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Relationship between Turbid Water and Coral Damage Distribution Using ALOS AVNIR-2 Images and Diving Survey Data Immediately after the Heavy Rain Disaster of the Amami-Oshima Island, Japan

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Abstract

To understand the relationship between turbid water and coral damage caused by the heavy rain disaster at the end of October 2010 in Amami-Oshima, Kagoshima Prefecture, Japan, turbid water and coral damage distribution monitoring was attempted using satellite imagery and a diving survey immediately after the disaster. ALOS AVNIR-2 images (spatial resolution: 10 m) on October 6 (before the disaster), October 24, October 30, and October 31 (after the disaster) were obtained as satellite data in 2010. The red-silt deposition index (RSI) map based on the method by Nadaoka and Tamura (1992) was also created. Moreover, a diving survey was conducted via the spot check method on December 18, 2010. As a result, comparison between the high turbidity (RSI) areas estimated using AVNIR-2 data and the coral damage areas judging from the field survey was considered relatively light. It is shown that satellite data such as AVNIR-2 can be a powerful tool to monitor damage distribution of coral reefs after heavy rain.

Keywords

ALOS AVNIR-2, Heavy Rain Disaster, Amami-Oshima Island, Red-Silt Deposition Index

1. Introduction

Catastrophic natural disasters in recent years, such as the volcanic ash due to the explosion of Eyjafjallajökull,

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Iceland in April 2010 [1] and the tsunami caused by the Great East Japan Earthquake disaster in the Japanese Tohoku district in March 2011 [2] have caused anxiety regarding their influence on aquatic animals and plants. In relation to this, a major problem is the sediment discharge that accompanies heavy rainfall and causes damage to corals in coral reef regions. The large-scale environmental evaluation of such coral reefs has often been performed using remote sensing techniques [3] [4].

In Japan, "red soil pollution" is notorious for causing the same problem as that caused by the sediment discharge in the coral reef region around Okinawa and the other Nansei Islands. When there is heavy rainfall on the island of Okinawa, coral reefs near river mouths often develop a "cloudy red" appearance where once there was clear water. Most of the red soil carried to the sea by rivers is deposited on semienclosed reef moats adjacent to the coast, and the red soil is often repeatedly stirred up by turbulence, including typhoons and monsoons [5]. Therefore, red soil monitoring is very important. For example, the development of the suspended particles in sea sediment method, which is a simple on-site red soil measurement technique [6], or the red soil deposition index by satellite data [7] has been undertaken. However, most of these studies are limited to the vicinity of Okinawa Prefecture (Okinawa Island and Ishigaki Island), and except for those conducted in Okinawa, there are very few studies on the influence of sediment discharge on coral and continuous soil sedimentation monitoring.

In the interior of the Amami-Oshima Island, Kagoshima Prefecture, Japan, a subtropical evergreen broad-leaved forest that is the largest in the country spreads across the study site. Many unusual and rare animals and plants live in this forest. Moreover, the coastal region has various environments such as coral reefs, mangroves, and tidal flats. Therefore, the land area and ocean space are highly valued for their biodiversity in an area of very high preservation importance, internationally as well as in the country. In such an important area, due to the record heavy rains late in October 2010, turbid water streams flowed out of the river into the sea, seriously damaging the coral reef. The circumference of the Sumiyo Bay, which has mangrove forests on a leading national scale, especially tidal flats, was most critically damaged. Because a field survey of the water area itself was conducted, measures against damage to land areas have been prioritized. In many cases, the area following such a catastrophic disaster is dangerous, and investigation of damage to corals immediately after a disaster is very difficult. In contrast, urgent observation by aircraft or satellites can be rapidly performed as one of the monitoring tools for large-scale disasters that have frequently occurred in recent years [8]. In this disaster, two or more aerial photographs and satellite images were actually obtained over several weeks immediately after the disaster.

From this background, satellite imagery immediately after the heavy rain disaster that occurred in Amami-Oshima and subsequent diving survey data of October 2010 are used, and the turbid water distribution of the coral reefs and understanding of the coral damage distribution situation are discussed in this study.

