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WATER QUALITY MONITORING OF THE ARIAKE SEA BY REMOTE SENSING AND UTILIZATION OF FIELD OBSERVATION

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ABSTRACT: A remote sensing is one of the most powerful solutions for estimating water quality in wide water bodies effectively. The earth observation satellites Landsat have been observing the land and ocean from space for a long time with consistent specification plus new additional technology. In this paper, a water quality in the Ariake Sea, Japan is estimated by using Landsat-TM and ETM+ images with field observation. The models for water salinity and chlorophyll-a concentration are developed by regression analysis like the transparency and water temperature models, and they are also validated by other observed data. In order to understand characteristics of water quality in the Ariake Sea, a continuous observation was also executed at a fixed observation tower in the bay for about five months. A GIS technique was also applied to consider spatial and seasonal characteristics of water environment of this bay.

INTRODUCTION

The Landsat-1 was launched by the United States in 1972. This is the first earth observation satellite in the world. Its excellent observation ability brought about the importance of state-of-the-art remote sensing. Following it, Landsat-2, 3, 4, 5 and 7 were launched, and currently Landsat-7 is operated as a main satellite in this series. The Landsat-4 and 5 are equipped with two kinds of sensors, MSS (Multispectral Scanner) and TM (Thematic Mapper). The MSS is an optical sensor to observe the reflected solar radiation from the earth surface in four different spectral bands. The TM sensor is a more advanced version of observation equipment than MSS, which observes the surface of the earth in 7 spectral bands ranging from visible to thermal infrared regions. The Landsat-7 is equipped with ETM+(Enhanced Thematic Mapper Plus), the successor of TM. The spectral bands for observation are basically same seven bands as TM except the newly added band 8 with a 15m of high resolution. It is important that the same bands and specifications of the sensors are continued for a long time in order to observe the earth's environment by the same eyes.

The Ariake Sea in Kyushu Island, Japan is a semi-closed bay and has the largest tidal range in this country. It causes this sea become the most activated water body with a plenty of life forces because a 40% of tidal flat in Japan concentrates in this sea. Therefore, a fishery product in this bay had been high and fishermen called this bay the Treasure Sea. There are many animals to be nearly extinct or valuable in this bay. With the development of coastal area, the Ariake Sea may become polluted with various materials, such as organic, nutrients and suspended solids. These phenomena may depend on water movement and discharge of pollutant loading from the land area. However, details have not clarified yet. Saga, Fukuoka and Kumamoto Prefectures facing this bay have been surveying many water quality indices every month for more than 20 years at 51 observation points. The results of the survey have been accumulated enormously. On the other hand, artificial satellites have been used for estimating environments of the earth from early 1970's as mentioned above and their information have been also accumulated so long. The authors have already developed the models for estimating 2-D distributions of Secchi disk depth (water transparency) and sea surface temperature of the Ariake Sea by using Landsat-TM and ETM+

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images (Gan, Ohgushi and Araki 2000; Ohgushi, Gan and Araki 2000).

In this paper, Landsat-TM and ETM+ data are used to estimate other water quality information, i.e. salinity and chlorophyll-a. In order to understand the seasonal and spatial fluctuation property of water quality in this bay, and also to estimate long-term temporal changes of the water quality, GIS techniques are utilized. To enforce the model for retrieving water quality indices from satellite images, not only the data of prefectures but also the results of field surveys by the authors' group are utilized. A field observation at fixed locations in the inner part of the Ariake Sea was also continued during about 5 months to grasp the characteristics of water quality fluctuations for a short term.

RESEARCH METHODOLOGY

Prefectures along the Ariake Sea have continued observations about many water quality indices in this bay at high tides in the every spring tide for more than 20 years. The authors collected these enormous data and the Landsat-TM, ETM+ images. To make a model for estimating water quality from artificial satellite images, it was necessary to obtain the images whose dates and times are almost same as those of the prefectures' observations. The Landsat-5 and 7 observe reflected and emitted radiance from the same land or sea location every 16 days and the climates are not always cloud-free. Therefore, amounts of images available for making a model is much limited. Finally, eight images are selected for modeling of water transparency, temperature, salinity and amount of plankton. Prefectures have observed concentration of chlorophyll-a at different schedule and at different locations, so that only three images were used for modeling chlorophyll-a estimation.

