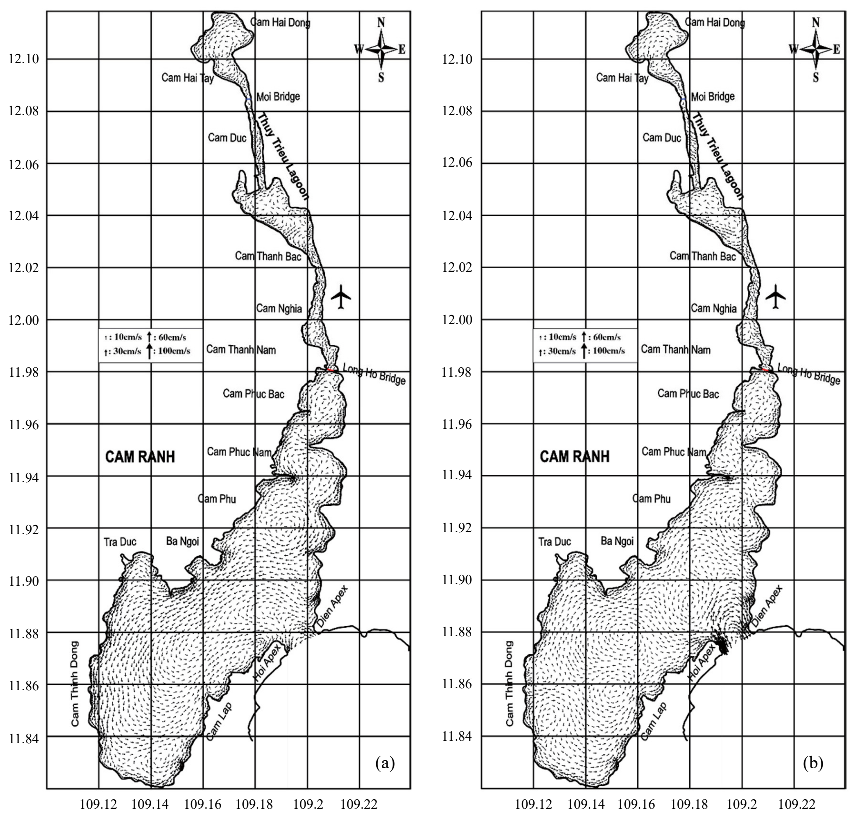

Fig. 7 Distribution of current in the surface layer in January (a) and July (b) in Cam Ranh Bay

