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Study on water quality purification method by aquatic plants at a reservoir for small-scale water supply

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ABSTRACT

The reservoir used for water supply on Haha-jima Island had been experiencing eutrophication. In order to improve water quality an experimental hydrophytic system was set up on-site in 2007. Full-scale operations began from 2009. In this paper, the effectiveness of hydrophytes in improving water quality purification was evaluated. The amount of total nitrogen and total phosphorus that was removed was calculated from the production of plants. Estimated equations of total nitrogen and total phosphorus levels were made by using multiple regression analysis, which were highly statistically significant. Due to the limited water quality data of total nitrogen and total phosphorus concentrations, past data of other recorded measurements for water quality were used and assigned as explaining variables. Furthermore, the concentrations of past total nitrogen and total phosphorus were calculated based on these estimated equations and the state of eutrophication of the reservoir was simulated as longitudinal data. The results of this research are applicable for water quality control and management of other isolated islands, depopulated areas, and developing countries where specialized measuring instruments to determine water quality may be unavailable.

Keywords: Water quality control; Reservoir; Multiple regression analysis; Total phosphorus; Total nitrogen

1. Introduction

Effective control of eutrophication in reservoirs used for water supply requires careful management of water treatment systems. Ogasawara village on Haha-jima Island is located 1,000 km south of Tokyo. Chibusa Dam is the village's sole reservoir for water supply and is the subject of this study. Water blooms occur annually and are accompanied by a pungent, foul odor. In order to control algal blooms, activated carbon powder is used during the water purification process. However, chemicals that are necessary for water purification are transported by ship from mainland Japan; this significantly adds to the cost of maintaining water quality [1].

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The concentration of total nitrogen and total phosphorus is high at the dam and is a major factor in the increase of water of blooms. Past measurements taken at the dam have found total nitrogen concentrations of 0.7 mg/L and total phosphorus concentrations of 0.15 mg/L [1]. These values exceed reference values for Lake Class IV or Class V for Lakes in the “Environmental Quality Standards for Conservation of the Living Environment” [2]. The fundamental issue is whether or not the concentration of total nitrogen and total phosphorus is maintained to less than Lake Class III, which is equivalent to Water Supply Class 3.

The area around the dam is mainly forest with no agriculture or housing. For comparison, the concentration of total nitrogen and total phosphorus in rivers that flow through forests in mainland Japan is lower than the stream flowing into Chibusa Dam. The high phosphorus concentration can be attributed to the subtropical forest with a climate of high temperature and humidity. The stream flows through fallen and decaying leaves, which results in higher concentrations of nitrogen and phosphorus. Moreover, it is surrounded by steep mountains, whose terrain prevents the construction of river purification facilities. Therefore, water purification and the control of blooms can only be carried out at the dam.

We conclude that in this case the optimal method to improve water quality is to cultivate aquatic plants and for this reason an experimental hydrophytic system was set up at the dam. After demonstrating an improvement in water quality, a full-scale hydrophytic system has been introduced using Chinese water spinach. In this paper, we examine and evaluate the effectiveness of the hydrophytic system at Chibusa Dam.

2. Details of the experiment

Chibusa Dam has an available water storage capacity of 32,000 m^3 with a water surface area of 5,520 m^2, a water depth of 10 m, and a basin area of 500,000 m^2. Thus the dam was regarded as a small-scale reservoir. Surrounding the basin area there was no housing, cultivated land, or industrial development to produce air pollution to affect the water quality due to precipitation.

The water purification method employed in this study was to use aquatic plants to absorb the nitrogen and phosphorus in water as fertilizer [3–6]. The use of plants for water purification was effective throughout the year. However, typhoons and tropical storms often approached Haha-jima Island, and at Chibusa Dam, this was a particular problem as it was located at the bottom of a narrow valley where strong winds frequently blew across its surface. Moreover, the dam was within a few hundred meters from the ocean and received unwanted sea spray.

