Water Exchange and Transport of Matter in the Seto Inland Sea

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Mechanisms determining the average residence time (ART) of the nitrogen in the Seto Inland Sea, Japan, are examined by using a simple numerical model. The ART of the nitrogen is larger than that of the riverine water by about twice. This is due to the coupled effect of the flow having vertical shear and biochemical processes. Strong vertical mixing at the straits reduces the ART of the nitrogen. Mixing through Naruto Strait also effectively reduces the ART of the nitrogen.

Enclosed coastal sea is regarded as a transport system as conceptually shown in Fig. 1, where F_0 is a flux of concerned matter and M_0 is its standing stock in the coastal sea. The ratio, $\tau_o = M_0/F_0$, has a dimension of time and is called 'average residence time' (which may be also called 'turn-over time' or 'average transit time') (Takeoka; 1984a). Our efforts to control water quality (i. e. control of M_0) may be classified into either controlling F_0 or controlling τ_o. Therefore, the average residence time (hereafter referred as ART) is quite an important factor in considering water quality management. If we are concerned with eutrophication problems, the ARTs of the matters such as nitrogen or phosphorus should be revealed. The present paper discusses how the ART of nitrogen is determined in the Seto Inland Sea (Fig. 2), which is the largest coastal sea in Japan and has experienced many kinds of environmental problems.

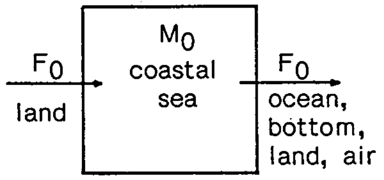

Fig. 1 Coastal sea as a transport system.

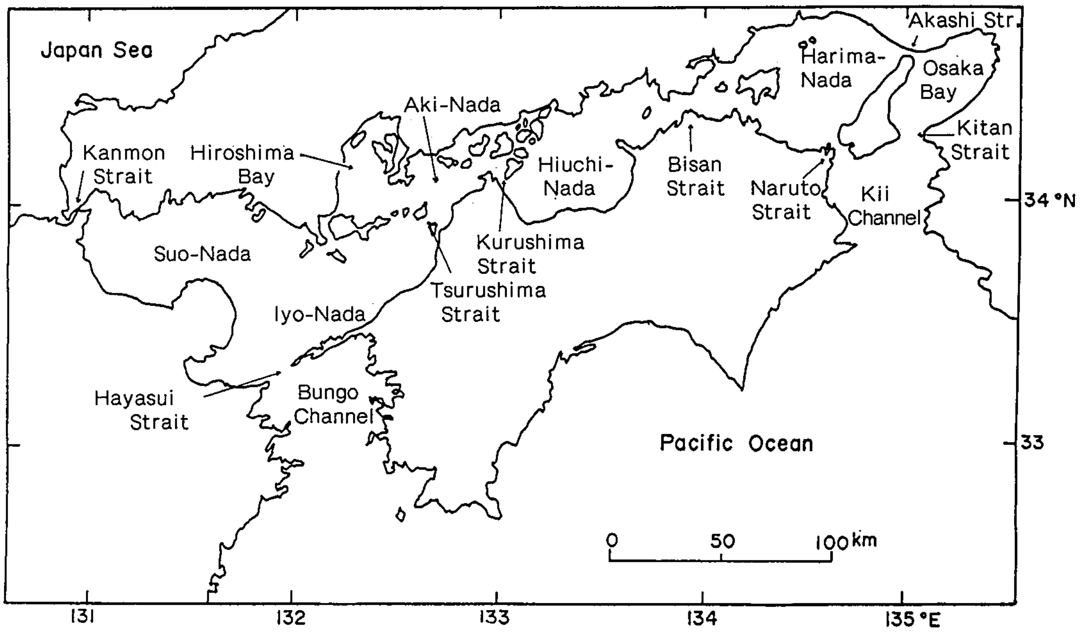

Fig. 2 Map of the Seto Inland Sea.

