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Model Estimation of the Water Purification Capacity of Lost Tidal Flats

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Abstract

The water environment of Ariake Bay has been degraded for decades, with some observers suggesting that this problem might be due to the decrease in tidal flat areas. However, for lost tidal flats, the water purification capacity cannot be estimated without sufficient historical data. A new procedure for estimating the water purification capacity of the Isahaya Tidal Flat (i.e., a lost tidal flat) was developed based on an ecosystem model. Given their similarities, an ecosystem model was first developed for the tidal flats of the Shiota River, and then recalibrated using the limited historical data available for the Isahaya Tidal Flat. The water purification capacity of the Isahaya Tidal Flat was estimated to be 0.39 t-N d^{-1} in 1988, when the tidal flat covered a total area of 35.64 km^2, which is equivalent to just 36% of total nitrogen loading from the basin (1.07 t-N d^{-1}). The denitrification capacity of the Isahaya Tidal Flat was shown to be 7.3×10^{-3} t-N km^{-2} d^{-1}. Both the water purification capacity and denitrification capacity estimated for the muddy Isahaya Tidal Flat were much less than those of sandy tidal flats (e.g., tidal flats at Sambanse).

Discipline: Agricultural engineering
Additional key words: Ariake Bay, bottom sediment, ecosystem model, denitrification, water quality

Introduction

Ariake Bay is located in northwestern Kyushu, Japan. The tidal range, which reaches a maximum of 6 m, has resulted in one of the largest tidal flat systems in Japan. Land reclamation for agriculture and industry has been done since the 1960s and 1970s, in order to support rapid economic growth; however, concerns remain over the loss of tidal flat areas. In recent years, Ariake Bay has experienced serious degradation of its water environment, including anoxic water and red tides, with some observers suggesting that such problems might be due to reduced water purification capacity of the tidal flat areas.

The water purification capacity of tidal flats can be estimated based on field studies; however, for lost tidal flats, this process is only possible with sufficient historical data. As a result, mathematical models represent the only way to estimate the previous water purification capacity of a reduced (or lost) tidal flat. Suzuki (2006) estimated the water purification capacity of tidal flats in the Mikawa and Ise bays as 360 t-N yr^{-1} based on field data collected using an enclosed chamber, and then input that capacity into a mathematical model of the ecosystem. In contrast, the Chiba prefectural government estimated the capacity of nitrogen removal from the tidal flats at Sambanse to be 574 t-N yr^{-1}, a rate that could remove 45% of total nitrogen loading into the flats (Kimura et al. 1992). Nishio et al. (2013) showed that the water purification capacity of tidal flats differs and is highly dependent on the characteristics and environmental conditions of a given tidal flat.

An ecosystem model based on chemical reactions, biological reactions, and nutrient transfer can be used to estimate purification capacity under limited but varying conditions, assuming that sufficient data are available to calibrate and validate the model (e.g., field studies). However, for lost tidal flats, such data cannot be collected, and if not already available, cannot be created. In this study, we developed a new method of estimating water purification

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capacity in lost tidal flats, using the Isahaya Tidal Flat as a case study. Given the varying definitions of water purification capacity, we define it in this study as the nitrogen removal capacity.

Methodology

1. Study area

In Ariake Bay (1,700 km^2 in total area), a large tidal range and enclosed coastal morphology that prevent an outflow of soil particles to the open sea have resulted in large tidal flats extending approximately 20.7 km^2. Five major tidal flats have formed at the mouths of the Chikugo, Shiota, Rokkaku, Kikuchi, and Midori rivers (Fig. 1). In addition, the Isahaya Tidal Flat formed at the mouth of the Hommyo River, which flows into Isahaya Bay, is located along the western inner shore of Ariake Bay. However, the Isahaya Tidal Flat was lost in 1997 as the result of a land reclamation project. The Isahaya Tidal Flat formed in a tropical environment with high biodiversity and a significant production of natural resources. In 1988, the tidal flat had a total area of 35.64 km^2, and was a typical mud flat with bottom sediments rich in nutrients and dominated by clay and silt (> 90%).

