Practical Paper

Economic evaluation of combined treatment for sludge from drinking water and sewage treatment plants in Japan

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ABSTRACT

In Japan, water supply utilities need to renovate their sludge treatment facilities. This study therefore evaluated treatment of the sludge from drinking water treatment plants (DWTP) by two approaches: an individual system and a combined system. In the individual treatment scenario, the DWTP treats the sludge using its own facilities, whereas in the combined treatment scenario, DWTP sludge is transported to a sewerage system. The construction cost is much lower for combined treatment than individual treatment, while the operation cost is higher for combined treatment owing to the sewer charge. However, the additional sewer charge is less than the increase in cost for constructing an individual sludge treatment system. With the combined treatment system, sludge must be transported from the DWTP to a sewage sludge treatment plant (SSTP). A cost analysis reveals that sludge transportation by road is less beneficial than by pipeline in the sewerage system unless the plants are nearby. In economic terms, combined treatment and a sludge liquor pipeline is the most advantageous of all cases. The total cost depends on the given conditions and assumed unit costs. Sensitive parameters are the sewer charge and the distance between the DWTP and sewer pipeline.

Key words | cost analysis, drinking water treatment, sewage works, sewer charge, sludge treatment, turbidity

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INTRODUCTION

In 1971, the Water Pollution Control Law (WPCL) was enacted to control the effluent discharge from specified facilities to public water bodies in Japan. Before the law was enacted, such discharge from drinking water treatment plants (DWTPs) was entirely unregulated. However, large-scale DWTPs were required to comply with the WPCL and so had to install new effluent and sludge treatment facilities. Those early sludge treatment facilities have now been used for more than 30 years and require renovation.

During Japan's period of rapid economic development, many DWTPs were constructed, but they have now become old. The renovation and reconstruction of such facilities is an issue of great concern. Indeed, the Ministry of Health, Labour and Welfare recently released its 'Water Supply Works Vision', pointing out that water supply utilities are entering a period of renovation. During this process, the basic policy is to recycle sludge to reduce environmental impact. Sewage sludge treatment plants (SSTPs) are also

working to enhance the recycling and utilization of sewage sludge as well as reduce the amount.

Figure 1 shows the cumulative frequency of annual average turbidity in raw water for different years. The median turbidity increased from 6 degrees in 1950 to 10 degrees in 1970. During this period, many treatment plants were designed and constructed based on the high turbidity prevailing at the time. Since then, the turbidity has decreased, falling below 5 degrees in 2002. Considering Japan's high dependency on surface water as a water resource, raw water with low turbidity has recently been used in many treatment plants. The turbidity in rivers has decreased because of the construction of dams to develop new water resources to meet the rapidly increasing water demand. In addition, the number of DWTPs taking raw water from reservoirs has increased and, owing to the resulting lower turbidity, DWTPs are expected to produce less sludge than before. Therefore, when renovating sludge treatment facilities originally designed in the 1970s, it is better to develop realistic scenarios to manage sludge production from DWTPs considering the current trend in turbidity and other circumstances.

Recently, it has been suggested that water supply plants and sewage works should cooperate with each other in municipalities. Combined treatment of sludge from both DWTPs and SSTPs is one good field of cooperation. There are two examples in Japan. In Yokohama, sludge effluent is discharged to a sludge pipe which was originally designed for transportation of sewage sludge liquor from a wastewater treatment plant to a SSTP. The other is in Kyoto, where sludge effluent is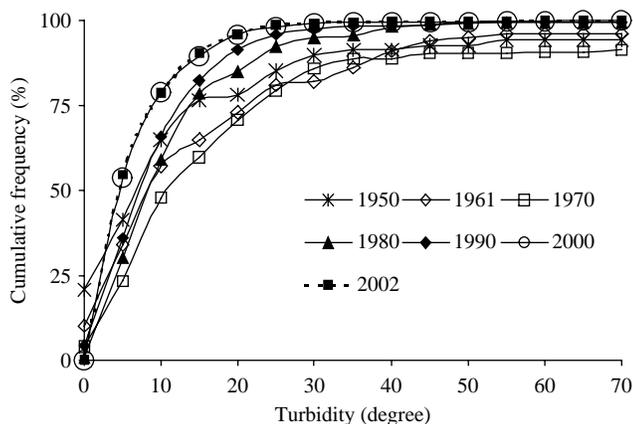 directly discharged to a sewer pipe. In this study, we investigated the effectiveness of discharging DWTP sludge effluent to the sewerage system, focusing on the economic aspect. We examined the applicability and feasibility of combined sludge treatment in sewage sludge treatment plants, and compared it with individual treatment.