2. Method

2.1. Study Area

The region of this study is the Amami-Oshima Island located in Kagoshima about 400 km southwest of Kagoshima City. The area in which the coral reef in the Amami Archipelago is located is 27˚ - 29˚ north latitude and accounts for a coral community of about 6000 ha calculated from the moat area. The diversity of hermatypic coral as compared with the coral reef community in the same latitude is also rich. Approximately 220 species of hermatypic corals have been identified in the Amami sea area [9]. Most of the reefs that fringe the island are seaward facing and are thus located in water that is largely oceanic. However, in the inner bays and straits, turbidity and sedimentation from the land can be observed [10]. There was heavy rainfall in the region from October 19 to October 20, 2010 on the island as shown in this figure. In various parts of the island, river floods and mudslides occurred due to such heavy rainfall. This resulted in damage to coral in the area, as shown by the red dots within **Figure 1**. In Sumiyo-cho, Amami-shi, which was especially heavily impacted by rain for a long time, large-scale flooding was accompanied by mudflow. In the ocean space near the stricken area, a considerable quantity of sediment discharge flowed into the sea. Regarding Sumiyo Bay, coral reefs such as *Acropora* and *Porites* exist in the mouth of the bay, as shown in **Figure 2**. The ocean space around an islet of southeastern Sumiyo Bay called "Tobira Island" is where the coral damage was the most serious. Tobira Island is an uninhabited island with an area of about 0.02 km^2 that appears approximately on the 300-m offing of Ichi, Sumiyo-cho, Amami-shi. This study particularly focuses on an approximately 2-km circumference of Tobira Island divided into four quarters.

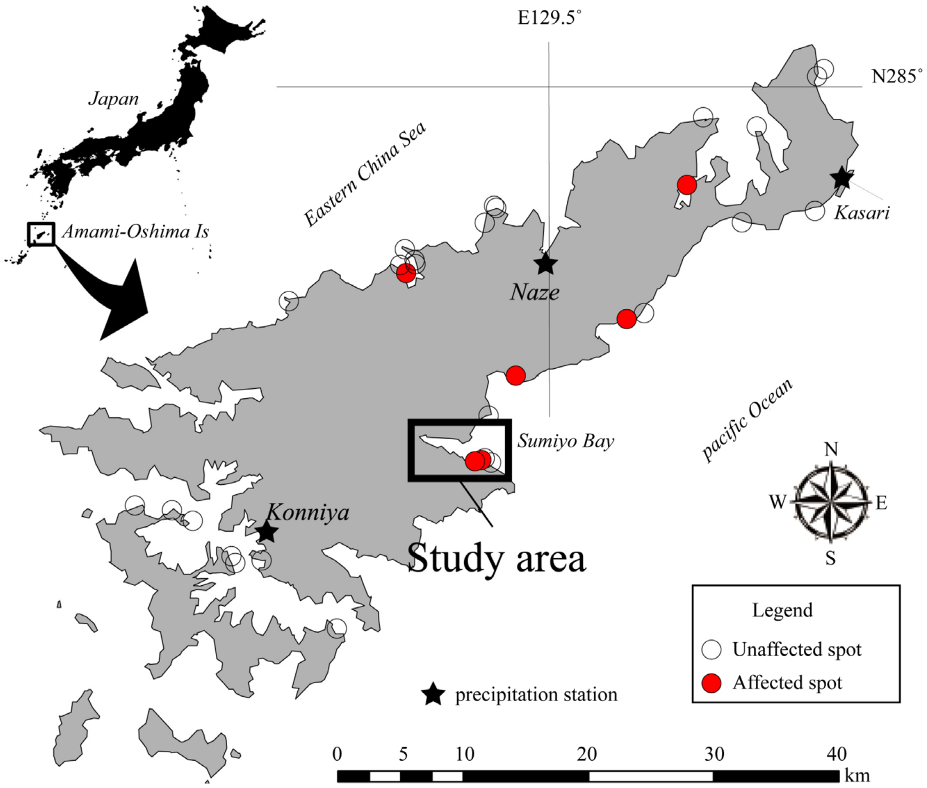


Figure 1. Study area map with the area affected by the heavy rain on the coral reef in Amami-Oshima, Japan.