2. Estimation procedure

To estimate the purification capacity of the lost Isahaya Tidal Flat (Fig. 2), we surveyed other Ariake Bay tidal flats in order to select the one most similar for use as a proxy, with the level of similarity based on benthic species, the properties of bottom sediment (i.e., particle composition, median diameter, moisture content, sulphide content), topology, and nutrient loads (Kyushu Regional Agricultural Administration Office, 2001, 2003). Based on this analysis, the tidal flats at the mouth of the Shiota River were selected for use in this study. Field surveys were then conducted on the tidal flats of the Shiota River, and the data were used to construct an ecosystem model for simulating the transport and cycling of materials. The model was then calibrated for the Isahaya Tidal Flat by incorporating historical data collected in the study area prior to loss of the tidal flat. Finally, the calibrated model was used to estimate the water purification capacity of the lost Isahaya Tidal Flat.

3. Ecological modeling

An ecosystem model for the tidal flats of Ariake Bay was first developed by Yasuoka et al. (2005a). Yasuoka et al. (2005b) also conducted field studies of the Shiota River tidal flats in order to construct a numerical ecosystem model of water-bottom sediment systems, in which the characteristic features of the material cycle in a shallow sea and tidal flats were taken into consideration (Yasuoka Model). The Yasuoka Model simulates water temperature, salinity, water quality, physicochemical concentrations, and benthic populations in the bottom sediment.

In this study, we refined the Yasuoka Model to precisely simulate biological and physical cycles in the tidal flats of the Shiota River by incorporating data from an intensive 2005 field survey conducted by Nishio et al. (2015). The model consisted of two sub-models: the seawater model and the bottom sediment model, which calculate the physical transport and biochemical reactions of nitrogen, phosphorus, and carbon in seawater and bottom sediment, respectively (Fig. 3). In developing this new model, the estimation accuracy of inflow loads from the Shiota River was improved.

To recalibrate the model for the target study area, the turbidity boundary conditions were designed to express characteristic changes in turbidity, and the model parameters were modified to provide the best fit possible with available field data from the Isahaya Tidal Flat that was collected from 1988 to 1989, before the tidal flat was lost (Nishio et al. 2016). Specifically, the topographic conditions, nutrient loading, boundary conditions (e.g., tidal regime, water temperature, salinity, water quality), initial conditions, and climatic conditions of the Isahaya Tidal Flat in 1988 were used to calibrate the material cycle and transport model. The initial population of the benthic community was taken from the results of comprehensive studies on the Isahaya Tidal Flat conducted by the Kyushu Regional Agricultural Administration Office, Ministry of

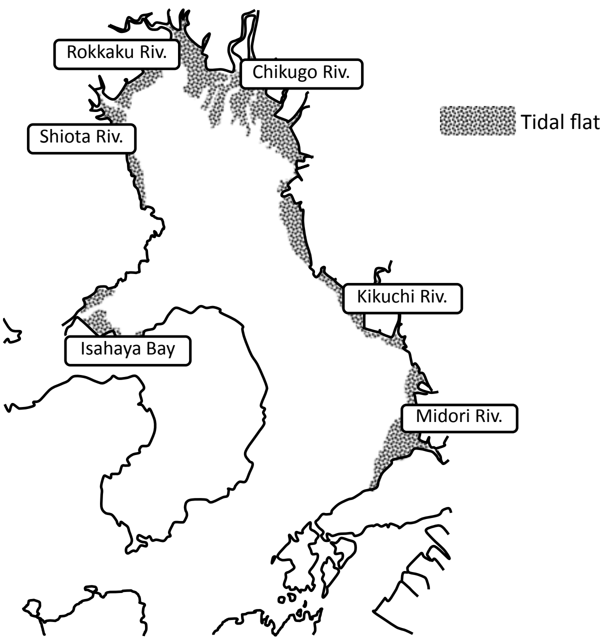

Fig. 1. Tidal flats in Ariake Bay.

