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Construction of a treated wastewater reuse system for renewal of a water cycle mechanism in urban areas — modeling analysis of reclamation treatment processes corresponding to target water quality by use

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ABSTRACT

Regarding the target water quality for reuse, it is important to pay attention to the COD taking into account countermeasures against pathogens and trace matters in public waters. The main types of secondary wastewater treatment used until now were conventional activated sludge processes. More recently, however, advance wastewater treatment processes have also been developed aiming at the removal of nitrogen and phosphorus, and so on, and an analysis of the water quality characteristics of treated wastewater obtained using these processes was carried out. In addition, reclamation treatment processes that meet the target water quality for each application were selected and also their design parameters were studied as well as a cost analysis based on those results. It was found that the treatment cost was greatly affected by the COD of treated wastewater, which is a given condition. Thus, the key to a biological reaction treatment system is the attainment of treated wastewater containing as low a concentration of COD as possible.

Keywords: Treated wastewater reuse system; COD; Ozonation

1. The changing water environment and reuse of treated wastewater

Japan has seen rapid growth in recent years, and urban areas and housing land have increased rapidly. As a result, forest and farming land has decreased, and also the impervious area has increased. Along with the progress of this urbanization, rainfall infiltration and water-bearing capacity have fallen, making it difficult to secure sound water cycle. As a result of the reduction in water and wooded area accompanying urbanization, the degree of pleasantness and comfort in urban living has fallen. In response to this situation, people living in urban areas are changing their awareness, and are coming to demand a pleasant and graceful amenity rather than the creation of cities and towns that are simply convenient and functional. The development of human lifestyle and social activities exceeds the frame of the natural water cycle mechanism, and in order to guarantee sustainable development it is necessary to construct a social system based on "cycle" which has little environmental impact.

The reuse of treated wastewater in Japan was started in earnest in Fukuoka City which experienced a major drought in 1978. However, the amount of treated wastewater that was reused externally was only 590,000 m^3/d [1], so it must be admitted that the reuse of treated

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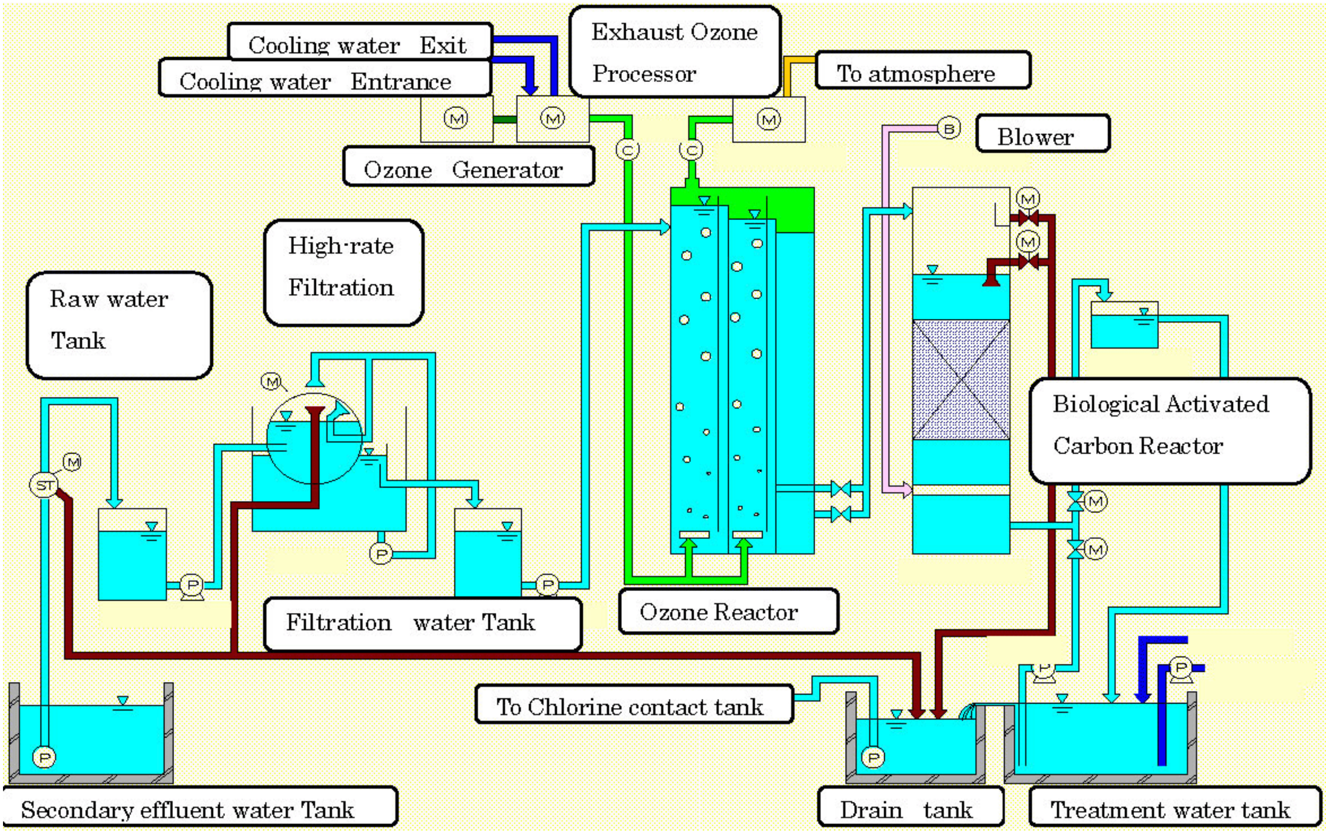