Fig. 1 Observation tower, Saga University

These images were first geometrically corrected by using a reference vector map. Next, the spectral values were atmospherically corrected using the Lowtran 7 atmospheric model and climate data, and then regressed against the field data collected from field points. Number of sampling points is usually 51 (by Saga, Kumamoto and Fukuoka Pref.). The climate data used in the Lowtran 7 were wind speed, rainfall, air temperature and visibility.

The authors' group observed some water quality indices by themselves at 11 points in the Ariake Sea when the Landsat acquired the images of the Ariake Sea. Used instruments were the MULTI-PROBE model U-22 and W-22P by HORIBA and the CLOROTEC model ACL-104-8M by ALEC ELECTRONICS. The former, U-22 and W-22P are portable multi-sensors for 10 water quality indices, such as pH, DO, salinity, temperature, turbidity, etc. The W-22P was immersed into the sea from a boat to observe water quality at sampling points. The U-22 was installed at an observation tower. The latter, CLOROTEC is a submersible fluorometer that records chlorophyll, turbidity and water temperature for a long period because this has a many memory and wiper to keep a sensor surface clean. The CLOROTEC had been set for 5 months at a depth of 1m with a float that was installed at the center bottom of the observation tower, Saga University (Fig. 1). The U-22 had been set under the CLOROTEC for 3 months to observe other water quality indices continuously. The location of the tower is in the inner part of the Ariake Sea, which is situated at latitude 33°05'52" N and longitude 130°16'42" E. and a water velocity at this point is comparatively high because of a large discharge from the Chikugo River.

REGRESSION ANALYSIS FOR ESTIMATING WATER QUALITY

Water Transparency (Secchi Disk Depth; SDD)

The water transparency or Secchi disk depth (SDD) is a measure of water clarity or the light attenuation due to suspended sediment and organic materials present in the seawater. Theoretically the amount of radiance that the satellite sensor receives should be inversely related to the Secchi depth measurements, and it should be possible to develop empirical relationships between them. The correlation coefficients show that visible channels of Landsat-TM or ETM+ data are inversely correlated to SDD.

From the magnitudes of spectral radiance calculated by Lowtran7, it is clear that in terms of magnitude, visible channels (bands 1 to 3) should exert considerably larger influence over the model results than that of bands 4 to 7 whose values could be several orders smaller. Many algorithms have been examined and the result shows the following equation gives the best one for estimating SDD.

$$\sqrt{SDD} = 1.8041 + 0.1472TM_1 - 0.2652TM_2 + 0.1076TM_3 \tag{1}$$

where $TM_i (i = 1,2,3)$ are spectral radiance corresponding to band 1,2 and 3 of the Landsat TM or ETM+ sensor. All visible bands (band 1 to 3) are found to be negatively correlated to SDD because seawater of higher SDD values should reflect less radiation into atmosphere. However, Eq(1) shows a balance of each band radiance with SDD so that some coefficients can be negative.

Sea Surface Temperature (SST)

It has been demonstrated theoretically and experimentally that sea surface temperature (SST) can be accurately retrieved from thermal infrared data, such as the band 6 of Landsat-TM. Among the six selected Landsat-TM images, only three images (9/27/1984, 11/15/1990 and 5/5/1995) have valid reflectance values for band 6. Then atmospherically corrected radiance, $L_W(\lambda)$ of these 3 images are regressed against SST collected over the same 51 sampling points of the Ariake Sea. To employ multi-date calibration data for SST which varies significantly from season to season, it is probably better to de-center SST or to remove the sample mean (μ_{SST}) from SST before doing the regression. The regression model for SST is finally obtained as follows:

$$(SST - \mu_{SST}) = -0.5742\ (TM_6 - \mu_{TM_6}) \tag{2}$$

where μ_{SST} and μ_{TM_6} are average sea surface temperature and average atmospherically corrected radiance of band 6 at any observation point respectively.

From regression analysis between observed SST and estimated one, the correlation coefficient obtained in the calibration stage is $\rho = 0.99$ for SST. However, that obtained in the validation stage is $\rho = 0.41$ for SST. More improvements are necessary for development of the retrieval algorithm on SST by introducing effects of seasons, etc. without de-centering data.