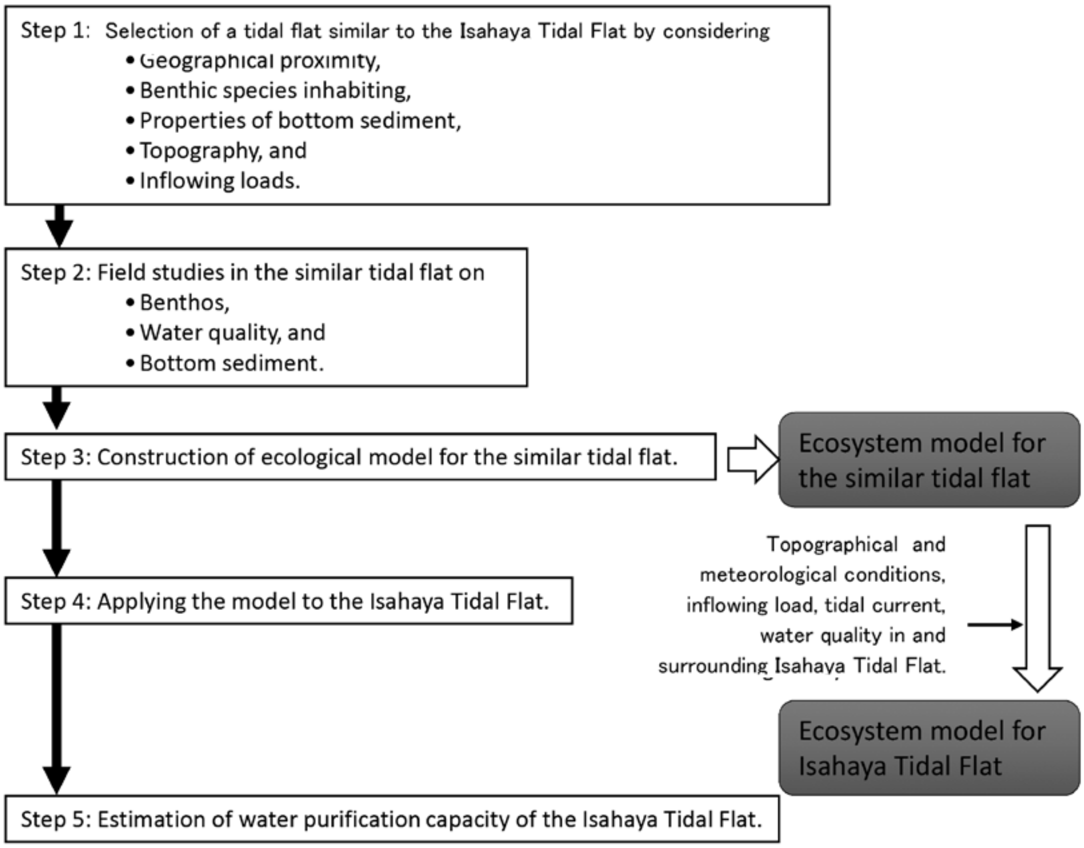

Fig. 2. Outline of the estimation procedure.

Agriculture, Forestry and Fisheries (1987). Meteorological and inflowing river conditions were set to those recorded in 2000. Missing data (e.g., quality of pore water, fraction of nitrogen on the surface) that were needed to formulate the model were substituted by using values taken from the tidal flats of the Shiota River. The newly developed model can perform highly accurate water quality simulations for the muddy tidal flats of Ariake Bay.

Results and discussion

1. Selection of the proxy tidal flat

(1) Benthic species

The benthic population census (Table 1) showed that benthic fauna in the tidal flats of western Ariake Bay, where the Isahaya Tidal Flat was located, differ from those in eastern Ariake Bay. In particular, the population densities of such bivalves as *Tegillarca granosa*, *Theora fraggilis*, and *Moerella iridescens* were significantly lower in eastern Ariake Bay, while *Meretrix lusoria* and *Mactra veneriformis* were abundant. Furthermore, the dominant snail in western Ariake Bay was *Iravadia elegantula*, but in eastern Ariake Bay it was *Reticunassa festiva*. On this basis, we excluded the tidal flats on the eastern side of the Bay (i.e., tidal flats of the Midori and Kikuchi rivers) as potential proxies for the Isahaya Tidal Flat.