For the examination, it would be desirable to consider a secondary effect of combined sludge treatment and environmental impact besides economic efficiency. It is known that there is a secondary effect where the adsorption rate of PO_4, Mn and Cd to biological sludge increases, and the dewatering rate and thickening rate of the sludge improve (Toyoshima *et al.* 1988). In this study, we mainly focused on a sensitivity analysis on several key parameters such as sewer charge in the combined treatment scenario, to develop economic criteria for judging whether to introduce the system.

STUDY METHODS

Sludge treatment options for economic evaluation

The economic evaluation is conducted for the six cases shown in Figure 2. The total cost of sludge treatment, including facility construction and operation, is determined and compared. It is assumed that a drinking water treatment plant treats $50,000 \, m^3$/day of river water with turbidity of 10 degrees (suspended solids of approximately $14 \, mg \, l^{-1}$) using an average dosage of polyaluminium chloride (PAC) of $15 \, mg \, l^{-1}$, and produces $0.815 \, t$/day of wet sludge with 65% water content. The sludge treatment system for DWTPs was classified into two scenarios: individual treatment and combined treatment.

Individual treatment scenario

The sludge treatment process of a DWTP consists of a settling and filtration tank, a drain tank, a sludge settling tank, a thickener tank, a storage tank, a filter press and a cake hopper in Case 1. When estimating the cost, it is assumed that the sludge treatment facility is newly constructed and the retention time of dewatered sludge cake is approximately 5 days. Two sub-categories were further considered according to the process of disposing of sludge cake: either the DWTP treats the sludge using its own facilities for disposal (Case 1-1), or recycles the treated sludge (Case 1-2) as a construction material and soil conditioner.

Figure 1 │ Cumulative frequency of annual average turbidity in raw water.
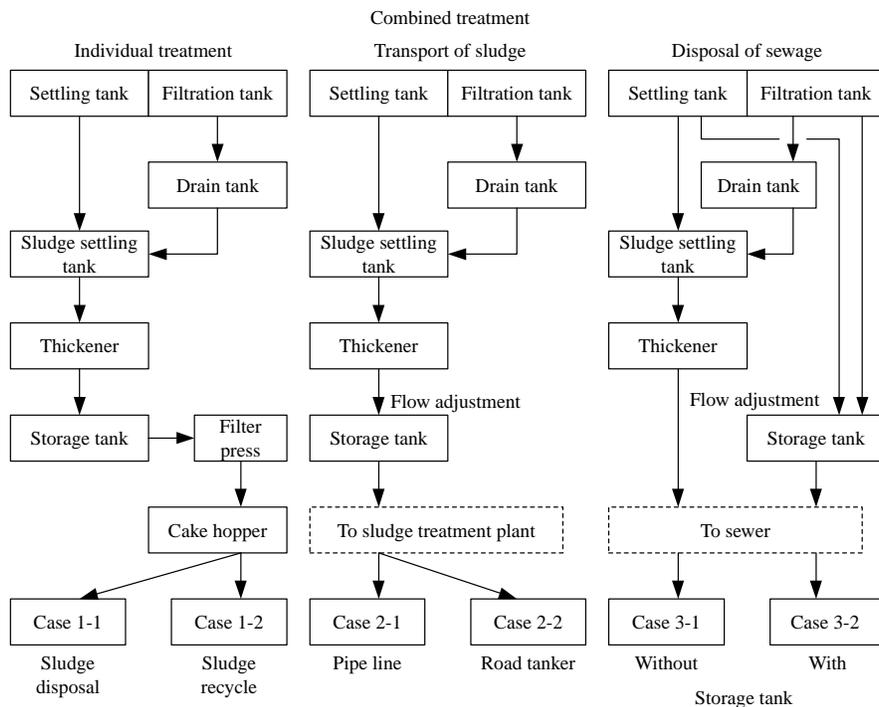
Figure 2 │ Six cases of sludge treatment system.

Combined treatment scenario

There are two methods of discharging sludge to the sewerage system from DWTPs: sludge transportation to SSTPs (Case 2) and sludge discharge to a sewer pipeline (Case 3). In Case 2, the sludge treatment process consists of a settling and filtration tank, a drain tank, a sludge settling tank, a thickener tank, and a storage tank with flow adjustment. Case 2-1 assumes direct disposal into the sludge liquor pipe to the SSTPs via a newly constructed pipe from the DWTP. Case 2-2 assumes that DWTP sludge is transported to the SSTP by road tanker. In the case of combined treatment, the storage tank capacity is designed for 24 hours mixing to adjust the flow rate and the sludge concentration, while mixing is not required in the individual treatment scenario.