Fig. 1. Reclamation treatment plant flow in M City.

wastewater in a form of circulating water in urban areas is still very much in its infancy. Factors that work against the promotion of the reuse of treated wastewater include securing safety and functionality of treated wastewater, and pursuing economical efficiency. These are issues which must be solved in the future.

On the other hand, as a result of the implementation of regulations concerning the total amount of nitrogen and phosphorous in closed water bodies such as the Seto Inland Sea, the amendment to the enforcement ordinance of the Sewerage Law, and so on, the adoption of full-fledged advanced treatment is now being promoted throughout Japan.

This paper, in response to such situation, summarizes the recent situation concerning the reuse of treated wastewater, the merits developing systems to reuse treated wastewater through advanced treatment, and the future direction of the reuse of treated wastewater, as follows:

(1) Illuminating the characteristics of each reclamation treatment process based on the results of demonstration runs in M city (Fig. 1).

(2) Analyzing the operational parameters of reclamation treatment processes for achieving the target water quality.

(3) Cost analysis.

2. Recent situation concerning reuse of treated wastewater

2.1. Situation concerning the external reuse of treated wastewater

The amount of treated wastewater at 1,118 wastewater treatment plants in Japan in fiscal 2003 reached 13.7 billion m^3/year. At the majority of wastewater treatment plants, treated wastewater is internally reused as anti-foaming water and washing water.

Treated wastewater is externally reused at 156 treatment plants. The reused amount of treated wastewater is 254 million m^3/year, which is about 1.9% of the total amount of treated wastewater. The various external applications include toilet flushing water, industrial water, agricultural water, and water for recreational and landscape use. Reclamation treatment processes used are also varied.

Fig. 2 shows the situation concerning external reuse of treated wastewater for each application. It can be seen that the greatest application is for snow melting water on a quantity basis, and for industrial water on the basis of number of instances. Compared to fiscal 1995, there has been a significant increase in the amount of snow melting water, and also water for recreational and landscape use.