The hydrophytic system used a floating plant raft for hydroponic farming that was connected to the bank of the dam. *Ipomoea aquatica Forsk*, commonly known as Chinese water spinach, was chosen for this study [7]. It was a non-indigenous species that was cultivated in the raft and was edible, which decreased plant waste. The roots grew to nearly one meter and effectively absorbed nitrogen and phosphorus in water. Investigations have been carried out and these results have found that the removal rate of total nitrogen is in the range of 0.2–1 g-N/m^2/d and total phosphorus is 0.02–0.1 g-P/m^2/d [8]. Aquatic plants, grown by hydroponics, also supplied oxygen which reduced biochemical oxygen demand [9].

The experimental hydrophytic system was set up in February 2007 and the harvesting began from mid-May. The size of the planting area was 10 m^2. In March 2009, when the operational system was established, the planting area was enlarged to 400 m^2.

3. Water quality at Chibusa Dam

On-site water analysis conducted daily for raw water and purified water includes pH, alkalinity, turbidity, color, and electro-conductivity (EC). Additional monthly analysis for odor, appearance, total organic carbon (TOC), iron, dissolved iron, manganese, dissolved manganese, chlorine ion, total hardness, standard plate count, welsh bacillus, and coliform bacteria was carried out. Measurement of TOC levels began in 2004. Chemical oxygen demand (COD_{Mn}) was also measured. Fig. 1 shows the changes in TOC for the past eighteen years. Fig. 2 shows EC, color, and turbidity, which was measured daily for one month. Monthly periodic measurements of the inflow water into the dam started from April 2008. The TOC fluctuated in the range of 5–10 mg/L. Shortly after the

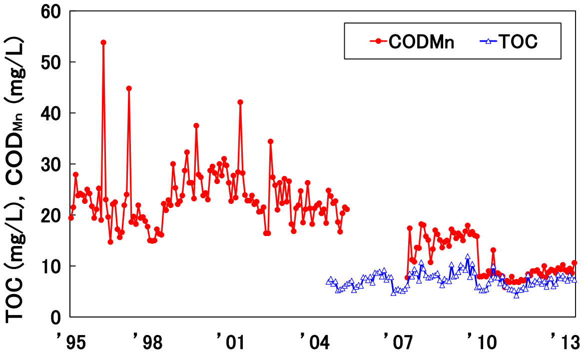

Fig. 1. Changes in TOC (monthly).

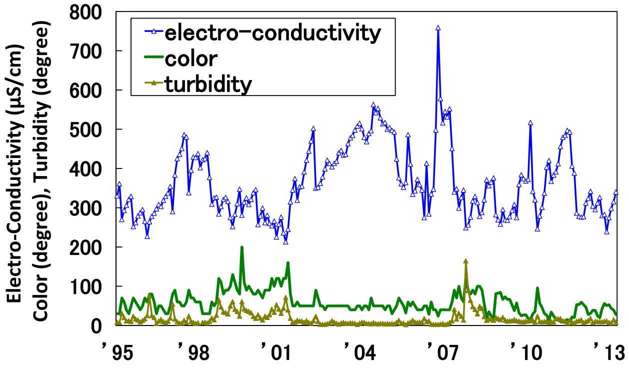

Fig. 2. Changes in EC, color, and turbidity (daily).

experiment began in May 2007, several typhoons struck the island and raw water quality rapidly worsened. The concentration of TOC increased and the values sometimes exceeded 10 mg/L. EC increased to 500–800 μS/cm for six months from November 2006. The turbidity was moderately high as raw water for water supply fluctuated around 20 units. After June 2007, the values increased to 50 units. In November of the same year, there were heavy rains followed by landslides, and the turbidity rapidly increased to 180 units. Heavy rains continued and the values stabilized around 30 units. This value lasted for six months.

Specialized instruments were unavailable to measure nitrogen and phosphorus, so these data went unrecorded. Water samples were taken from Chibusa Dam and the nitrogen and phosphorus were fixed onsite by adding an acid. Analysis was conducted by our laboratory. The measured results of total nitrogen and total phosphorus are shown in Figs. 3 and 4. To estimate the condition of water weeds, an automatic monitor to record chlorophyll a, turbidity, and water temperature was placed at a depth of one meter to the side of the floating plant raft.

