Material Balance of Phosphorus in a Semi-Closed Bay Calculated with Actuality Measurements and Data of an Observation Satellite over a Long Period

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The material balance of phosphorus in a semi-closed bay (Omura bay) has been calculated by actuality measurements and data from an observation satellite (LANDSAT 5) over the last eleven years. It appeared that the phosphorous inflows to the bay from the 696 places of business and the twelve rivers were 293 tons/year and 20 tons/year, respectively. About 90% of the phosphorus from the places of business was released into the bay from only six sewage treatment plants. The phosphorus outflows from the bay, which occurred with the tide changes and with the catching of fish, were 219 tons/year and 7 tons/year, respectively. The urban areas inside the watershed that were calculated from the LANDSAT data using the normalized difference vegetation index (NDVI) value showed an increase each year with a wide range of variation. This slope was closer to the one showing the increasing amount of phosphorus in the bay than to the slope of the increase in population inside the watershed.

Key words —— phosphorus, material balance, remote sensing, semi-closed bay

INTRODUCTION

Pollution levels in the seas, lakes and rivers caused by human activity have recently become extreme. The eutrophication and worsening of the water quality are often observed, especially in closed or semi-closed water areas.[1)] This is because the physical character of pollutants allow them to easily accumulate in an area into which large amounts of nitrogen and/or phosphorus flow continuously. Because these are as should be turned over to the next generation in a useful condition, it is of the at most importance to understand a wide range of material cycles and of N, P, C *etc*. Several researchers investigated the balance of nitrogen and carbon in the environment,[2–7)] however, the calculation of these balances were very complicated because of the possibility of gasification. In contrast, phosphorus balance was expected to be more easily calculated because there is no need to consider gasification.[8)]

Omura Bay is a typical semi-closed bay which is 47.3×10^8 m^3 in seawater volume, and 320 km^2 in surface area and is connected to the open sea by two very narrow straits (Hario Strait and Haiki Strait, see Fig. 1). Therefore, the seawater tends to be stagnant. This bay was designated by the Director-General of the Environmental Agency of Japan as an area that should be monitored periodically since it has high concentration levels of N and P. There is a fear of an excess proliferation of phytoplankton.

The purpose of this study was to understand the mutual relationship between the following: the phosphorous balance in the bay calculated by the inflow and the outflow in it, and the rate of increased by the city area inside the watershed; on the latter there is a great deal of data gathered for the past eleven years by an earth observation satellite. The TM sensor of LANDSAT 5 that has long transmitted stable data was chosen as the satellite. LANDSAT I was launched in 1972 by the US was the first earth ob-

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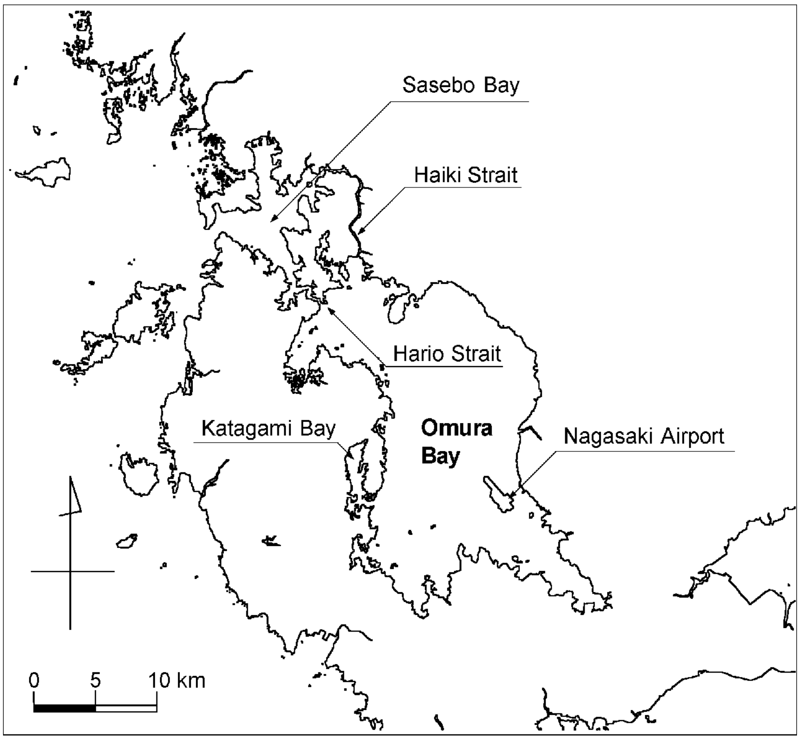