Table 1
Revised water quality standards

	Toilet flushing	Spraying	Landscape	Recreational
Escherichia coli	Not detectable	Not detectable	1000 CFU/100mL	Not detectable
Turbidity	2 degrees max	2 degrees max	2 degrees max	2 degrees max
pH	5.8–8.6	5.8–8.6	5.8–8.6	5.8–8.6
Appearance	Must not be unpleasant	Must not be unpleasant	Must not be unpleasant	Must not be unpleasant
Color	—	—	40 degrees max	10 degrees max
Odor	Must not be unpleasant	Must not be unpleasant	Must not be unpleasant	Must not be unpleasant
Residual chlorine	1[a]	1[a]	Not stipulated	1[a]

[a]Free residual chlorine: 0.1 mg/L or combined residual chlorine: 0.4 mg/L min.

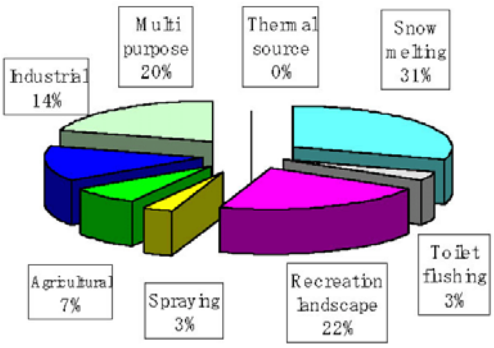

Fig. 2. Situation concerning external reuse.

2.2. *Manual of water quality standards for the reuse of treated wastewater*

In order to promote the appropriate reuse of treated waste-water, the Sewerage and Wastewater Management Department of the Ministry of Land, Infrastructure and Transport revised the previous water quality standards, target water quality, and so on, for the reuse of treated wastewater, in a Manual of Water Quality Standards for the Reuse of Treated Wastewater [2]. Table 1 shows the revised water quality standards. Because of these changes, when designing a reclamation treatment process, it is absolutely necessary to install a turbidity removal facility such as sand filters and a chlorination facility.

3. Reclamation treatment process for attaining the target water quality

It goes without saying that when treated wastewater is reused in various ways such as toilet flushing water, the cost of construction, and O&M for a reclamation treatment facility and the water transmission and distribution facilities must be kept as low as possible. Great attention must be given to the advanced or tertiary wastewater treatment processes, as a mean to upgrade the effluent to water suitable for reuse [3].

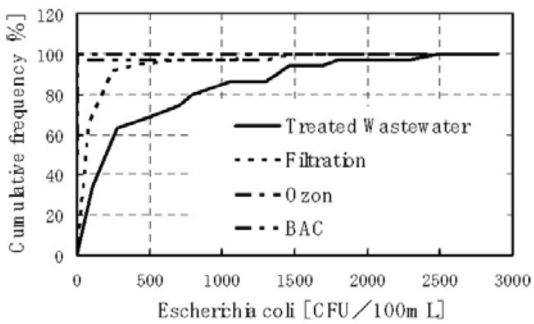

Fig. 3. Change in the number of coliform groups.

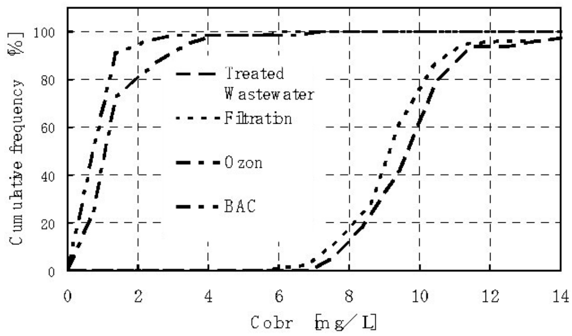

Fig. 4. Chromaticity due to treatment process.

According to the revised water quality standards, the most stringent standards are those for recreational water. This is because it is assumed that the human body will come into direct contact with reclaimed water through immersion of the hands or feet.

Figs. 3 and 4, obtained from reclamation treatment runs conducted in M city, show the change in the number of coliform groups when filtration, ozonation, and biological activated carbon (BAC) treatment are carried out on secondary treated wastewater by conventional activated sludge processes.