Takeoka (1984b) obtained five kinds of ARTs for the water in the Seto Inland Sea. For example, the ART of the total water is 440 days, which is regarded as a time scale of exchange or renewal of the water in the inland sea. The ART of the riverine water is 230 days. Since nitrogen is supplied mainly from the rivers, this value may be regarded as the first order approximation of the ART of the nitrogen. More direct method to estimate the ART is to use the relation $\tau_o = M_0/F_0$. The standing stock and the flux of the nitrogen in the Seto Inland Sea calculated from the data by Nakanishi (1985) are 2.3×10^5 tons and 492 tons/day, respectively, and hence the ART is

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47.0 days. Thus the ART of the nitrogen differs from that of the riverine water by about twice. A similar bifference appears in the case of Osaka Bay ; the ARTs of the nitrogen and the riverine water are 2.5 and 1.5 months, respectively, (Yanagi and Takahashi ; 1988).

Takeoka & Hashimoto (1988) explained the mechanism causing this difference as follows. Nitrogen is transformed between dissolved nutrients and particulate organisms by biochemical processes. In coastal waters, there is often a seaward mean flow in the upper layer and a landward one in the lower layer mainly due to inflow of river water. In such a flow system, particulate matter settles down to the lower layer, and is carried back to the inner region by the landward flow there. Then it turns to dissolved form by decomposition, and returns to the upper layer. Thus such a circulation will make its average residence time larger than that of a matter which is dissolved and does not change its form.

Here the effects of such transport mechanism including biochemical processes and some other physical structures in the Seto Inland Sea are examined by using a simple numerical model.

Model

Since the Seto Inland Sea is a long channel, it is simplified horizonatally to a one-dimensional channel of 500 km long as shown in Fig. 3a. Two-layered structure as shown in Fig. 3b is assumed vertically to incorporate above mentioned mechanism of determining the ART of matters such as nitrogen. Harima-Nada and Kii Channel is connected by a by-path, which represents Naruto Strait. The length of the by-path is neglected in the calculation.

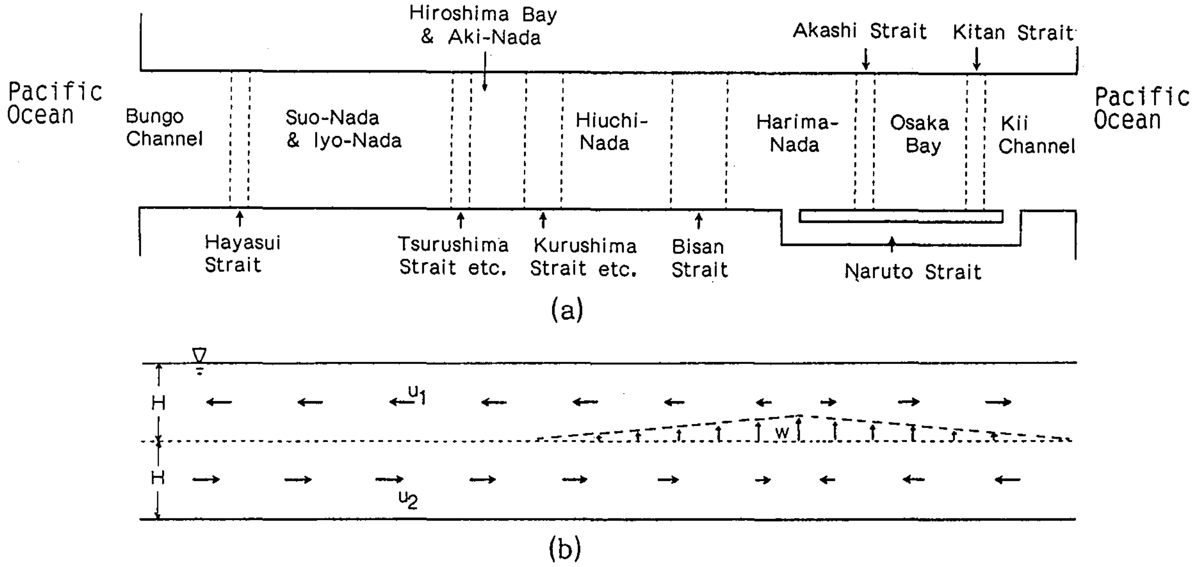

Fig. 3 Model of the Seto Inland Sea.