(2) Bottom sediments

Bottom sediment properties (i.e., particle composition, median diameter, moisture content, sulphide content) were assessed based on 1988-1989 Isahaya Tidal Flat data and 1999-2001 data for the other western Ariake Bay tidal flats (Fig. 4). Of the four western Ariake Bay tidal flats considered, bottom sediments from the tidal flats of the Shiota River were the most similar.

(3) Topographic conditions and nitrogen loading

Of the four western Ariake Bay areas considered, the topographic conditions and nitrogen loading in the Shiota River tidal flats were most similar to those of the Isahaya Tidal Flat (Table 2). In particular, the area of the Isahaya Tidal Flat (35.64 km^2) was consistent with that of the Shiota River tidal flats (40.14 km^2), while nitrogen loading of the Shiota River tidal flats was 3.43×10^{-2} t-N km^{-2} d^{-1}, and that

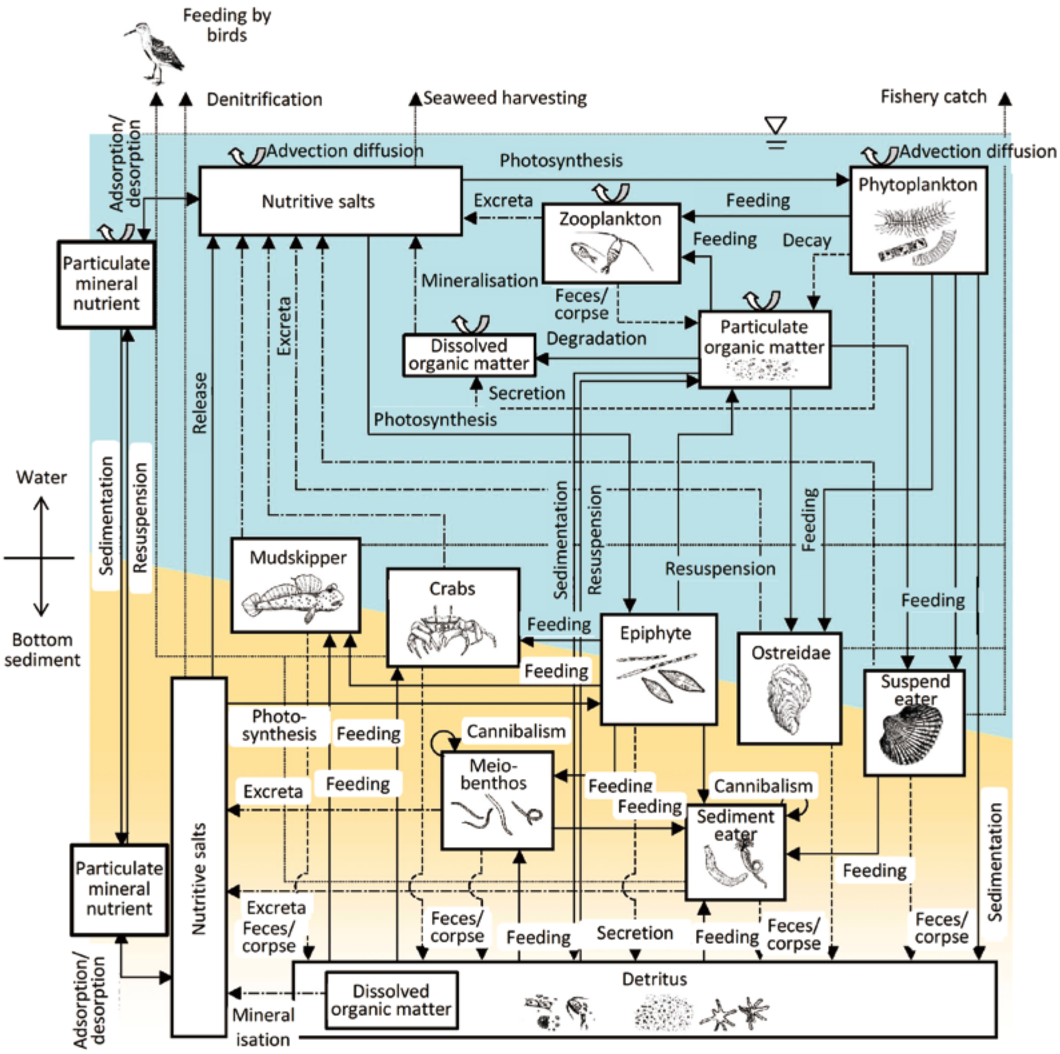

Fig. 3. Conceptual model of the ecosystem (Yasuoka et al. 2005a).

of the Isahaya Tidal Flat was 2.67×10^{-2} t-N km^{-2} d^{-1}.

2. Water purification capacity

In order to estimate the water purification capacity, changes in the seawater quality, chemical properties, and benthic populations of bottom sediments were calculated using the newly developed model. Nishio et al. (2016) confirmed the high precision of the model in agreement with water qualities observed over several years by using the Taylor diagram (Taylor 2001). The model was particularly improved in its precise calculation of the transport dynamics of nitrogen and suspended matter that were major pathways concerning water purification in tidal flat areas. The water purification capacity of the Isahaya Tidal Flat, which was defined as the balance between nitrogen input from the land into a tidal flat area and output to the sea, was estimated to be 0.39 t-N d^{-1} in 1988 (Table 3), when 35.64 km^2 of the tidal flat remained. This value corresponds to 1.09×10^{-2} t-N km^{-2} d^{-1}, and the capacity per unit area was far smaller than that of