Looking at these results, it can be seen that while the number of coliform groups resulting from filtration has roughly attained the standard of 1000 CFU/100 mL for

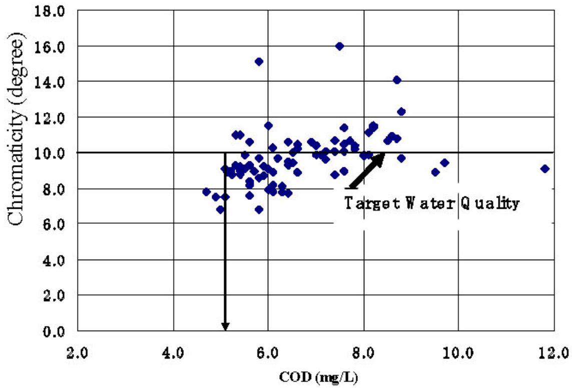

Fig. 5. Correlation between COD and chromaticity (filtered water).

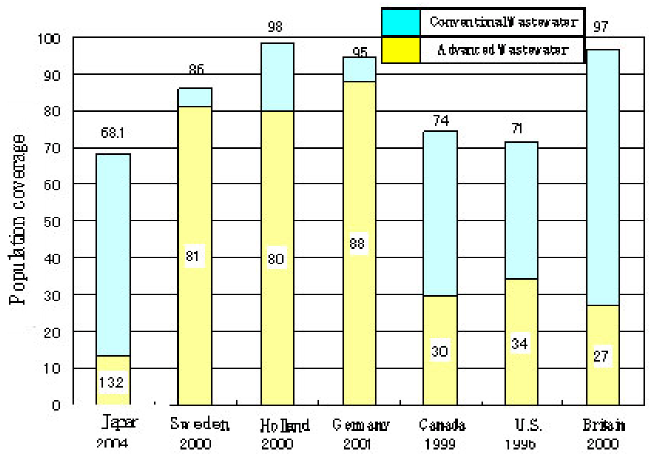

Fig. 6. Situation concerning advanced wastewater treatment in various countries.

water for landscape use, it fails to reach the not detectable level in the standards for other applications, but attain the not detectable level after ozonation.

The water quality standard of chromaticity of water for recreational use is 10 degrees. The figure for secondary treated wastewater cannot meet 10 degrees, but the standard can be completely cleared by means of ozonation.

Also, from the relationship with the chromaticity of filtered treated wastewater, it can be said that the chromaticity falls along with the COD, and that removal of the COD component is effective for controlling the chromaticity (Fig. 5). In addition, it is anticipated that the quantity of pathogenic microorganisms and also toxic organic trace matters will decrease along with the COD removal. From these facts, it can be concluded that it is necessary to set the COD around 4 mg/L or 5 mg/L.

Based on the foregoing, the basis of reclamation treatment to meet the standards for water for recreational use is as follows.

↓ Coagulant

Treated wastewater → Filtration → Ozonation

→ Biological activated carbon treatment

→ (chlorination) →water supply

It is necessary to install BAC facilities in order to minimize the increase in BOD and O&M costs due to the increase in the ozone dosing rate.

4. Promotion of reuse of treated water by beans of advanced wastewater treatment

As shown in Fig. 6, the population coverage by advanced wastewater treatment in Japan is very low—about 12% [3] compared to those in other advanced countries. In order to rectify this situation, the Ministry of Land, Infrastructure and Transport intend to amend the enforcement ordinance of the Sewerage Law and also the Sewerage Law itself to permit the full-fledged promotion of advanced wastewater treatment. The adoption of advanced wastewater treatment is expected to significantly raise the level of the quality of secondary treated wastewater compared to that realized by the conventional activated sludge processes.

Comparing the nationwide COD cumulative frequency distribution of secondary treated wastewater by the conventional activated sludge processes to that for effluent from advanced treatment shown in Fig. 7, it can be seen that the COD level after advanced treatment has improved and remains below 10 mg/L.