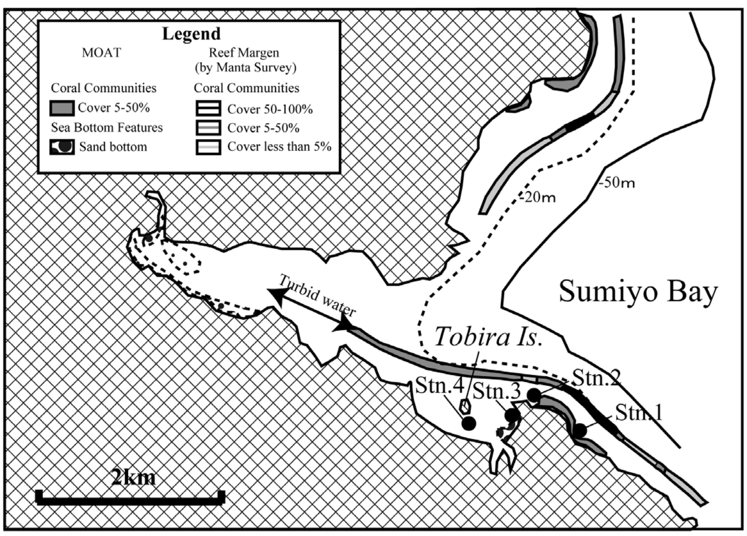


Figure 2. Coral map [11] of Sumiyo Bay and the diving survey stations (Stn. 1, Stn. 2, Stn. 3, and Stn. 4).

2.2. Field Survey

A diving survey was conducted at four points at a depth of 3 - 4 m around Tobira Island on December 18, 2010, two months after the heavy rain disaster, as shown in Figure 2 and Table 1. The spot check method in a 50-m × 50-m range was adopted. Survey items were "coral coverage", "coral growth type", "coral death rate", "coral bleaching rate", and "water transparency (hereafter transparency)".

Table 1. Positions of the diving survey and water depth.

Stn.	Name	Latitude	Longitude	Depth
1	Takahama-Higashi	28˚13'50.4"	129˚27'27.5"	4 m
2	Takahama	28˚14'00.7"	129˚27'11.8"	3 m
3	Hatonosaki	28˚13'56.9"	129˚27'02.5"	3 m
4	Tobira	28˚13'53.2"	129˚26'46.1"	4 m

2.3. Satellite Data

To determine the turbid water distribution on the coral reef before and after the heavy rain disaster, ALOS AVNIR-2 data (level 1B product) were used over four days, *i.e.*, October 6, 2010, October 24, October 30, and October 31, as shown in **Table 2**. ALOS AVNIR-2 is a satellite sensor that has four spectral bands and performance with a resolution of 10 m in the visible and near-infrared bands, as shown in **Table 3**. Although the nominal observation cycle is 46 days, in this study, one image can be acquired over several days by changing the angle of the sensor at the time of targeting the disaster area. Moreover, because AVNIR-2 data differ in the imaging range according to the observational day, if geometric correction processing is not carried out, comparison using pictures of the object region is difficult. Therefore, geometric correction processing (WGS84 ellipse, UTM zone 52N) was performed using the position information on the four corners and center, which is written in the header information of the satellite image. A picture of the target area was then extracted in the same respective size. Furthermore, because these image data are also acquired under different observation conditions (sun elevation, camera angle, and tide level), certain atmospheric corrections are required. Among these, sun elevation and camera angle were rectified via the "atmospheric correction" method explained later. Moreover, tidal level correction was conducted using the red-silt deposition index.