Fig. 1. Location of Omura Bay and the Two Straits

servation satellite and thereafter others have been launched in series. LANDSAT 5 has two sensors that are called MSS (multi spectral scanner system) and TM (thematic mapper). The TM sensor has seven band of wavelength and its ground resolution is 30 m except for the 7th band. Only a few studies have referred to Omura Bay as the subject of study in the region of remote sensing.[9,10] Other conventional research papers have focused on the high ground resolution of the satellite or the virtual resolution of the sea surface:[11–15] for example, the calculated two-dimensional distribution of the water quality from the satellite data compared with the real experimental results performed at the same time.[16,17] There are few studies of time series analysis used in satellite data over a long period as done in this work.[18–20]

MATERIALS AND METHODS

Calculation of Annual Variation in Phosphorus Amount —— The annual variation in the total amount of phosphorus in Omura Bay was calculated from an average of seventeen point measurement values in the bay each year from 1985 to 1996 and the total amount of seawater. The seventeen point values were measured by the Nagasaki Prefectural Institute of Public Health and Environmental Sciences.

The variation of annual phosphorus inflow from the rivers into the bay was also calculated from annual measurement values of the twelve major rivers over the same period by the above institute. The surface area in the watershed and the average of six points of data of the amount of precipitation in this area were also used in these calculations. The ratio of evapotranspiration per year the outflow of rain to the rivers was calculated as 600 mm and 80%, respectively, because no one had measured the flow rates of the rivers.

Annual variation of phosphorus outflow was determined by the amount of total fish caught every year from 1985 to 1996 as documented by the fifteen fishery cooperative societies (Saseho, Hario, South Saseh, Kawatana, Higashisonogi, Matsubara, Shinjyo, East Omura, Matsuyama, Tarami, Nagayo, Togitsu, Kinkai, Seihi, Segawa) inside the bay, and the phosphorus content of each kind of fish (thirty-one kinds of fishes).

Calculation of Annual Variation in Population Inside the Watershed —— Variation in annual population was calculated from the total population of the cities and towns located in the watershed, from 1985 to 1998. In Nagasaki, the city population was based on the ratio inside and outside the area, because the watershed actually bisects the city.

Calculation of Annual Variation of the Urban Area Using LANDSAT Data —— Annual variation in the urban area was calculated from eighteen TM data of LANDSAT 5 selected from 1984 to 1997. The viewpoint of the selected data had very few clouds. The watershed areas were omitted from the TM data using 1/25000 and 1/50000 maps published by the Geographical Survey Institute of Japan. The water areas (bay and rivers) were then omitted from the watershed area when the area had low values in bands 3, 4 and 7. The water area often had a low normalized difference vegetation index (NDVI) value and in order to avoid confusing the urban and water areas, these steps were essentials. These processes from the TM data were employed using the Erdas Imagine (Erdas Inc., U.S.A.), an image processing software.

In this study, the NDVI value was used with the calculation of the urban area, because a huge amount of data was handled and artificial errors. The NDVI value was useful to get a general, objective long-term tendency. The NDVI value, which is an index of plant activity, is used widely to investigate vegetation, etc. in a remote sensing region. The NDVI value has the following relation:

$$NDVI = (NIR - VIS)/(NIR + VIS) \quad (1)$$

NIR and VIS indicate values at the near infrared and the red range of the visible range, respectively. In the TM sensor of LANDSAT, bands 3 and 4 correspond to VIS and NIR, respectively. The NDVI value indicates a high value in a forest area and a low value in an urban on water area. The plant activity of the land area inside the watershed was calculated using these characteristics, and an area 0.15 or less in NDVI value was defined as an urban area in this study.

Calculation of the Exchange Rate of Seawater with Tides and the Total Amount of Phosphorus in Sediment —— Hyodo and Gotoh estimated that the exchange rate of seawater from Omura Bay to the open sea was about 0.2% to 0.4% in a single tide.[21] An exchange amount of seawater per year was calculated in a progression using 0.3% as the exchange rate. The amount of phosphorus in the total coastal sediment at the bottom of the bay was calculated using a phosphorus concentration of 0.7 mg/g in the sediment, a surface area of 320 km^2 in the bay, a thickness in 10 cm of the sediment and a density in 1.3 g/cm^3 of the sediment.