5. COD treatment characteristics in a reclamation treatment process, and cost analysis

As mentioned above, reclamation treatment processes consist mainly of filtration, ozonation and BAC processes. The relationship between the quantity of COD removed at each treatment process and the quality of treated wastewater for reclamation and the target water quality is shown in the following equation.

$$S = F + O + B + C \quad (1)$$

where S is the COD in treated wastewater for reclamation, F the quantity of COD removed by filtration, O the quantity of COD removed by ozonation, B the quantity of COD removed by BAC, and C is the COD in treated wastewater after biological activated carbon treatment.

The quantity of COD removed by filtration conforms to the following equation, based on the above-mentioned run results.

$$F = S \times (1 - 0.9) \quad (2)$$

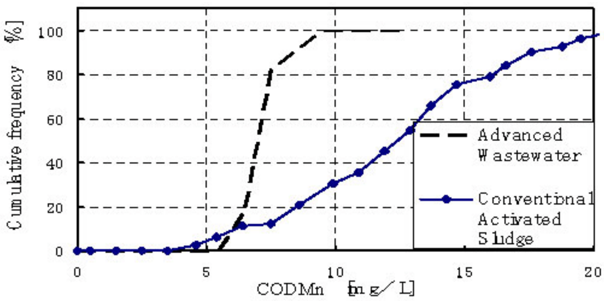

Fig. 7. Comparison of the nationwide COD cumulative frequency distribution of treated wastewater.

where F is the quantity of COD removed by filtration [mg/L] and S the COD in treated wastewater for reclamation [mg/L].

Based on the results of ozonation carried out on filtered treated wastewater, the quantity of COD removed by ozonation can be determined by the following equation (Fig. 7):

$$O = 0.119\,X + 1.04 \tag{3}$$

where O is the quantity of COD removed by ozonation and X the quantity of effective ozone [mg/L].

Thus, the quantity of COD removed by ozonation is slightly less than 20% of the quantity of effective ozone used, which means that the quantity of effective ozone required is about five times the quantity of COD to be removed (Fig. 8).

The relationship between the cumulative COD loading and the efficiency of COD removal by BAC treatment is determined by the following equation (Fig. 9):

$$L = 1.34\,[1 - N/100)\,100/(1.34 + 0.0321\,M(1 - N/100)]^2 + N \tag{4}$$

where L is the efficiency of COD removal [%], M the cumulative loading [kg-COD/m^3-AC], and N the final efficiency of COD removal [%], assumed to be fixed at 25%.

Also, the relationship between the quantity of COD removed by BAC treatment and the efficiency of COD removal is determined by the following equation:

$$B = L/100^* \,(S - F - O) \tag{5}$$

where B is the quantity of COD removed by BAC treatment [mg/L], and L the efficiency of COD removal by BAC treatment [%].

The function of the water-passing rate and the COD in treated wastewater for reclamation is used to obtain the cumulative loading, as shown in the following equation:

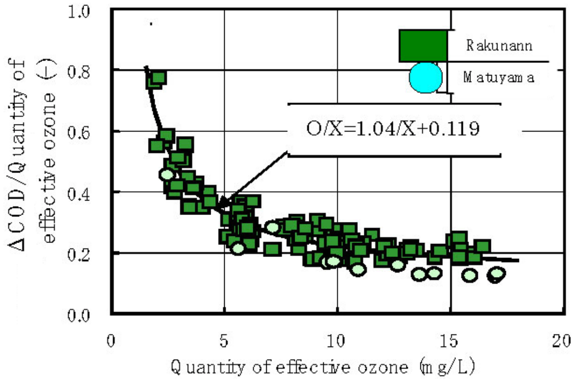

Fig. 8. Comparison of the quantities of effective ozone consumed and COD removed.