2.4. Atmospheric Correction

Data were acquired under observation conditions (different sun elevation and camera angle) from which AVNIR-2 target data differ each day. That is, in addition to the change in spectral characteristics reflecting the change in muddiness of the offshore water, there are also spectral changes due to atmospheric absorption and dispersion. Thus, atmospheric correction was performed to reduce the influence of spectral change on interpreting the color or brightness under turbid water conditions. There is a method assuming the near-infrared reflectance of open sea to first be 0 as the atmospheric correction of ocean space [12], and aerosol removal of short wavelengths for every pixel is performed. The visible and near-infrared reflectance of open sea is assumed to be 0, and the aerosol distribution on a screen is constant; this is an easy method called the "dark pixel subtraction method," which deducts the data of open sea uniformly in each band [13]. Unfortunately, because reflectance cannot be assumed to be 0 in turbid water areas, this method is unsuitable. However, in this analysis, if the relative relation of the image just before a disaster is known, such an absolute atmospheric correction is not necessarily required. Then, a relative atmospheric correction known as remote sensing monitoring technique [14] [15] can be used in lakes or wetlands. Data were made into reference data on October 6, which was the day when the sun elevation was the highest during the observations, and, specifically, the conversion factor for each data item was calculated by a revolution calculation with the same target on another day (**Table 4**). Three points, *i.e.*, asphalt (runway of Amami Airport) around the coral reef, whose covering state is generally considered uniform throughout the seasons, as a standard ground object, concrete (roof of the Amami Airport terminal), and white lines (runway display of the Amami Airport), were selected.

2.5. Red-Silt Deposition Index

To estimate the deposition of sediment from the land, the red-silt deposition index (RSI) by Nadaoka and Tamura [7], which employs the simplest method, was used in this study. This method employs an equation that serves as a bottom feature index for which the radiance ratio of band 1 (420 to 520 nm) and band 2 (520 to 600 nm) of Landsat TM does not depend on the depth of the water (or tide level) based on optical theory. RSI is determined from the following equation and becomes large when there is a large amount of bottom sediment.

Table 2. List of satellite data and sea level under satellite observation.

Date	Time	Sun Elevation	Pointing Angle	Sea Level (MSL)
		(˚)	(˚)	(cm)
Oct. 6	10:50	53	–30	43
Oct. 24	11:32	49	39	98
Oct. 30	10:41	44	–41.5	151
Oct. 31	11:22	47	24	143

Table 3. Specifications of the ALOS AVNIR-2 sensor.

Band	Band 1: 420 - 500 nm Band 2: 520 - 600 nm Band 3: 610 - 690 nm Band 4: 760 - 890 nm
Spatial resolution	10 m (at nadir)
Swath	70 km
Quantization	8 bit

Table 4. Conversion coefficients of relative atmospheric correction in 2010.

Date	Band	*A*	*b*	R^2
Oct. 24	1	1.21	8	0.92
	2	1.12	8.7	0.99
	3	1.17	6.6	0.97
	4	1.18	4.4	0.90
Oct. 30	1	1.51	–84.5	0.91
	2	1.48	–48.1	0.96
	3	1.31	–10.2	0.92
	4	0.81	–1.5	0.96
Oct. 31	1	1.26	7.6	1.00
	2	1.15	13.5	0.99
	3	1.26	2.2	1.00
	4	0.75	7.1	1.00

Coefficient of relative atmospheric correction = $a + b \times$ (DN), R^2 = Coefficient of determination.

$$\mathrm{RSI} = \frac{V_{\lambda 2} - V_{\infty}}{V_{\lambda 1} - V_{\infty}} \tag{1}$$

Here, $V_{\lambda 1}$ and $V_{\lambda 2}$ are TM band 1 (420 - 520 nm) and TM band 2 (520 - 600 nm), respectively, and V_{∞} shows the darkest pixel value (clear open ocean water) at each band. In this study, $V_{\lambda 1}$ and $V_{\lambda 2}$ were transposed to AVNIR-2 band 1 (420 to 500 nm) and band 2 (520 to 600 nm), respectively. In addition, for V_{∞}, the radiance value (average value of 11 × 11 window pixels) of a water area (N28˚14'26", E129˚27'26"), which had sufficient depth in Sumiyo Bay on October 6 (before the disaster), was used.

2.6. Depth and DEM Data

To investigate the relation between satellite imagery and geographical features, the water depth expected for the diving survey and elevation data used are from the "Bathymetric Chart" of the Japan Coast Guard and "Digital Map 50 m Grid (Elevation)" from the Geospatial Information Authority of Japan (GSI), respectively. A Bathymetric Chart was made from overlays to obtain true color images of AVNIR-2. Digital Map 50 m grid. It was changed to a 3-D image using the AVNIR-2 image with Digital Map 50 m grid interpolated at 10 m.