the Sambanse tidal flats in Tokyo Bay (8.74×10^{-2} t-N km^{-2} d^{-1}) as reported by Kimura et al. (1992). The percentage of the capacity to total nitrogen loading in the Isahaya Tidal Flat (1.07 t-N d^{-1}) was just 36%, which is also less than that of the Sambanse tidal flats (54%), mainly because nitrogen exports through clam harvesting were lower than those of the Isahaya Tidal Flat.

The major contributors to water purification in tidal flats are denitrification and the transport of nitrogen from the water to bottom sediments, including the sedimentation of particulate nitrogen, primary production by epiphyte, and feeding by bivalves. However, as the transport to bottom sediments does not actually remove nitrogen from the tidal flat area, nitrogen released from bottom sediments (e.g., from benthos excreta, resuspension of soil particles, release

Table 1. Benthic species observed in tidal flats of Ariake Bay (Kyushu Regional Agricultural Administration Office 2001, 2003).

	Western Ariake Bay								Eastern Ariake Bay			
	Isahaya Tidal Flat		Shiota River tidal flat		Rokkaku River tidal flat		Chikugo River tidal flat		Kikuchi River tidal flat		Midori River tidal flat	
year	1987	1992	1999	2000	1999	2000	1999	2000	1999	2000	1999	2000
bivalves												
Tegillarca granosa	●	●	●	○	●	●	●	○				
Theora fragilis	●	○	●	●	●	●	●	●		○	○	○
Sinonovacula constricta	●											
Glauconome chinensis Gray	○	●										
Moerella iridescens	●	●	●	●	●	●	●	○				
Scapharca subcrenata	○		○	●				○		○	●	
Potamocorbula laevis Hinds			●	○	●	●	●	○				
Meretrix lusoria								○	●	○	●	●
Estellarca olivacea	○			●	○	●						
Trapezium liratum				○							●	
Mactra veneriformis								●	○	●	●	●
Ruditapes philippinarum									●	●	●	●
Musculista senhousia									●	●	●	●
Crassostrea gigas											●	●
snails												
Iravadia elegantula	●	●	●	●	●	●	○	○				
Acteocina decorata		●										
Salinator takii		●		●		●						
Niotha livescens	○							○				
Stenothyra edogawaensis			●	●	●	●	○		○		○	
Reticunassa festiva		○	○	○	○	○	○	●	●	●	●	●