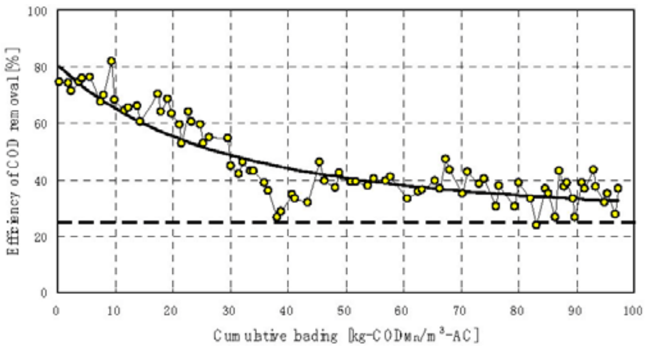

Fig. 9. Relationship between the cumulative COD loading and the efficiency of COD removal.

$$M = CV\,[0.9\,S - (0.119 \times X + 1.04)]/1000 \tag{6}$$

where CV is the water-passing rate [m^3/m^3-AC], M the cumulative loading [kg-COD/m^3-AC], S the COD of treated wastewater for reclamation [mg/L], and X the quantity of effective ozone [mg/L].

The water-passing rate is determined by the following equation:

$$CV = LT \times 365 \times 24 \times SV \tag{7}$$

where LT is the replacement cycle of activated carbon [years], assumed to be not more than 3 years; and SV is the water-passing velocity [1/h], assumed to be 3.

Equations and values are inserted into Eq. (1), and the COD of treated wastewater for reclamation is calculated as a variable. When the concentration of effective ozone = 10 mg/L, the activated carbon replacement cycle = 3 years and SV = 3 h^{-1}, the concentration of COD in treated wastewater for reclamation that enables a COD after biological activated carbon treatment of less than 4 mg/L to be attained will be 9.1 mg/L.

The treatment costs (running costs) required for ozonation and activated carbon treatment were reckoned, and their characteristics were analyzed.

The conditions used for reckoning the treatment costs are as follows:

- Quantity of electricity per generated ozone: 15 kWh/kg-O_3
- Unit cost of electricity: 20 yen/kWh
- Unit cost of ozone: 300 yen/kg-O_3
- Unit cost of activated carbon: 300,000 yen/m^3-AC

Fig. 10 shows the relationship between the effective ozone and the treatment cost for attaining the target water quality of 4 mg/L when the COD concentration in treated wastewater for reclamation is 10 mg/L. From this, the following can be deduced.

The treatment cost of activated carbon is higher than that of ozonation. Consequently, the total treatment cost is a minimum when the quantity of effective ozone used corresponds to the case where the activated carbon has reached the end of its life. Therefore, the longer the life of the activated carbon, the lower the total treatment cost.

It is predicted that if an attempt is made to keep the COD at a value of no more than 4 mg/L by means of filtration, ozonation, and BAC treatment, the required quantity of effective ozone when advanced treatment is used will be about 1/2.5 that of secondary treated wastewater, and the facility and electricity costs will be greatly reduced, as shown in Fig. 11.

Thus, because the cost of ozone and activated carbon treatments is greatly affected by the COD concentration in secondary treated wastewater, which is a given condition, it is important to generate treated wastewater for reclamation of which the COD concentration is as low as possible in the biological reaction treatment system.

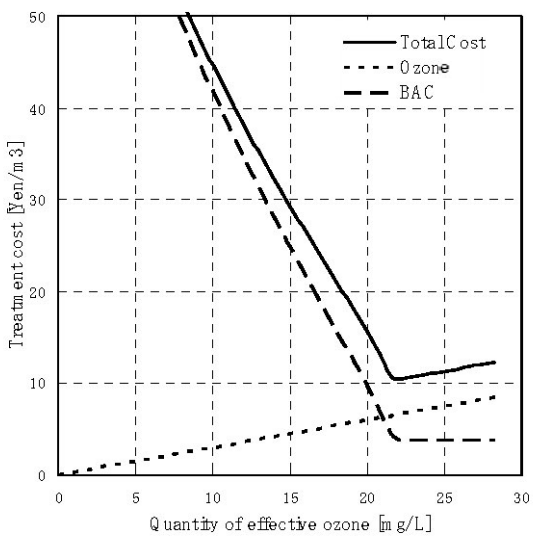

Fig. 10. Relationship between the quantity of effective ozone and treatment cost.