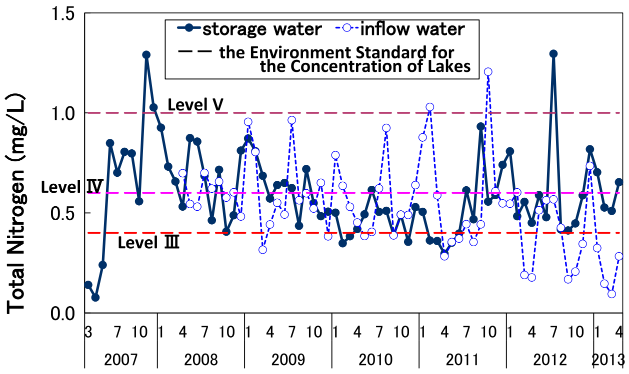

Fig. 3. The measured results of total nitrogen.

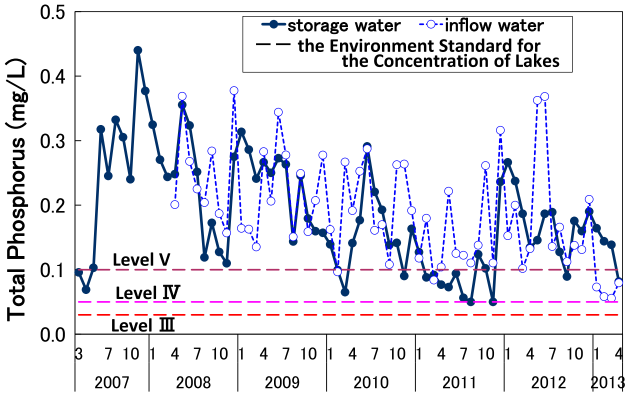

Fig. 4. The measured results of total phosphorus.

4. Formulating estimated equations for total nitrogen and total phosphorus

Prior to this study, data were not collected for nitrogen and phosphorus levels, thereby precluding a before and after comparison of water quality. In order to understand past nitrogen and phosphorus levels, it was necessary to develop an equation to estimate these levels from continuously and periodically collected water quality data. A correlation analysis was performed utilizing the data of total nitrogen and total phosphorus from March 2007 to November 2010 with the periodically measured water quality items collected at the same time. The results are shown in Table 1. The total nitrogen and total phosphorus in reservoir water had a strong positive correlation to turbidity, color, and TOC. Conversely, the total nitrogen and total phosphorus had a strong negative correlation to pH and EC. The total phosphorus of inflow water had similar results, but for total nitrogen, the correlation was reversed, due to the presence of an overabundance of humic substances dissolved from leaf mold.

The concentration of total nitrogen in inflow water had nearly the same value as the concentration of "nitrite nitrogen + nitrate nitrogen"; a positive correlation was seen between EC and total nitrogen. However, total nitrogen and total phosphorus in storage water and inflow water had a negative correlation with EC. The EC of both inflow and storage water had a very high correlation coefficient with chlorine ion. The alkalinity indicated the content of ingredient materials, which consumed weak acids such as carbonate and phosphoric ion and had a negative correlation with phosphorus.

We took into consideration the above relationships, used the measured values of water quality items, and estimated the values of total nitrogen and total