Calculation of Amount of Phosphorus Amount Inflow from Places of Business —— Phosphorus inflow from places of business to the bay were calculated based on the average amount of wastewater per day and the concentration of phosphorus amount in 1998. This data included about 50 different kinds of business, and total of 696 businesses were evaluated. However, only about 11% of these businesses had data on the phosphorus concentration in their wastewater. For the others, we used an average concentration at a similar type of business. The overall tendency of the amount of phosphorus was not influenced by this treatment, because most of the relatively large business places knew their phosphorus concentration.

RESULTS AND DISCUSSION

Annual Variations in the Urban Area from the LANDSAT Data

Figure 2 shows the TM data after it was analyzed on August 11, 1996. The entire cut-out region is the watershed. The black region, which is the urban area, had higher NDVI value of less than 0.15. The blank white center is Omura Bay, and the island in the lower right corner of the bay is Nagasaki airport. The gray regions are coniferous forests or high vegetation areas. The increasing level of urbanization in this area is relatively slow, because it does not include the large cities of Nagasaki and Sasebo.

Figure 3 shows the variation in the urban areas inside the watershed calculated by the LANDSAT TM data. A solid line was drawn using the least squares method. From this figure one can see that the urban area has increased over a long period of time with wide variation. There are two possible reasons for this variation: 1) Plant activity depends on the season, and precipitation amount has an effect on it. 2) The NDVI value tends to be higher when the berght of the sun is low in the winter. The open circles in the figure the data from the month of May to September and the triangles from other months. It seems that the wide range of variation does not depend solely on the season.

Annual Variations in Phosphorus Amounts in the Bay in Comparison with LANDSAT Data

Figure 4 shows annual variations in the total amount of phosphorus in water of the bay. It also shows the variations in the total amount of phos-

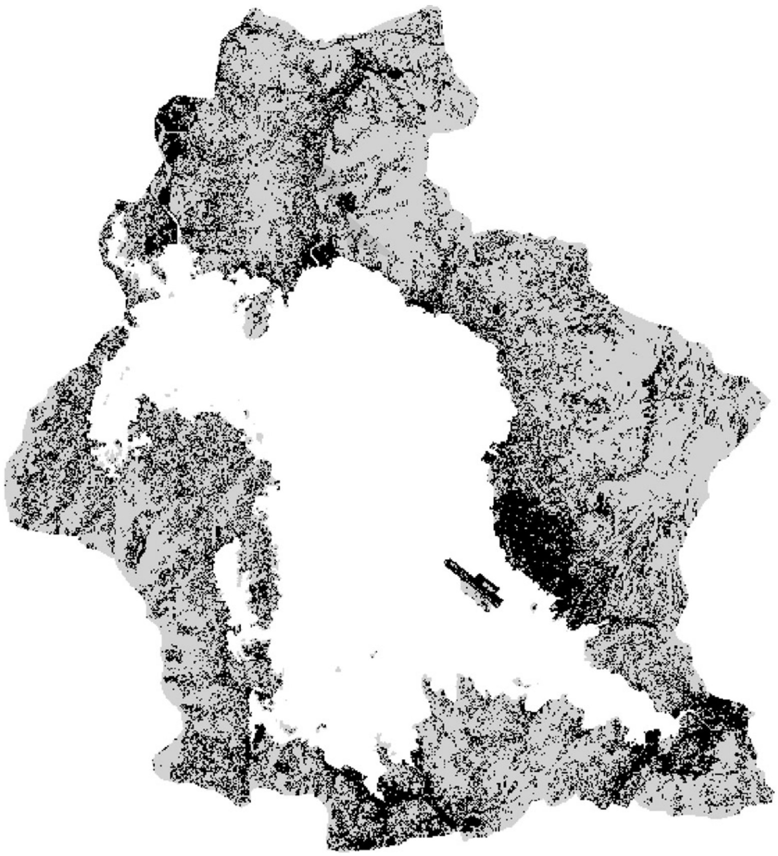

Fig. 2. Typical TM Data Calculated with NDVI Value Inside the Watershed in Omura Bay on August 11, 1996
The blank white center, black, and gray region show Omura Bay, urban areas, and high vegetation areas, respectively.