Flow structure is assumed as shown in Fig. 3b, where u_1 and u_2 are the flow speeds in the upper and lower layers, respectively, and w the upwelling speed. The flow is directed outward in the upper layer and inward in the lower layer. Since the river discharge is larger in the eastern part of the inland sea as shown in Table 1, the center of the upwelling is assumed to be located in the

TABLE 1

Discharge rates of river water and nitrogen into the seas or bays of the Seto Inland Sea (after Nakanishi(1985)).

area	river water ($\times 10^5 m^3$/day)	nitrogen (tons/day)
Kii Channel	248	33
Osaka Bay	236	188
Harima-Nada	173	77
Bisan Strait	148	26
Hiuchi-Nada		38
Hiroshima Bay & Aki-Nada	129	28
Iyo-Nada	81	30
Suo-Nada	156	47
Bungo Channel	34	

eastern part. These flows are the averages in a large time scale compared to tidal periods. The effects of tidal currents on the transport are incorporated in the horizontal diffusivity.

There are many narrow straits in the Seto Inland Sea, and their effects should be incorporated in the model. Waters in the straits are vertically well mixed due to strong tidal currents. Hence we assume larger vertical diffusivity in the straits than that in other regions. The flux of matters through the straits might be reduced due to its small cross-sectional area. This effect is replaced by giving smaller horizontal diffusivity in the straits. Thus for vertical and horizontal diffusivities (K_z and K_h, respectively), we assume $K_z = \alpha K_{z0}$ and $K_h = \beta K_{h0}$ in the straits shown in Fig. 3 and $K_z = K_{z0}$ and $K_h = K_{h0}$ in other regions.

Following Takeoka & Hashimoto (1988), the basic equations which govern the concentration of dissolved and particulate nitrogen are assumed as

$$H\frac{\partial d_1}{\partial t} = HK_h\frac{\partial^2 d_1}{\partial x^2} - Hu_1\frac{\partial d_1}{\partial x} - K_z\frac{d_1 - d_2}{H} + wd_2 - HPd_1 + HDp_1 \tag{1}$$

$$H\frac{\partial d_2}{\partial t} = HK_h\frac{\partial^2 d_2}{\partial x^2} - Hu_2\frac{\partial d_2}{\partial x} - K_z\frac{d_1 - d_2}{H} - wd_2 + HDp_2 \tag{2}$$

$$H\frac{\partial p_1}{\partial t} = HK_h\frac{\partial^2 p_1}{\partial x^2} - Hu_1\frac{\partial p_1}{\partial x} - K_z\frac{p_1 - p_2}{H} + wp_2 - sp_1 + HPd_1 - HDp_1 \tag{3}$$

$$H\frac{\partial p_2}{\partial t} = HK_h\frac{\partial^2 p_2}{\partial x^2} - Hu_2\frac{\partial p_2}{\partial x} - K_z\frac{p_2 - p_1}{H} - wp_2 + sp_1 - HDp_2. \tag{4}$$

Here, x is the horizontal axis, t the time, H the thickness of each layer (15m). $d_1(x, t)$ and $d_2(x, t)$ are the concentrations of dissolved nitrogen in the upper and lower layers, respectively, and $p_1(x, t)$ and $p_2(x, t)$ are those of particulate nitrogen in the upper and lower layers, respectively. s is the settling velocity of particulate nitrogen, and P and D the rates of primary production and decomposition, respectively. It is assumed that the primary production occurs only in the upper layer while the decomposition occurs in both layers. At the both boundaries to the Pacific Ocean, the concentrations are assumed to be zero.

Equations (1) to (4) are approximated by finite difference forms, and numerical experiments for the concentrations are carried out. The method to obtain the ART follows Takeoka (1984a) and Takeoka & Hashimoto (1988).