Table 1
Results of correlation analysis

	Storage water		Inflow water	
	Total nitrogen	Total phosphorus	Total nitrogen	Total phosphorus
Temperature	−0.020	−0.008	−0.030	0.092
Water temperature	−0.091	−0.136	−0.146	0.192
Turbidity	*0.741*	*0.682*	−0.217	*0.711*
Color	*0.749*	*0.901*	*−0.362*	*0.811*
pH	*−0.523*	*−0.635*	*0.477*	*−0.693*
Alkalinity	−0.274	*−0.463*	*0.437*	*−0.789*
EC	*−0.755*	*−0.792*	*0.416*	*−0.813*
TOC	*0.677*	*0.757*	−0.275	*0.737*
Iron	*0.846*	*0.908*	−0.173	*0.539*
Dissolved iron	*0.827*	*0.889*	−0.110	*0.458*
Manganese	0.203	0.214	−0.063	*0.670*
Dissolved manganese	*0.491*	*0.626*	−0.133	*0.544*
Chlorine ion	*−0.739*	*−0.710*	*0.353*	*−0.811*
Total hardness	*−0.753*	*−0.768*	*0.421*	*−0.824*
COD_{Mn}	*0.671*	*0.658*	−0.252	*0.709*

phosphorus. The following were used as explanatory variables: (1) periodically measured items, which had a high correlation with total nitrogen and total phosphorus and (2) continuously measured items, which can be daily and easily measured on-site such as pH, turbidity, color, alkalinity, and EC.

The TOC was the standard indicator of organic substances and had a high correlation with nitrogen and phosphorus. TOC measurements were collected from July 2004 and multiple regression analysis was performed. Eqs. (1) and (2) show an internal correlation among the explanatory variables, physical significance, and adjusted multiple correlation coefficient R^*.

《Estimated equation of total nitrogen concentration (y_n^s) in storage water》

$$y_n^s = 3.034 + 0.1872 \times Ln(x_1) - 0.5110 \times Ln(x_2) \qquad n = 45, \quad R^* = 0.903 \tag{1}$$

where x_1: turbidity, x_2: EC, and *Ln*: natural logarithm.

《Estimated equation of total phosphorus concentration (y_p^s) in storage water》

$$y_p^s = 0.0519 \times Ln(x_1) - 0.0024x_2 + 88.9556x_3^{-1} - 0.1123 \qquad n = 45, \quad R^* = 0.942 \tag{2}$$

where x_1: turbidity, x_2: alkalinity, and x_3: EC.

In the case of inflow water, as with storage water, the explanatory variables were chosen and multiple regression analysis was performed. Estimated equations are shown in Eqs. (3) and (4). However, unlike storage water, data on the quality of inflow water were not collected before this study began. Therefore, estimating prior inflow water quality was unfeasible.

《Estimated equation of total nitrogen concentration (y_n^I) in inflow water》

$$y_n^I = 9.727 \times 10^{-9} \times x_1^{8.798} \qquad n = 32, \quad R^* = 0.657 \tag{3}$$

where x_1: pH.

《Estimated equation of total phosphorus concentration (y_p^I) in inflow water》

$$y_p^I = 0.3827 + 0.0495 \times Ln(x_1) - 0.0002x_2 \qquad n = 32, \quad R^* = 0.878 \tag{4}$$

where x_1: turbidity and x_2: EC.

All of the adjusted multiple correlation coefficient R^* obtained from Eqs. (1)–(4) had more than 99% level of significance. The results for total nitrogen and total phosphorus in storage water, using Eqs. (1) and (2) are shown in Fig. 6. During the estimated period, the N/P ratio was about three. It was concluded that water weed growth was limited by lower nitrogen levels.

5. Discussion on environmental conservation

5.1. Changes in nitrogen and phosphorus

Fig. 5 shows large fluctuations in total nitrogen and total phosphorus, which are obtained from