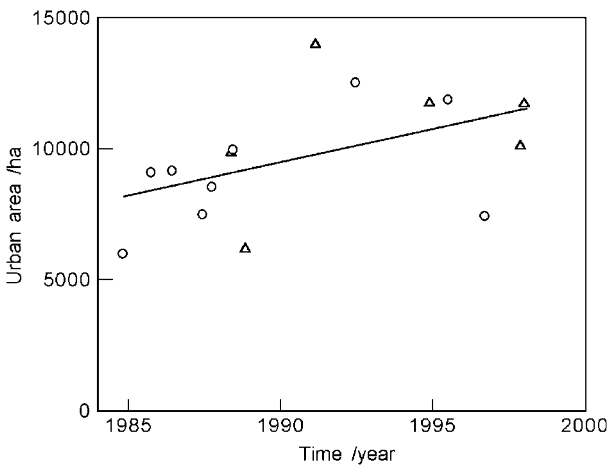

Fig. 3. Annual Variation of Urban Areas Inside the Watershed Calculated by the LANDSAT TM Data
The open circles indicate the data from the month of May to September and the triangles indicate the data from the other months.

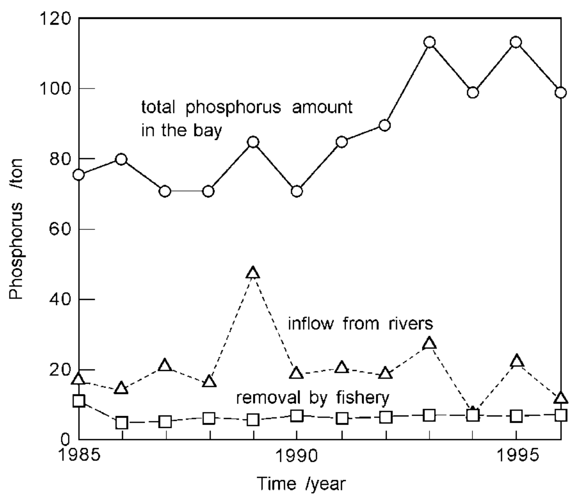

Fig. 4. Annual Variations of the Total Amount of Phosphorus in the Bay Water (Circles), the Total Amount of Phosphorus from Rivers in the Bay (Triangles), and the Removal of Phosphorus from the Bay as a Result of Fishery (Squares)

phorus flowing from the rivers into the bay and the removal of phosphorus from the bay, as a result of fishery. The total amount of phosphorus appears to have increased about 4% each year, indicating that eutrophication is gradually progressing. On the other hand, both phosphorus inflow from rivers and its removal due to fishery are almost constant; these

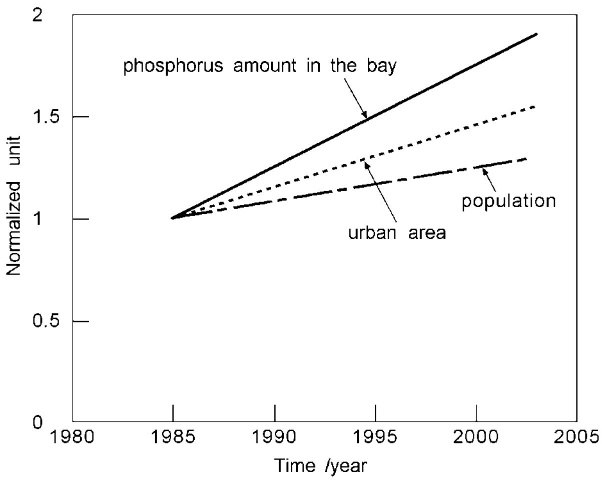

Fig. 5. Normalized Lines of the Increasing Curves of the Urban Areas, the Phosphorus Amount in the Bay, and the Population in the Watershed That was Normalized to Each Line on the Basis of 1985 Data

percentages are about 24% and 7.5% of the total amount of phosphorus in the bay, respectively. The data of the inflow from rivers in 1989 is different from other data, since this year was a dry year.

Figure 5 shows the normalized lines of the increasing curves of the urban area, the phosphorus amount in the bay, and the population in the watershed that was normalized to each line on the basis of the 1985 data for easy comparison. It is clear that the slope of phosphorus was much larger than that of the population. This is most likely because the phosphorus outflow to the bay, per man, increased each year as a result of excessive food consumption, fertilizer and/or feed, *etc*. It also indicates that people lived in grater luxury every year. Slope of the urban area was closer to that of phosphorus than to the population, although the slope did not correspond. The reasons that for this could be because of the high density and multistoried buildings, *etc*.