Chlorophyll-a (CHL)

Although there are chlorophyll-a, -b, -c, -d in nature, what exists in all algae is the chlorophyll-a. The concentration of chlorophyll-a is often used as an index for amount of phytoplankton in water body. In Tokyo Bay, the satellite images are used to estimate chlorophyll-a (Mizuo *et al.* 1998). Some other researches are seen on publications. However, in the Ariake Sea, the SDD often have a value less than 1m, so that it is necessary to formulate another estimating equation in this field. It is known that a distribution of wavelength for radiance emitted from water surface depends on the concentration, but its dependency is comparatively low at wavelength of 0.52-0.60μm, which is the same as band 2 of TM sensor. Therefore, it is known that the combination of some radiances including the one whose dependency is low on the concentration shows better result for estimation of chlorophyll-a. In this study, some combinations of spectral radiance were considered to estimate the chlorophyll-a, but correlation coefficients were very low. The best model obtained from regression analysis is as follows.

$$Log(CHL) = 2.34 - 0.33\frac{TM_2}{TM_4} \tag{3}$$

where *CHL* is a concentration of chlorophyll-a in the sea surface. It is necessary to increase the number of field measurements for more accurate modeling in the future.

Salinity (SAL)

Salinity is one of the basic water quality indices. This material is considered to be conservative in the water body and has been used for determining a diffusion coefficient. Through many regression analyses, the following equation is obtained.

$$SAL = \exp(k + \alpha_1 TM_1 + \alpha_2 TM_2 + \alpha_3 TM_3 + \alpha_4 TM_4 + \alpha_5 TM_5 + \alpha_6 TM_6 + \alpha_7 TM_7) \tag{4}$$

where $k = 3.3778$, $\alpha_1 = -0.0056$, $\alpha_2 = 0.0001$, $\alpha_3 = -0.0071$, $\alpha_4 = 0.0268$, $\alpha_5 = 0.0096$, $\alpha_6 = -0.0320$, $\alpha_7 = 0.0352$. The correlation coefficient of Eq.(4) against observed data is about 0.74.

RESULTS OF FIELD OBSERVATION

Figure 2 shows the observed data of chlorophyll-a and water temperature at the observation tower from October 20, 2001 to March 13, 2002. There is 1-week break during this period because of maintenance of the CLOROTEC. The water temperature gradually decreases with minimum temperature in the top of January. The chlorophyll-a has started to increase in the spring, which is called the spring blooming. In November, this increased a little.

Figure 3 shows changes of turbidity at the observation tower and sea level that was observed at another observation tower that was managed by the Ministry of Land, Infrastructure and Transport. The distance between two observation towers is about 3km so that sea levels of both are almost the same for a slow change of sea level, such as a tide. The turbidity has a tendency to synchronize with the sea level fluctuations. The turbidity becomes high at the spring tides because tidal current in the spring tide is fast and may roll up the sea bottom's mud so much. The chlorophyll-a does not change always with the turbidity because phytoplankton depend not only the turbidity but also other environments, such as quantities of sunshine, temperature and organic materials, etc.

Changes of pH and DO are shown at Fig. 4. These are the results of observation by HORIBA U-22P Sensor. The pH decreased from 8.4 to 8.1 or 8.2 in January but later it returned to the previous value. The DO has gradually decreased from February to March. This can be explained by the amount of phytoplankton, that is, the chlorophyll-a has increased in spring as mentioned above.

Figure 5 is an observed result at the same observation tower from October 23, 2002 to February