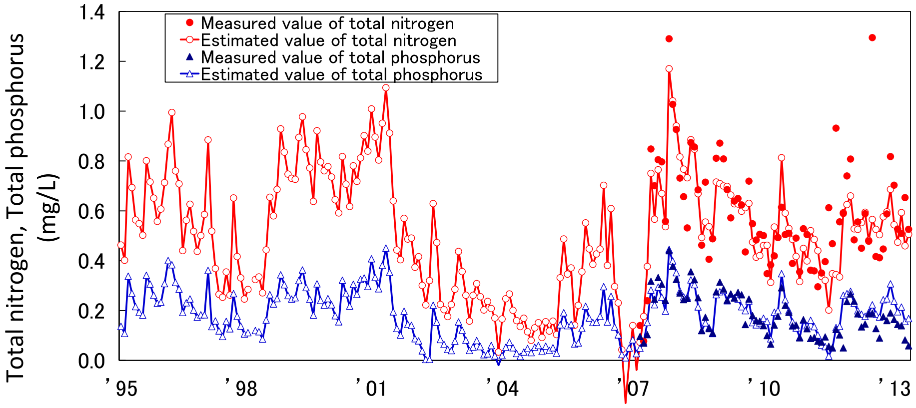

Fig. 5. Estimated value of TN and TP in storage water.

estimated equations. These are similar to actually recorded results. The average values derived from estimated equations through one year are shown in Figs. 6 and 7. The estimated values of total nitrogen in the past are nearly below the standard value for Lake Class V. Moreover, from 2002 to 2005, the estimated amount of total nitrogen fulfilled the standard for Lake Class IV, and in 2004, the amount of estimated total nitrogen was under the standard for Lake Class II. However, the estimated concentration of total phosphorus exceeded standard values for Lake Class V except for three years from 2002 to 2004. During this period, there was less than normal rainfall. This causes additional phosphorus to be absorbed in the soil and lower inflow, which decreases the amount of soil particles flowing into the dam.

After 2005, the total nitrogen and phosphorus in storage water increased due to a typhoon that triggered landslides around the basin of the dam. This caused water turbidity to increase. Fig. 8 shows the change of turbidity and chlorophyll a. In autumn 2009, again after a typhoon, high turbidity water flowed into the dam and the turbidity of storage water increased to nearly 900 units. Moreover, in autumn 2010, turbidity of storage water had an extremely high value of about 1,000 units following another typhoon. Due to these events, Figs. 3 and 4 show the extreme fluctuations in the value of total phosphorus. The fluctuation of total nitrogen is similar to total phosphorus, but the fluctuation range is narrower, demonstrating water quality improvement.

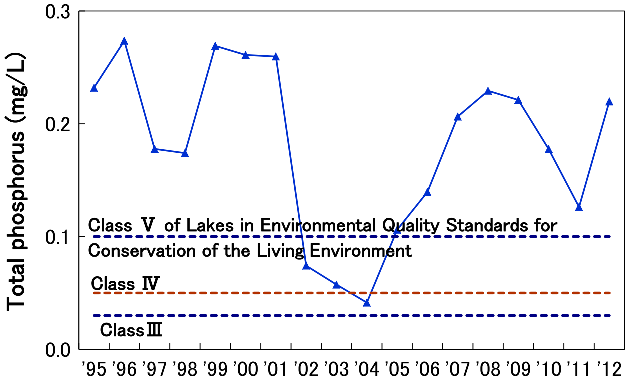

Fig. 7. Annual average for estimated value of TP.

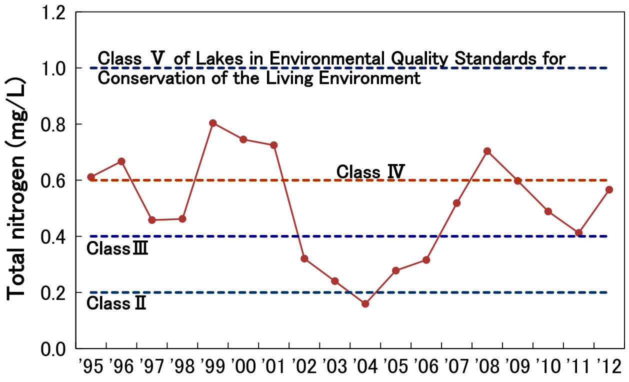

Fig. 6. Annual average for estimated value of TN.