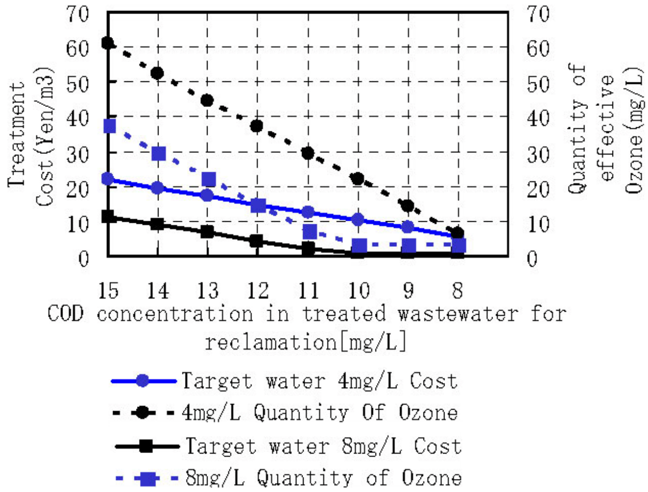

Fig. 11. Relationship between the COD of recycled raw water and treatment cost.

Also, it is considered that the cost of electricity required for air supply in the nitrification-denitrification process is only about 10 yen/m^3 (assumed to be twice the figure of 0.25 kwh/m^3 × 20 yen required for air supply in the conventional activated sludge processes). For this reason, it is predicted that adequate cost benefit can be obtained even when the target COD water quality is attained using the nitrification-denitrification process instead of the conventional activated sludge processes.

6. Conclusions

The findings gained through this research are as follows:

1. Regarding the target water quality for reuse, it is important to pay attention to the COD, taking into consideration measures against pathogenic microorganisms and trace matters.

2. The treatment process was filtration → ozonation → biological activated carbon, based on the assumption of nitrification during secondary treatment.

3. Compared to the conventional activated sludge processes, the nitrification–denitrification process significantly reduces the concentration of COD in treated wastewater.

4. As a result of reclamation treatment demonstration run, it was found that the efficiency of COD removal in the filtration process is about 10%. The quantity of COD removed by ozonation is slightly less than 20% of the quantity of effective ozone. This means that the quantity of effective ozone required is about five times the quantity of COD to be removed. The efficiency of COD removal by BAC treatment depends upon the cumulative COD

loading which flows into the biological activated carbon treatment process. The final efficiency of COD removal is 25%.

5. Based on the above results, the relationship between the quantity of COD removed at each treatment process and the target water quality and treated wastewater for reclamation was quantified. As a result, the relationship between the concentration of COD in treated wastewater for reclamation that enables a COD after advanced treatment of less than 4 mg/L to be attained and the quantity of effective ozone consumed was clarified.

6. The treatment costs (running costs) needed for ozonation and activated carbon treatment were calculated, and as a result of obtaining a grasp of their characteristics, it was found that these costs were greatly affected by the concentration of COD in treated wastewater for reclamation. Consequently, the key is to reduce the concentration of COD in secondary treated wastewater as low as possible in the biological reaction treatment system.

The earth that we live on is also called the "planet of water". All living organisms including mankind need water to exist. The water on the earth is not limitless, and in order to maintain a sustainable society and environment, we must effectively utilize and protect the water, air, soil and resources on the earth.

To this end, it is important to construct a circulatory social system that matches the situation and characteristics of each country and region, and we intend to continue working toward this end.

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