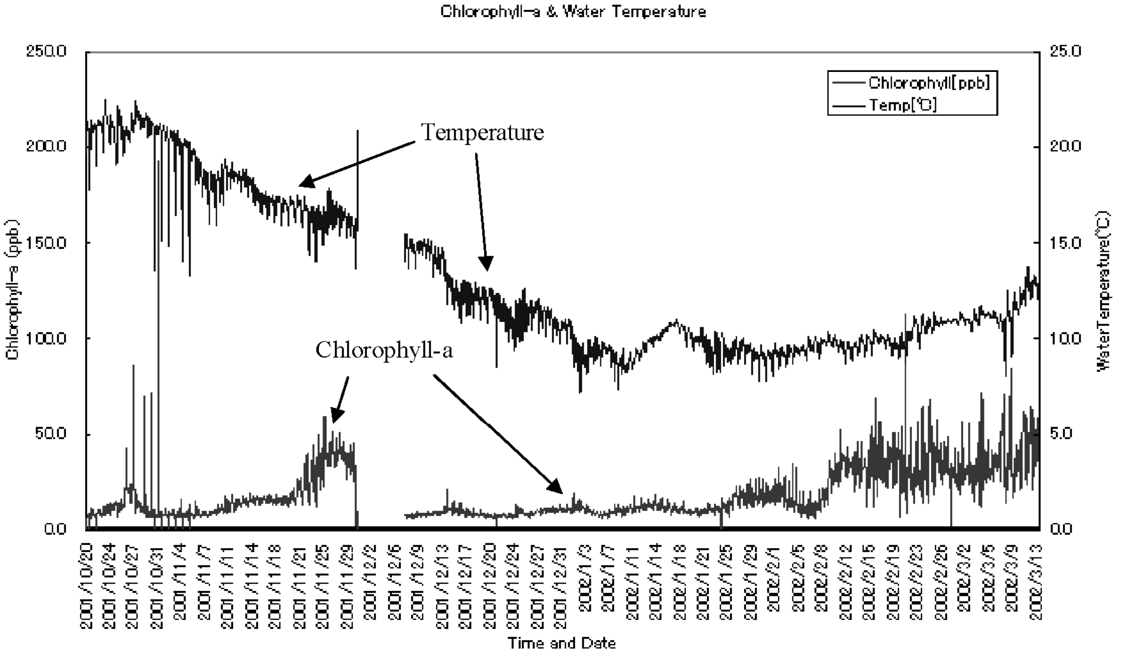

Fig. 2 Chlorophyll-a and water temperature at observation tower

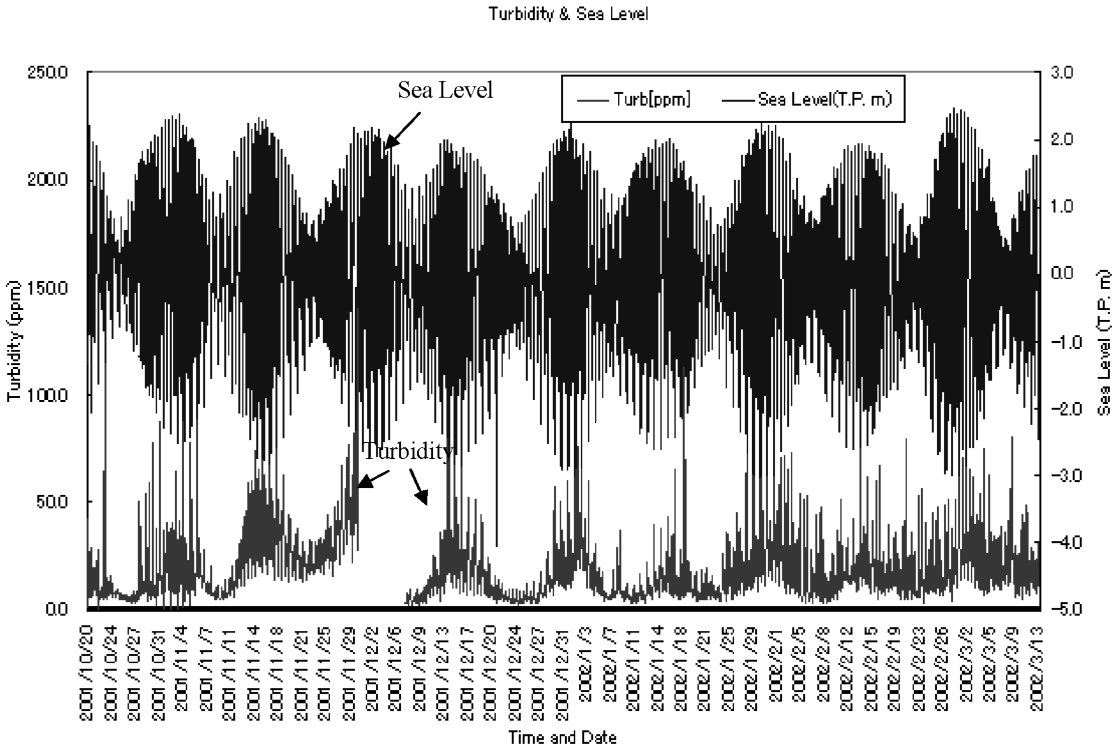

Fig. 3 Turbidity and sea level at observation point

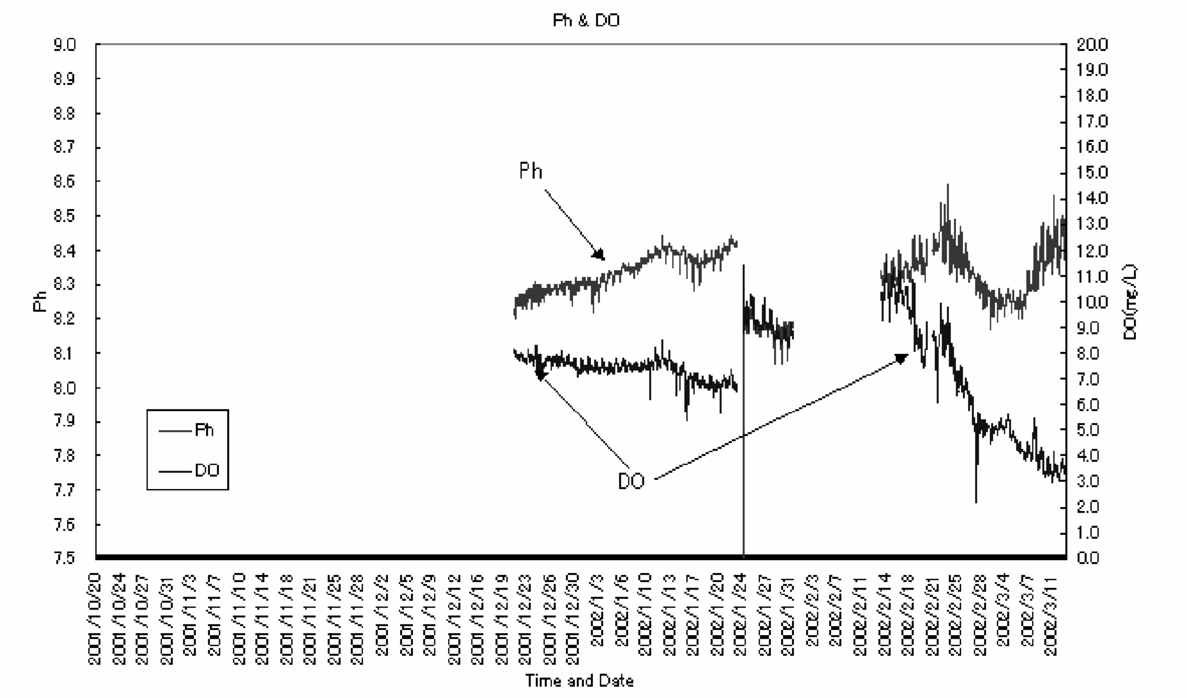

Fig. 4 pH and DO at observation tower

3, 2003. Compared to Fig. 2, a concentration of chlorophyll-a is much lower than the previous year. Saga Prefecture has explained there was few nutrients supply from the main rivers in this year because of draught so that products of cultured laver were decreased so much than 2002.

WATER TRANSPARENCY ESTIMATED BY REMOTE SENSING

From the Landsat-ETM+ images of October 20, 2001 and March 13, 2002, water transparency (SDD) of the whole Ariake Sea were estimated by using Eq.(1) and Lowtran7 atmospheric correction program(Figs. 6 and 7). Both in 10/20/2001 and 3/13/2002, tide is in the spring tide period as seen in Fig.3. Therefore, turbidity for each period should be high, but it is clear that the water transparency near and outside of the bay in 3/13/2002 is much larger than 10/20/2001. By using both remotely sensed images and long term continuous observation of the field in the Ariake Sea, advantages of each method could be functioned very well.

APPLICATION OF GIS

The data observed by Saga, Fukuoka and Kumamoto Prefectures are analyzed by using GIS (Geographic Information System). The number of observation points is 51 and these prefectures have continued the observation every month for more than 20 years at each point. Quantities of these data are enormous so that the GIS may be one of the most effective tools to pick up the characteristics of the data. In this study, SDD, SST and salinity are visualized by a GIS software, ArcView 3.2.

Period of visualization is from January 1993 to December 2000. There occurred a poor harvest for cultured laver in the Ariake Sea in winter, 2000. Figure 8 shows the results of visualization for SDD (transparency). A general feature is that the SDD becomes lower in summer because of rainfall and supply of river discharge. However, SDDs in summer of 1994 and 2000 don't show the typical results because there were draught in these years (see Figs. 9 and 10). The poor harvest of cultured laver is directly caused by abnormal breeding of phytoplankton but a background of these situations should be taken into account for future research.