We estimated the total nitrogen and total phosphorus for these two cases: (1) when no hydrophytic system was present and (2) when the system was set up from October 2009, with the enlarged floating plant raft and Chinese water spinach. The two cases were then compared. Although measurements were taken for total nitrogen and total phosphorus flowing into the dam, surface contamination was unknown since the volume of inflow water was unrecorded. In this case, the volume of inflow water was estimated from precipitation. The volume of inflow water and discharged water are assumed to be equal. Another assumption is that the amount of water was at its

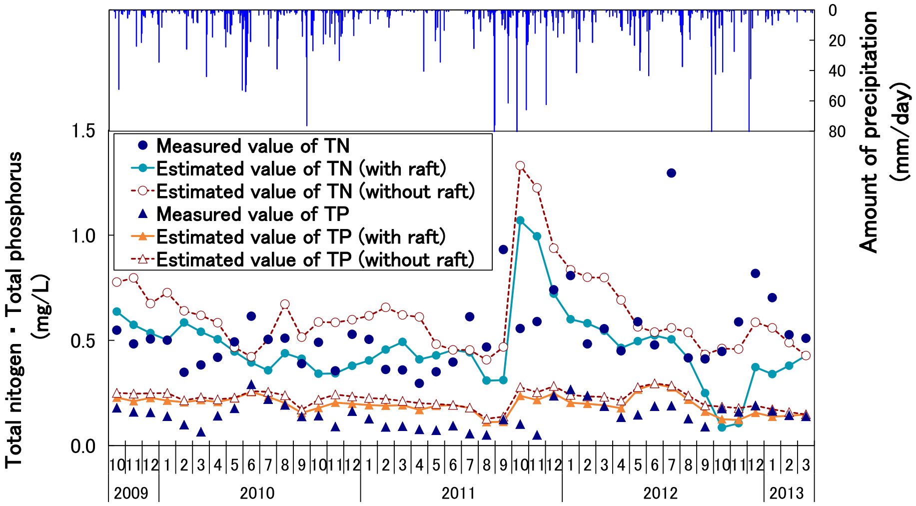

Fig. 8. Simulation results.

maximum monthly storage volume of 32,000 m^3. The hours of sunlight is unknown, therefore the amount of evaporation from the dam is omitted. The estimated equation of the total phosphorus without the hydrophytic system is shown in Eq. (5). The total nitrogen concentration is also estimated in the same way.

$$C_{pt} = \frac{C_{p(t-1)} \times V + I_{pt} \times (P_t \times 10^{-3}) \times r}{V + A_V \times (P_t \times 10 - 3) \times r + A_r \times (P_t \times 10^{-3})} \quad (5)$$

where C_{pt}: estimated total phosphorus concentration in t month; I_{pt}: measured value of total phosphorus concentration in inflow water in t month; V: quantity of storage water (32,000 m^3); A_r: water surface area of storage dam (5,520 m^2); A_V: basin area of storage dam (500,000 m^2); P_t: precipitation in t month (mm); r: precipitation ran-off coefficient (0.2).

Simulation results are shown in Fig. 8. The measured values of the concentration of total nitrogen and total phosphorus sometimes show higher values than those estimated values in the case of no hydrophytic system. This phenomenon is caused by two factors. First, heavy rains, over 50 mm/d from four to seven days before sample collection caused storage water quality to worsen. Second, the weather two days prior to water sample collection was fine and high quality water was sampled. However, from Fig. 8, it is clear that the measured values of total nitrogen and total phosphorus are lower than in the case of no hydrophytic system. For example, the average values of total nitrogen and total phosphorus with the floating plant raft in place are 0.48 and 0.16 mg/L, respectively. The estimated average values of total nitrogen and total phosphorus in the case of no hydrophytic system are 0.62 and 0.23 mg/L, respectively. Therefore, simulation results clearly show that the water quality has improved with the hydrophytic system.