3. Results and Discussion

3.1. Diving Survey Results

An outline of the diving survey results on December 18, 2010, two months after the disaster, in an approximately 2-km^2 area of Tobira Island of Sumiyo Bay is shown in **Table 5**. There is slight environmental change over two months, but it is assumed that the relative position of each spot does not change much from continual eye-measurement from a diving investigation. Photographs of a typical coral situation at the time of the survey are shown in **Figure 3**. The influence of the heavy rain disaster was not seen in Takahama-East (Stn. 1) or Takahama (Stn. 2), which accounts for more than 40% coverage of coral in the bay. On the other hand, in Hatonosaki (Stn. 3) and Tobira (Stn. 4), deposition of silt to the seabed, death, and blanching of coral communities were seen. The damage near Stn. 4 of Tobira Island was especially serious.

3.2. Satellite Data Overview

AVNIR-2 natural color composite images of before and after the heavy rain disaster are shown in **Figure 4**. After

Table 5. Basic results of the diving survey on December 18, 2010.

Stn.	Coral Coverage (%)	Dominant Coral Community	Death/ Bleaching Rate (%)	Transparency (m)
1	60	Tabular *Acropora*	0	<10
2	40	Tabular *Acropora*	0	<10
3	<5	Massive *Porites*	<5/<5	<3
4	10	Massive *Porites* & Branching *Acropora*	30/30	<3

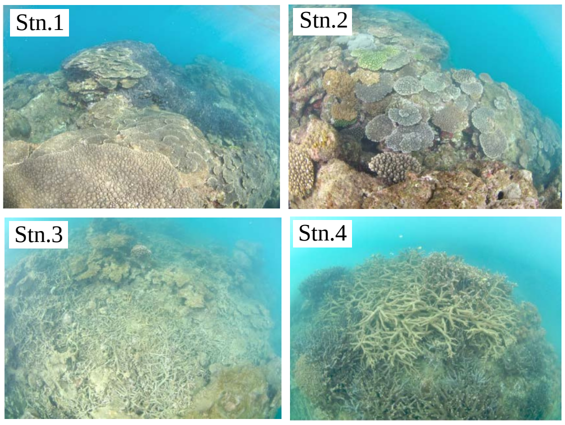
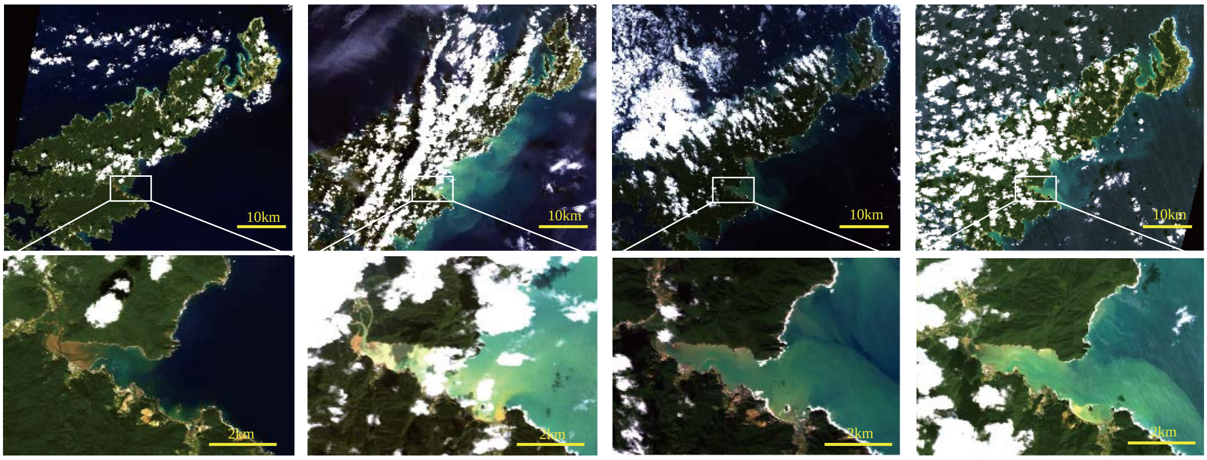


Figure 3. Photographs of the typical coral habitation situation in Sumiyo Bay two months after the heavy rain disaster on December 18, 2010.