* ●: More than 10/m^2 or 1 g/m^2 of wet weight or more were gathered.
○: Not ● but only a few exist.

of dissolved nitrogen) pollutes the water. When the nitrogen cycles in both the water and bottom sediments of tidal flats are treated as a total system, estimating export processes is important for analysing the persistence of water purification capacity. The major export processes that remove nitrogen from the water-bottom sediment system are denitrification, the harvesting of shellfish and seaweed, and feeding by birds.

The denitrification flux was the largest among the major export processes identified (Table 3). The denitrification capacity of the Isahaya Tidal Flat was 0.26 t-N d^{-1}, which corresponds to 0.73×10^{-2} t-N km^{-2} d^{-1}, just 12% of that of the Sambanse tidal flats (6.1×10^{-2} t-N km^{-2} d^{-1}) as reported by Kimura et al. (1992). We concluded that the denitrification capacity of muddy tidal flats (e.g., those in Isahaya Bay) is smaller than that of sandy tidal flats (e.g., Sambanse) due to differences in bacterial habituation and the chemical properties of bottom sediments.

A simpler and more conventional way to estimate purification capacity is by considering the purification capacity per unit area (unit purification capacity) in similar tidal flats. Nishio et al. (2016) estimated the 2005 purification capacity of the Shiota River tidal flats (40.14 km^2) to be 0.22 t-N d^{-1} and 0.55×10^{-2} t-N km^{-2} d^{-1}. Taking the unit