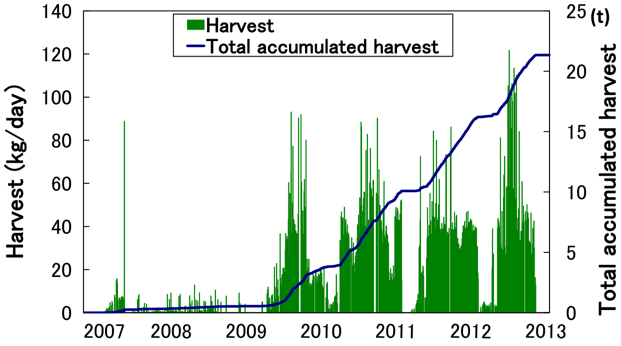

Fig. 9. Harvest of Chinese water spinach.

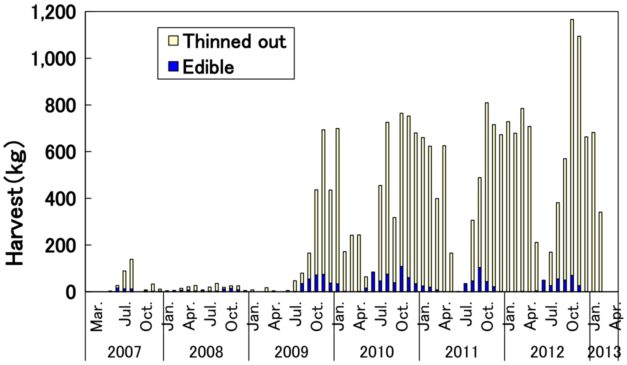

Fig. 10. Monthly harvest of Chinese water spinach.

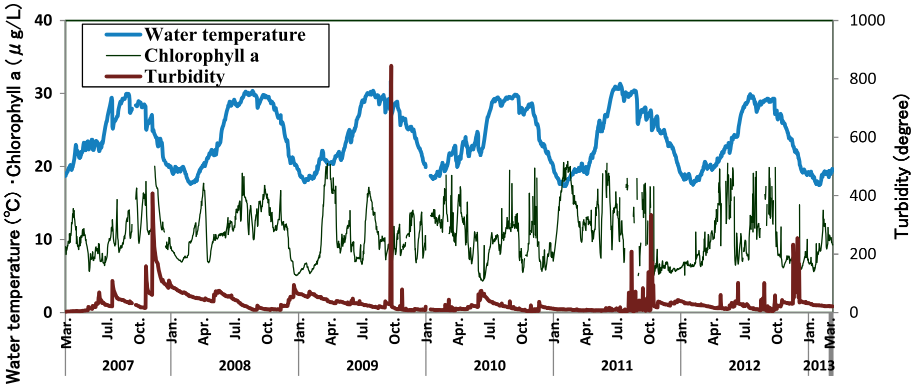

Fig. 11. Change of turbidity and chlorophyll a.

5.2. Evaluation of the floating plant raft with Chinese water spinach

Figs. 9 and 10 show the harvest of Chinese water spinach. About 21 tons of water spinach have been harvested since the hydrophytic system began. The amount of nitrogen, phosphorus, and carbon contained in the water spinach was measured [10,11]. The measurements reveal that 5.15 mg/g of nitrogen, 0.82 mg/g of phosphorus, and 53.1 mg/g of carbon were absorbed. From these values, we calculated the amount of nitrogen and phosphorus that was removed. Seven percent of the harvested water spinach was served as food, while the remainder was inedible. The total mass of nitrogen and phosphorus calculated from the gathered weight of Chinese water spinach is 110 and 17 kg, respectively.

Fig. 11 shows the level of chlorophyll a, which has been lower than 20 μg/L since March 2007, when the hydrophytic system was introduced. Since an accepted criterion for the generation of water blooms is about 100 μg/L, it was predicted there would be no water blooms during the measurement period. The hydrophytic system has been quite effective in ending water blooms at the dam.

The cultivation of Chinese water spinach was expanded by a factor of 40 in March 2009. Fig. 9 shows the harvest rapidly increasing. Harvesting was carried out daily, especially during summer. At its peak, 100 kg/d was harvested, consequently increasing labor costs. In the future, not only Chinese water spinach, but other high value plants, such as paddy rice, Okinawan spinach, and basil should be considered for cultivation [12] to offset labor costs.