(a) Oct.6 (b) Oct.24 (c) Oct.30 (d) Oct.31

Figure 4. True color composite images of ALOS AVNIR-2 (bands 1, 2, and 3) used in the study area before (Oct. 6) and after (Oct. 24, Oct. 30, and Oct. 31) the heavy rain in 2010.

the heavy rain on October 20, the sea surface of eastern Amami-Oshima became remarkably turbid, as seen in the image for October 24 (upper part of **Figure 4(b)**) as compared with before the heavy rain. In Sumiyo Bay, *i.e.*, the study area, it became especially turbid on the outskirts of Tobira Island, as can be seen from the images for and after October 24 as compared with the image for October 6 (very bright ocherous portion). From the images after October 24 when compared with the image for October 6, it can be seen that become turbid around Tobira Island. A highly turbid area (extremely bright ocher) can especially be seen from the images after October 24 around Tobira Island. From the image of the bay on October 24 and October 31, it can also be seen that the very high concentration turbidity distribution had spread. Expanded AVNIR-2 images near Tobira Island on October 24 and October 31 are shown in **Figure 5** with an interpretation figure. According to this figure, offshore from Ichi, high concentration turbid water passed through point 3 and was flowing northward offshore (water depth: 30 m) about 1 km on October 24. On the other hand, high concentration turbid water separated from the land area of the southeastern part of Tobira Island on October 31, and it flowed through the main stream eastward along the depth contour at a depth of 10 m and reached up to Stn. 4 in the southeasterly area.

3.3. Relation between Turbid Water Distribution and Coral Damage

As mentioned above, from the result of the diving investigation, chlorosis of *Acropora* and *Porites* was observed at Stn. 3 and Stn. 4, but healthy coral remained at Stn. 1 and Stn. 2. A massive amount of sediment brought about from the small river due to the heavy rain (photograph on the leftmost side of **Figure 6**) and the quarry in the land area (photograph on the rightmost side of **Figure 6**) flowed out. It is conjectured that mud accumulated on the seabed is as shown by the satellite imagery, which expresses **Figure 6** in three dimensions. The quite different turbidity conditions such as at Stn. 3 and Stn. 4 are also caused by not only the topographic elements in the sea and islands but also a temporal change in the state of the basin topography and soils. **Figure 7** is the RSI distribution calculated from AVNIR-2 imagery. From this figure, it is estimated from this figure that there was a great deal of deposition, especially of mud, off Ichi from southwestern Tobira Island on October 24 and October 31. This coincides well with the fact that mud had also been deposited as found by the diving investigation on November 8 (immediately after the heavy rain) conducted separately about 10 km from Tobira Island in this study. On the other hand, it is located behind the peninsula and facing the open sea, and because the environment is one where turbid water is easily flushed by typhoons (e.g., Typhoon No. 14, which approached the island on October 29), etc., a high concentration of mud was not readily deposited at Stn. 1 or Stn. 2. As a result, as compared with Stn. 3 and Stn. 4, the damage to the coral was relatively light at Stn. 1 and Stn. 2. Most red silt, on which a survey observation was carried out on the Yakata coast in Okinawa Prefecture, is known to be deposited between capes, and it diffuses offshore depending on the disturbance conditions such as surges [16], and it was thought that this result and the actual situation correlated well. In general, it is well known from analysis using satellite and GIS data [17] [18] that SST, UV, and so on have the highest influence on coral stress. It was