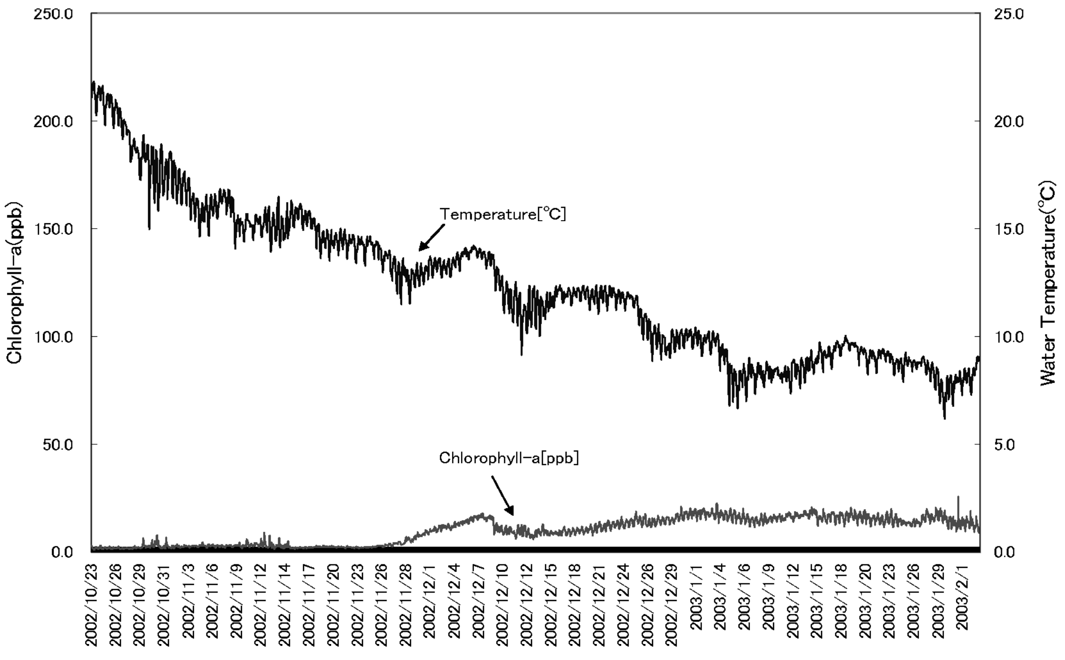

Fig. 5 Chlorophyll-a and water temperature at observation tower

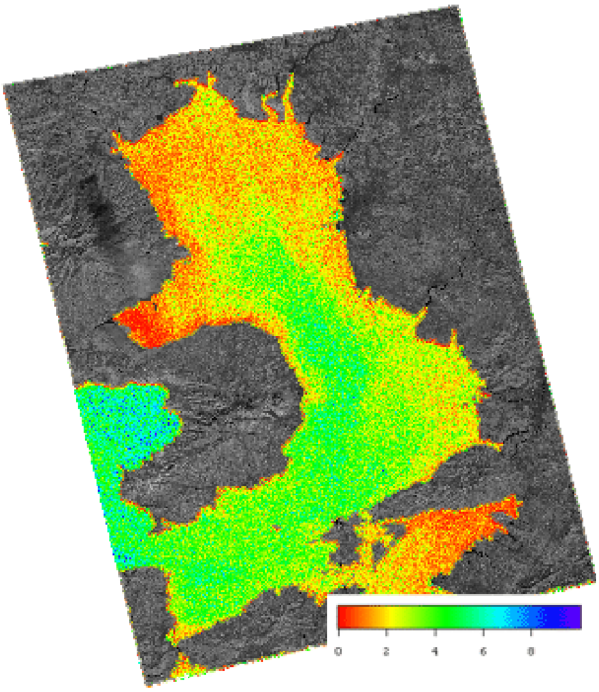

Fig. 6 Estimated SDD map on Oct. 20, 2001 by Landsat

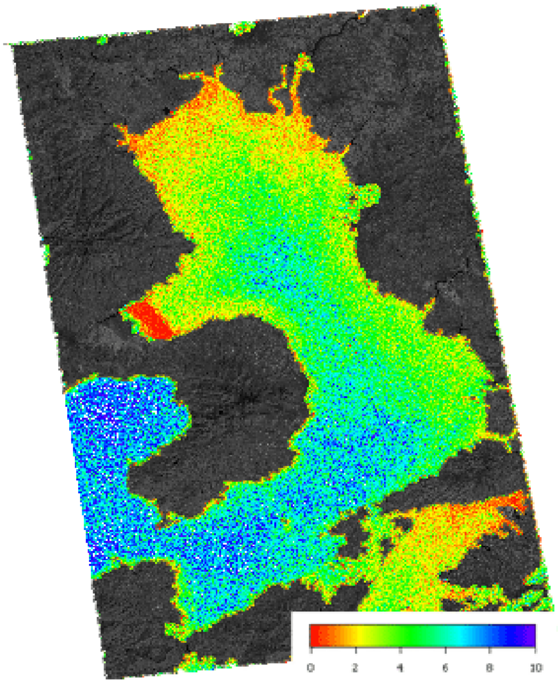

Fig. 7 Estimated SDD map on Mar. 13, 2002 by Landsat

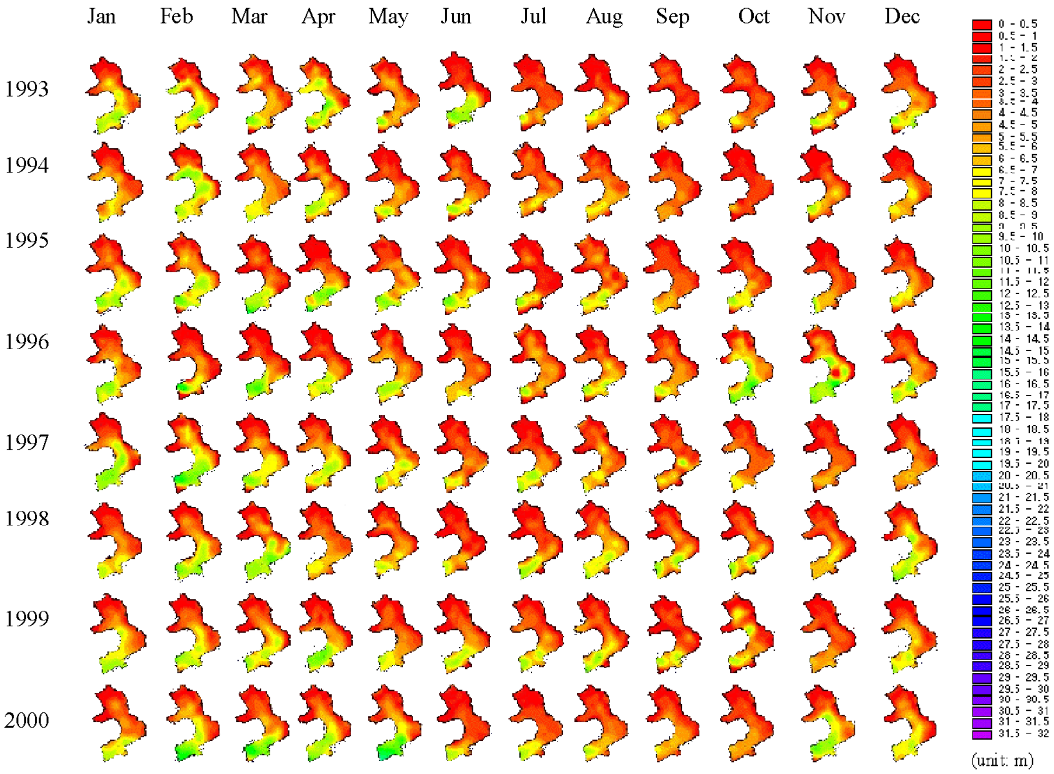

Fig. 8 Visualized SDD change by GIS for 8 years in the Ariake Sea

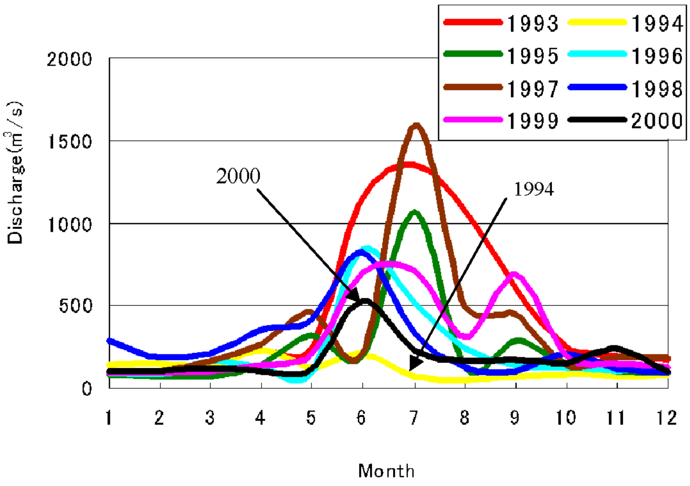

Fig. 9 Monthly averaged discharge of 8 main rivers flowing into the Ariake Sea

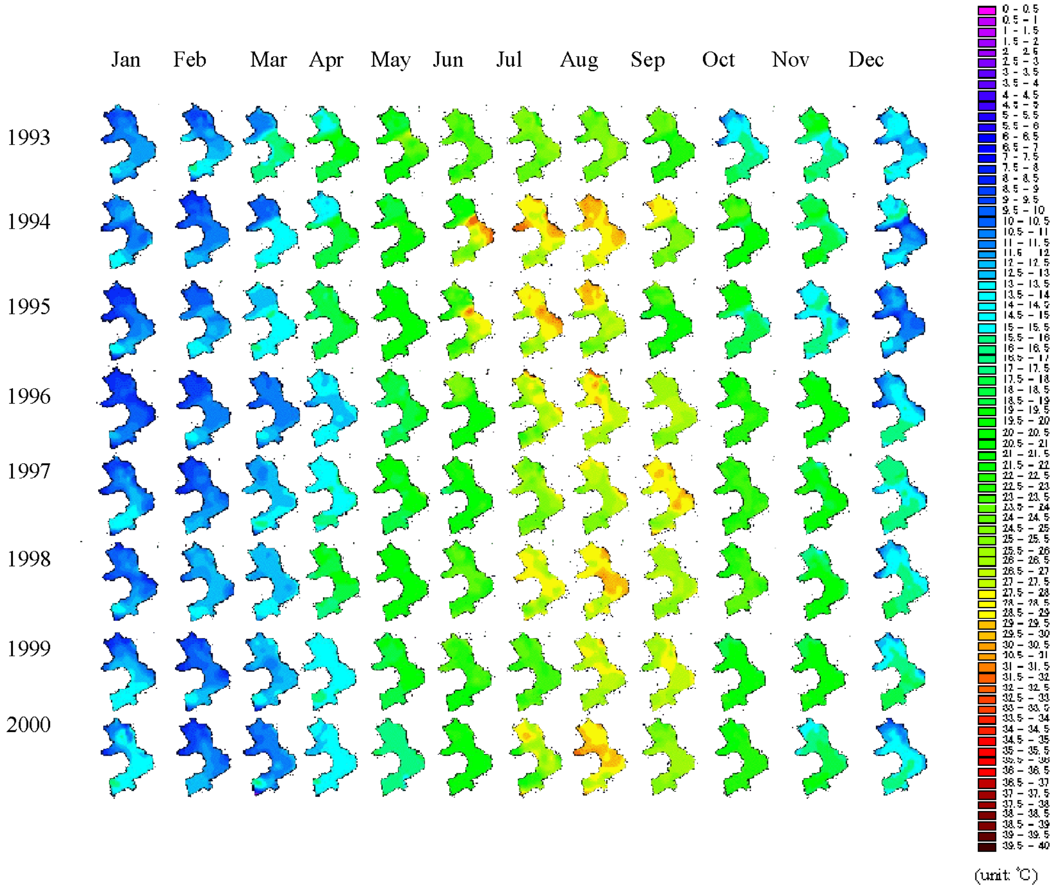

Fig. 10 Visualized SST change by GIS for 8 years in the Ariake Sea

In this way, the GIS can provide many information for us to evaluate water quality but these information are almost taken at high tide of flood tide in the bay. If it is necessary to discuss tidal current and water quality change, remotely sensed information will cover this disadvantage.

CONCLUSIONS

Using observed data of water quality in the Ariake Sea by prefectures and authors' group, the estimation model is constructed. This model can retrieve water quality indices from the Landsat-TM and ETM+ images. The estimation model for not only the water transparency and temperature but also the salinity and chlorophyll-a are developed through regression analysis. Continuous field observations at fixed locations (including observation tower) in the Ariake Sea were executed during about 5 months. The results obtained by these observations could explain the characteristics of the water quality in the inner part of this bay. The turbidity tends to synchronize the tide. The chlorophyll-a increases in spring and it consumes dissolved oxygen. The pH shows usually from 8.2 to 8.4 but in January it decreased a little. And these observations complement the estimated water quality by the satellite images and the remote sensing technique also has much capacity to help the field observation as well. A GIS schematize field observation results and characteristics of this bay become clear.

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