Material Balance of Phosphorus in the Bay

Table 1 shows the amount of phosphorus discharged into the bay from places of business and what percentage these were of the total amount. The total amount of outflow from all places of business was calculated to be 293 tons/year. It was found that only six sewage treatment plants were discharging about 90% of the phosphorus. The forty-two human excreta treatment plants were discharging about 5%, the next largest business. The food-related businesses, hotels, and hospitals, which have a direct and close connection with human activities also discharged high levels of about 6.4%.

Table 1. Amount and Percentage of Total of Phosphorus Discharged into Omura Bay from Places of Business

Type of business	Amount of phosphorus discharged (tons/year)	%
Sewage treatment plants	262.28	89.53
Human excreta treatment plants	13.77	4.70
Foodstuff-related business	6.69	4.14
Others	6.87	2.35
Total	292.96	100.0

The total amount of phosphorus in the sediment of the bay was calculated to be about 29100 tons. Because of our survey, dredging to remove the phosphorus from the sediment, had not been done in this bay yet. The phosphorus outflow from the bay to the open sea was calculated to be 219 tons/year. However, it seems that the actual value is smaller than this, because the seawater with the highest phosphorus concentration is found in the innermost recess of the bay. In other words, most people live at the south part of the bay; therefore, the dirty seawater tends to remain there, and the clean seawater in the northern part of the bay changes with the tide.

Figure 6 schematically shows the phosphorus balance around the bay. The arrow sizes indicate the approximate amount of phosphorus. The total amount of phosphorus inflow into the bay was 313 tons/year, and the total outflow from the bay was 226 tons/year. The excess inflow was calculated to be 87 tons/year, and the excess phosphorus would accumulate in the sediment in the bottom of the bay every year. There was a large amount of phosphorus in the sediment, which has a buffering action on the phosphorus concentration in the seawater. This result indicated that large-scale dredging was less effective in improving the phosphorus concentration. The Chemical Oxygen Demand value in the bay has exceeded 2.0 mg/l (which is the environmental standard) since 1983, and has a tendency to increase gradually. In this study, only the phosphorus balance in the bay was studied in this study, however, other materials that cause the eutrophication are expected to have the same tendency as the phosphorus.

The results thus showed that the main contributor to the increasing phosphorus in the bay was the places of business. Just six sewage treatment plants were the major sources. If the effluent from one of

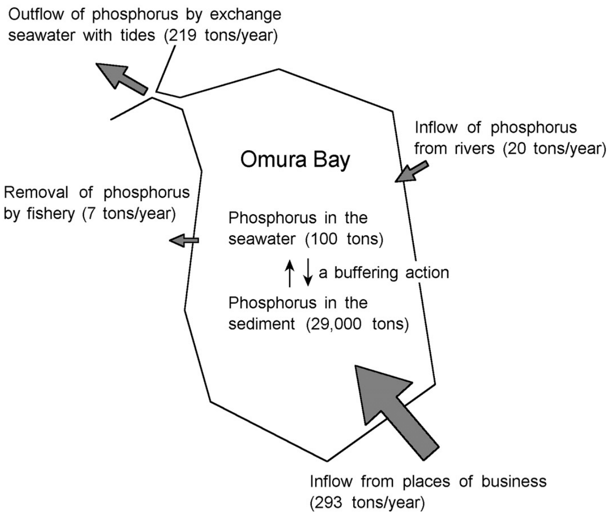

Fig. 6. Phosphorus Inflow and Outflow in Omura Bay

these plants that is emitting the largest amount of phosphorus were treated with equipment that achieved a 60% phosphorus removal rate, the total amount of phosphorus inflow into the bay would be 207 tons/year. This is smaller than the total amount of phosphorus outflow, a difference of 19 tons/year. Therefore, eutrophication advancement could be prevented.

In conclusion, urban areas inside the watershed of Omura Bay that were calculated from the LANDSAT data using the NDVI value varied widely but showed an increase every year. The slope was closer to that slope showing the increasing amount of phosphorus in the bay than the slope showing increase in the population amount of the watershed.

The phosphorous inflows into the bay from 696 places of business and quantity from twelve rivers were 293 tons/year and 20 tons/year, respectively. About 90% of the phosphorus from the places of business was released into the bay from only six sewage treatment plants. The phosphorus outflows from the bay, which occurred with the tide changes and the catching of fish, were 219 tons/year and 7 tons/year, respectively, indicating that there was an excess of 19 tons/year understood.

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