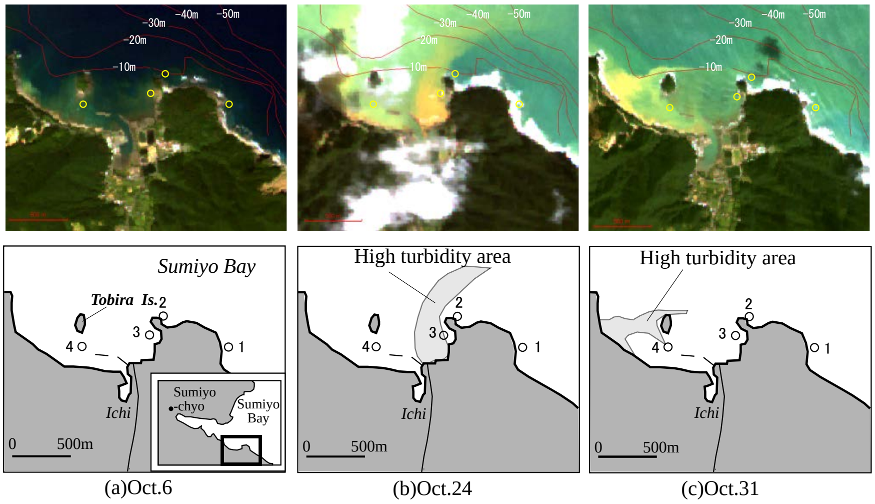


Figure 5. Comparison of ALOS AVNIR-2 images with the bathymetric line around Tobira Island before and after heavy rain in 2010.

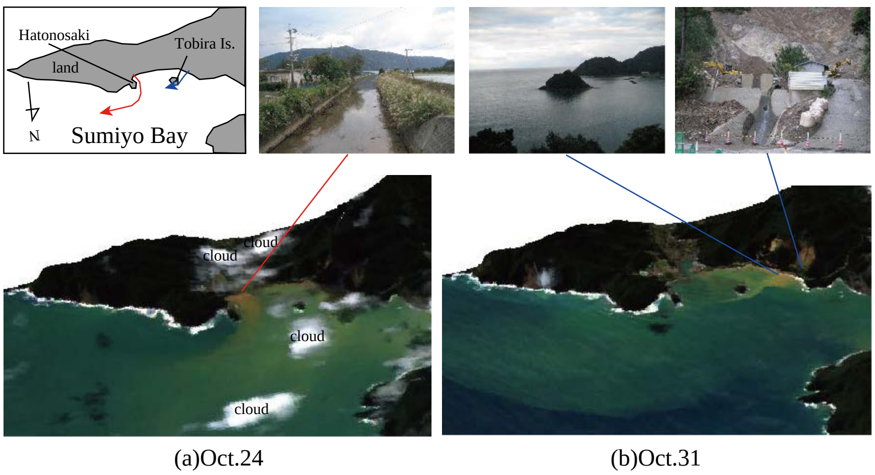


Figure 6. Estimation of the supply source of sedimentation in the water by 3-D images from AVNIR-2 in 2010.

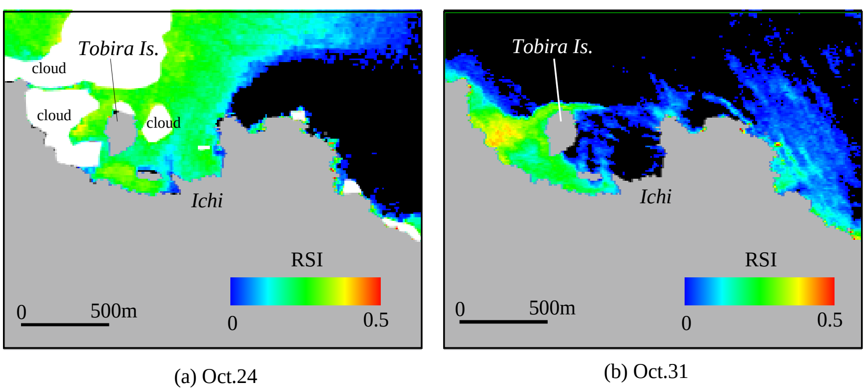


Figure 7. RSI map calculated from AVNIR-2 data in 2010.

confirmed once more through this study using high-resolution satellite data such as AVNIR-2 that turbidity and geographical features are also very important parameters to growing coral.

4. Conclusions

In this study, to understand the relation between turbid water and coral damage, turbid water and coral damage distributions were estimated in some areas of the circumference of Tobira Island whose coral damage was serious using a diving survey and satellite imagery of the heavy rain disaster that occurred at the end of October 2010. As a result, comparison between the high turbidity (RSI) areas estimated using AVNIR-2 data and the coral damage area judging from field survey was considered relatively light.

These observations can continue for a long period of time in this water area from now on as a method of elucidating the mud deposition mechanism on the coral reefs of Amami-Oshima. I would like to estimate the amount of mud deposition by combining satellite data and local observational data in the future.

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