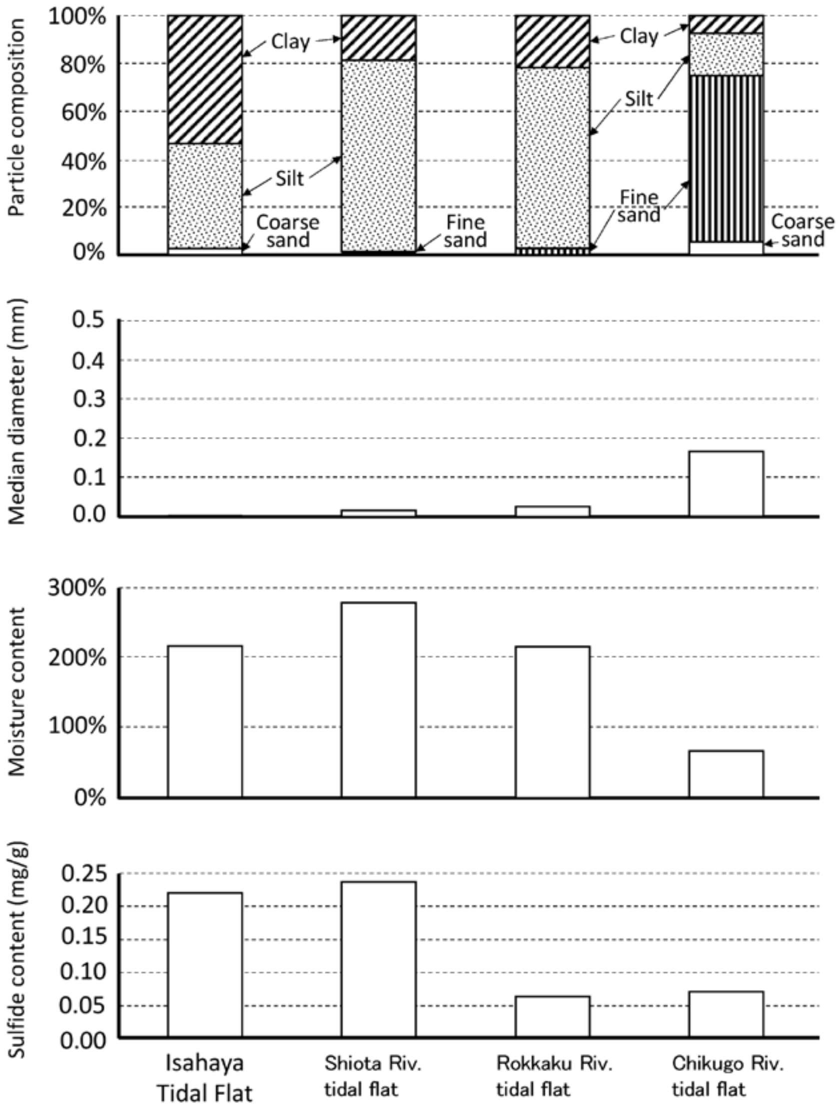

Fig. 4. Properties of bottom sediments in tidal flats in the western part of Ariake Bay
(Kyushu Regional Agricultural Administration Office 2001, 2003)

purification capacity of 0.55×10^{-2} t-N km^{-2} d^{-1} as a proxy for the Isahaya Tidal Flat (35.64 km^2), the water purification capacity was estimated to be 0.20 t-N d^{-1}, or just 50% of that simulated using our model (0.39 t-N d^{-1}). Therefore, it could be concluded that the simple conventional procedures used to estimate purification capacity cannot always be applied to other tidal flats, even when they appear similar.

Conclusion

A new method of estimating the water purification capacity of lost tidal flats, for which little basic data are available, was developed based on an ecosystem model. We focused on the Isahaya Tidal Flat in Ariake Bay that was lost to land reclamation, by using the Shiota River tidal flats, also located in Ariake Bay, as a proxy.

The water purification capacity of the Isahaya Tidal Flat was estimated to be 0.39 t-N d^{-1} in 1988, when 35.64 km^2 of the tidal flat remained. This value corresponds to 1.09×10^{-2} t-N km^{-2} d^{-1}, and is equivalent to 36% of total nitrogen loading from the basin (1.07 t-N d^{-1}). The denitrification capacity of the Isahaya Tidal Flat was found to be 0.73×10^{-2} t-N km^{-2} d^{-1}. The water purification capacity was found to be lower than that observed for the Sambanse tidal flats in Tokyo Bay (Kimura et al. 1992), likely due to lower nitrogen exports through clam harvesting.

Table 2. Topographic conditions and nitrogen loading of the tidal flats in western Ariake Bay (Kyushu Regional Agricultural Administration Office 2001, 2003).

	Isahaya Tidal Flat	Shiota Riv. tidal flat	Rokkaku Riv. tidal flat
Area (km^2)	35.64	40.14	99.2
River basin area (km^2)	215.98	189.15	357.7
River discharge in 2000 ($\times 10^3 m^3 d^{-1}$)	702	783	1,933
Nitrogen loading ($t\text{-}N d^{-1}$)	0.95	1.38	13.92
Nitrogen loading per unit tidal flat area ($\times 10^{-2} t\text{-}N km^{-2} d^{-1}$)	2.67	3.43	14.03

Table 3. Annual mean budget of nitrogen, and fluxes concerning water purification on the Isahaya Tidal Flat.

	Nitrogen flux ($t\text{-}N d^{-1}$)
Total budget	
Input from land to tidal flat area with water (a)	1.07
Output from tidal flat area to sea with water (b)	0.68
Nitrogen removal in tidal flat area (a–b)	0.39
Export from tidal flat area	
Denitrification	0.26
Feeding by birds	0.08
Shellfish and seaweed harvesting	0.01
Total export from tidal flat area	0.35
Transport between water and bottom sediment in tidal flat area	
From water to bottom (c)	
Primary production of epiphyte	4.94
Sedimentation	4.03
Feeding by bivalves	1.23
From bottom to water (d)	
Benthos excreta	3.31
Release from bottom sediment	2.98
Resuspension	3.38
Total transport from water to bottom (c–d)	–0.53

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