TABLE 2

Physical parameters applied to the model.

u_1 and u_2 (at both ends)	3	cm/s
K_{h0}	5.0×10^6	cm²/s
K_{z0}	0.5	cm²/s
α	50	
β	0.5	

Before calculating the ART of the nitrogen, that of the riverine water is calculated to arrange the physical factors. After some experiments to obtain the ART close to that obtained by Takeoka (1984b), they are determined as shown in Table 2. The values of the horizontal velocity and diffusivity agree rather well with those obtained by Murakami *et al.* (1985).

TABLE 3

Parameters and conditions given for the cases 1 to 8 and the average residence times (ART) for these cases.

case	s(m/day)	α	Naruto	ART(days)
1	0	50	o	222 (PDM)
2	2	50	o	457 (N)
3	0	1	o	147 (PDM)
4	2	1	o	483 (N)
5	0	50	c	260 (PDM)
6	2	50	c	709 (N)
7	0	1	c	156 (PDM)
8	2	1	c	865 (N)

(o : opened, c : closed, PDM : permanently dissolved matter, N : nitrogen)

Other parameters are determined as $P = 0.3$/day, $D = 0.4$/day and $s = 2$m/day, which are the same as those applied to Osaka Bay by Takeoka & Hashimoto (1988). Cases of the experiments to calculate ART of the nitrogen are arranged to examine the effects of the biochemical processes, the vertical mixing at the straits and the mixing through Naruto Strait. That is, the cases are considered where the biological processes do not work, or the vertical mixing at the straits is the same as in the other regions, or Naruto Strait is closed. The biochemical processes here mean the transformation of the nitrogen between the dissolved and particulate forms. The imaginary case where they do not work is shown sufficiently by $s = 0$. Accordingly the eight cases of the experiments to obtain the ART of the nitrogen are carried out as shown in Table 3. The rates of the nitrogen load to the seas or bays are as shown in Table 1(Nakanishi ; 1985).

Results and Discussion

The results of the calculations are shown in Table 3. The nitrogen for the cases of $s = 0$ is an imaginary one, and we call such a matter a permanently dissolved matter (PDM) as Takeoka & Hashimoto (1988) did.

The results of the cases 1 and 2 agree rather well with the ARTs of the river water and the nitrogen shown before. Hence we see that coupled effect of the flow system having vertical shear and the biochemical processes makes the ART of the nitrogen in the Seto Inland Sea larger than that of PDM by about twice.

The ART of case 3 is smaller than that of case 1, and that of case 4 is larger than that of case 2. Cause of these results is explained as follows. The matter is supplied in the upper layer in any case. Hence, in the case of PDM, the concentration in the upper layer is higher than in the lower layer. This feature is intersified in the case of weak vertical mixing and the matter concentrated in the upper layer is effectively carried away by the outward flow there, leading to the smaller ART. In the case of the nitrogen, settling of the particulate matter makes the concentration in the lower layer large, and the matter is carried into the inner region by the inward flow there. This effect is reduced by strong vertical mixing at the straits. Thus the difference of the ARTs of PDM and nitrogen is reduced by strong vertical mixing at the straits.

The ARTs of cases 5 to 8 are larger than those of cases 1 to 4, respectively, suggesting that Naruto Strait plays quite an important role in determining the ARTs of the matters in the Seto Inland Sea. The differences are larger for the cases of the nitrogen ; the ARTs in the cases where Naruto Strait is closed is larger by 1.5 to 1.8 times than those where Naruto Strait is opened. Naruto Strait may have an effect to carry out the matters supplied not only into Harima-Nada but also into Osaka Bay. The distribution of the nitrogen load which is intensive in Osaka Bay and Harima-Nada may also make the effect of Naruto Strait larger.

Accordingly the mechanism determining the ART of the nitrogen in the Seto Inland Sea is summarized as follows. The coupled effect of the flow having vertical shear and the biochemical processes makes the ART of the nitrogen larger than that of the riverine water or other permanently dissolved matter. Strong vertical mixing at the straits reduces the ART of the nitrogen. Mixing through Naruto Strait also effectively reduces the ART of the nitrogen. Without these two effects, difference between the ART of the nitrogen and that of the riverine water might reach more than 5 times as shown by the results of cases 7 and 8 in Table 2. The difference is reduced to about twice by these two effects.

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