6. Conclusions

Aquatic plants were introduced to improve the water quality of Chibusa Dam, which annually experienced water blooms. In this paper, the effect of establishing a hydrophytic system is evaluated and discussed. Where past total nitrogen and total phosphorus data were not available, a multiple regression analysis was carried out using selected water quality items as explanatory variables. From these equations, highly accurate estimates are obtained for total nitrogen and phosphorus after 1995. Since estimated equations are also derived for inflow water, the equations are available not only for reverse estimation of past data, but also for understanding the concentration of total nitrogen and total phosphorus using easily measured daily water quality items on-site in real time. Moreover, readily obtainable measuring instruments can be used to gather data, which are usually present at small-scale water services and developing countries where state-of-the-art instruments may be limited.

One remarkable result from this study is that no water blooms have occurred since the hydrophytic system has been set up. This method to improve water quality is quite suitable for many remote areas, such as Haha-jima Island, where electricity may be limited and herbicides cannot be used. The harvest of plants requires considerable labor, so a variety of plants should be considered to decrease maintenance and labor costs.

Topics for future research include the effect of precipitation on reservoir water, location of the floating plant raft, and the selection of plants suitable for the conditions on Haha-jima Island.

References

[1] K. Yamazaki, Studies on Improvement of Water Quality for Agricultural Water in Ogasawara Islands, Research Report, Research Programme by Bureau of Industry and Labor affairs Tokyo Metropolitan Government, 2005 (in Japanese).

[2] Ministry of the Environment, Government of Japan, Environmental Quality Standard, 2009.

[3] W. Agata, S. Son, 2002 Water Surface Utilization for Plant Production Improvement of Landscape, Soft Science Co., 2007 (in Japanese).

[4] T. Hashimoto, H. Izawa, T. Okamoto, M. Mizuta, Development of water quality purification system by flowerpot planting and activities of water purification using this system in Hiroshima Prefecture, the health and environment centre of Hiroshima Prefecture, Environ. Technol. 27(8) (1998) 13–19 (in Japanese).

[5] S.J. Chung, H.K. Ahn, J.M. Oh, I.S. Choi, S.H. Chun, Y.K. Choung, I.S. Song, K.H. Hyun, Comparative analysis on reduction of agricultural non-point pollution by riparian buffer strips in the Paldang Watershed, Korea, Desalin. Water Treat. 16 (2010) 411–426.

[6] L.L. Osborne, D.A. Kovacic, Riparian vegetated buffer strips in water-quality restoration and stream management, Freshwater Biol. 29 (1993) 243–258.

[7] A. Endut, A. Jusoh, N. Ali, W.N.S. Wan Nik, A. Hassan, Effect of flow rate on water quality parameters and plant growth of water spinach (Ipomoea aquatica) in an aquaponic recirculating system, Desalin. Water Treat. 5 (2009) 19–28.

[8] NPO Corporation, Urban Environment Research Association, River Water Purification Project by Hydroponics, Final Report 14 (2005) (in Japanese).

[9] Y. Shimatani, M. Hosomi, K. Nakamura, Water Purification of Rivers and Lakes by Technology, Soft Science Co., 2003, 117–122 (in Japanese).

[10] K. Yamazaki, A. Koizumi, Y. Otsuka, H. Otsuka, Experimental study on water purification in Haha island, Ogasawara, Ogasawara Study Annual Report 31 (2003) 657–675 (in Japanese).

[11] K. Yamazaki, A. Koizumi, Y. Otsuka, Water quality conservation for water supply by plant raft, J. Water Waste Water 50(11) (2008) 57–64 (in Japanese).

[12] S. Yanai, K. Yamazaki, A. Koizumi, B.D. Min, M. Komine, H. Otsuka, One consideration on comparative experiment using plant for the aim of water quality purification, Proceeding of the 61th Workshop, Japan Water Works Association, 2010, pp. 138–139 (in Japanese).