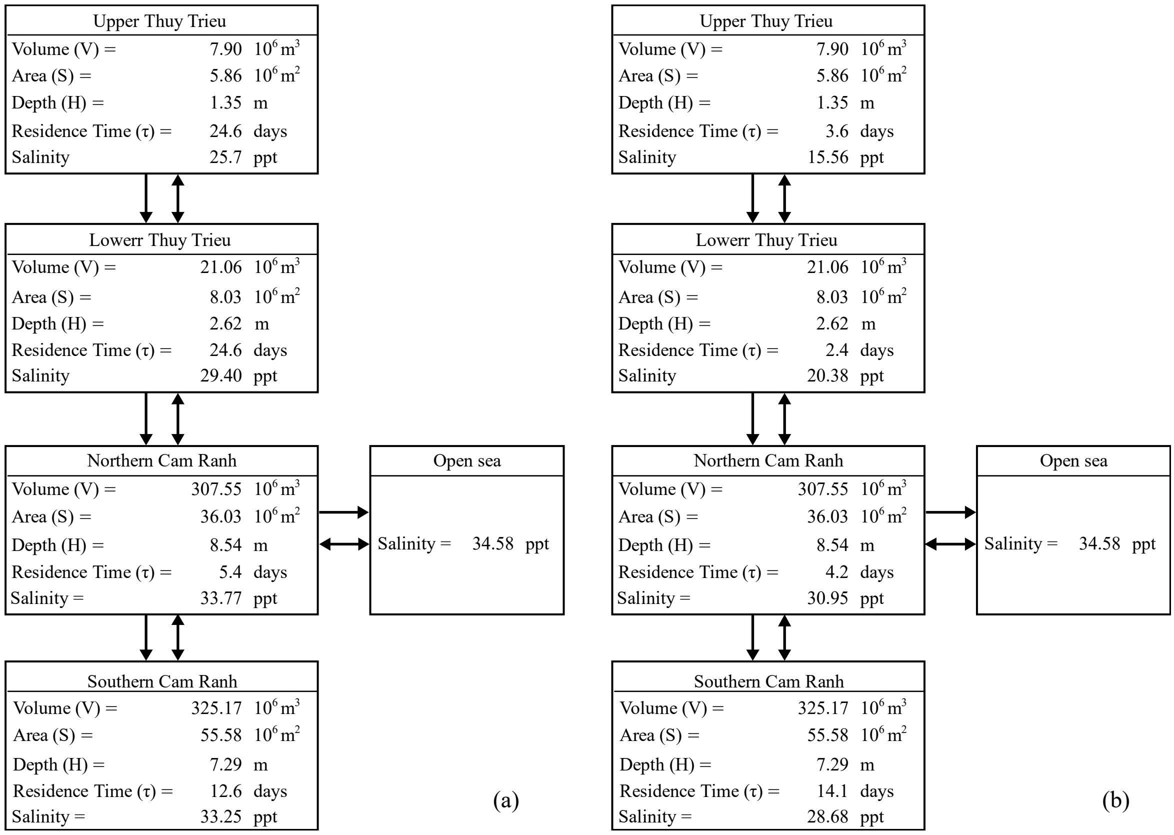

Fig. 8 LOICZ modeling results in Cam Ranh Bay for dry (a) and rainy (b) seasons.

IV. DISCUSSIONS AND CONCLUSIONS

There was a significant difference in Cam Ranh Bay residence times depending on the type of analysis used. The residence time determined from radioactivity was higher than that obtained through other methods, whereas results of numerical hydrodynamic modeling and the LOICZ approach are similar. The results from Tomasky-Holmes et al. (2013) with regard to the estimation of residence time also supports our findings; the water mass age measured by the radium method was higher than that found in other observations and modeling. The following are possible explanations of these disparities: the residence time in the entire Cam Ranh Bay water body was 15–25 days using numerical hydrodynamic modeling, which obviously depends on the transportation of water masses through the gate transect as well as full pictures of hydrodynamic regimes. With the LOICZ approach, four boxes of water bodies were identified in this study; in every box, characteristics of the whole water mass were assumed to be homogenous. Thus, when a water mass was transferred across the boundary of a box, it overlapped with other boundaries. As a result, the residence time of the LOICZ method was about 18.90 days in the dry season and 16.02 days in the rainy season. With the radioactivity method, the ratio of $^{228}Th/^{228}Ra$ could be used for the estimation of the fractions of seawater and freshwater in a water mass (Moore, 2000; Rutgers van der Loeff et al., 2012; Zhang et al., 2012); this method could therefore identify the water exchanges in coastal water both qualitatively and quantitatively. The residence time obtained from the radioactivity method was approximately 15.38–66.88 days, with an average of 30.88 ± 14.40 days. However, the results were based on instantaneous value; they could not present full images of water exchanges in Cam Ranh Bay. Thus, integrating the radioactivity method within numerical modeling can improve the accuracy of estimation of water exchanges.

wFurthermore, the requirements of the three methods contributed to the selected way for estimation of residence time by users. The LOICZ approach is the simplest method to use, the residence time is calculated by river inflow, rainfall, salinity, and bathymetry (Gordon et al., 1996). The use of climatology data in the model would cause the results to vary, owing to the randomness and variability in the data. The model was easy to use even for non-specialists (Ramesh et al., 2015). This model can be applied for a one-box model or complex systems with compartments spread horizontally and/or vertically. In these systems, the output of one box would be the input of another. Estimating residence time by numerical hydrodynamic modeling relies more on input and observed data, software, and hardware (van Sebille et al., 2018), especially if it needs to have the long-term observed data both in local, regional and global scales. The model needs to run by experts; however, the modeling can assume various scenarios for changes in residence time due to climate change and human impacts. With the radionuclide method, residence time is estimated based on the balance of ^{228}Th and ^{228}Ra as well as their decay in the natural systems/coastal or marine waters. Like the numerical hydrodynamic modeling, the radionuclide approach needs to be handled by experts and requires costly equipment and protocols pertaining to safety from radioactivity (Meisenhelder and Bursik, 2018). Thus, residence time approaches need to be considered based on the purpose of marine environmental research and governance, and the results obtained can be implemented support sustainable development of coastal and marine waters.

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