In Case 3-1, the sludge treatment process consists of a settling and filtration tank, a drain tank, a sludge settling tank, and a thickener tank. In Case 3-2, only the settling, filtration and storage tanks with flow adjustment are used in the sludge treatment process. Cases 3-1 and 3-2 assume flow-controlled discharge of sludge effluent and direct discharge of sludge effluent without flow and concentration adjustment, respectively.

When examining the combined treatment scenario, it is assumed that the DWTP is located 1 km away from the sewer pipeline or sludge liquor transport pipe, and 30 km away from sewage sludge treatment plants. As well as geographical conditions, there are several other issues such as the maintenance of sewer pipes, sludge pipelines, fluctuations in sludge concentration and some rules governing discharge. In the case of processing sewage sludge into bricks, the change in chemical composition of the sewage sludge due to mixing with waterworks sludge will change the quality of commercial bricks (Anderson *et al.* 2002). In the cost analysis, it is assumed that these issues can be overcome by cooperation between the water supply and sewerage utilities.

RESULTS AND DISCUSSION

Cost comparison of individual and combined sludge treatment systems

Table 1 shows the total cost of treating DWTP sludge by individual treatment and by combined treatment with sewage sludge, including construction and operation and

Table 1 | Total cost of construction and operation & maintenance for 20 years

Cost items (× JPY million)	Case 1-1 Individual treatment Sludge disposal	Case 1-2 Sludge recycle	Case 2-1 Combined treatment Transport of sludge Pipeline	Case 2-2 Road tanker	Case 3-1 Discharge to sewer of sludge Without storage tank	Case 3-2 With storage tank
Construction cost	2,041	2,041	948	852	586	550
Operation cost						
Electric power	80	80	72	68	78	22
Filter press	38	38	–	–	–	–
Disposal	170	–	–	–	–	–
Transport	–	–	–	759	–	–
Sewer charge	–	–	JPY100,000/DS		Base charge + JPY16/m^3 + quality charge	
			595	595	1,505	1,505
Labour costs	200	200	80	80	20	20
Products (cake)	–	JPY10/kg-DS − 60	–	–	–	–
Total cost	2,529	2,299	1,695	2,354	2,189	2,097
Each case/case 1-1(%)	100	91	67	93	87	83

maintenance (O&M) costs. The O&M cost was estimated based on an operation period of 20 years.

For Cases 1-1 and 1-2 of individual treatment, the complete construction of the new sludge treatment facilities costs JPY2,041 million (Japanese yen = US\$20.57 million (JPY/US\$ = 99.21 November 10, 2008)). For combined treatment, a storage tank with flow adjustment and other necessary facilities are installed, and the construction cost is much lower than the individual treatment scenario. The difference between Cases 2-1 and 2-2 arises from the construction of the 1-km discharging pipeline from the DWTP to the sludge liquor transport pipe in Case 2-1. The O&M costs of individual and combined treatments were divided into seven categories: electric power cost, O&M cost of filter press, disposal cost, transportation cost, sewer charge, labour cost and revenue from sludge cake. The electric power costs are similar except for Case 3-2 which has fewer pumps, because electric power is mainly required for the pumping process and the total number of pumps is the same except in Case 3-2. The operation and maintenance cost of the filter press was required only in individual treatment Case 1-1 and 1-2. The disposal cost of dewatered sludge cake of JPY170 million was necessary for Case 1-1, while the transportation cost by tanker and

sewer charge are required for the combined treatment cases only.

Yokohama city has already introduced a combined treatment system like Case 2-1, in which the unit sewer charge of JPY100,000/t-DS is incurred for sludge treatment and processing (Matsumoto 2002; Matsumoto *et al.* 2003). When the unit value is applied, the sewer charge in both Cases 2-1 and 2-2 is estimated to be JPY595 million for 20 years. While Case 2-1 has a higher construction cost owing to the newly constructed pipe from the DWTP, Case 2-2 has a higher cost for transporting sludge by road tanker from the DWTP to the SSTP.

Kyoto City used the following equation to determine the sewer charge for discharging sludge from DWTP to the sewer pipeline (JWWA 2000):

$$Sewer\,charge = Base\,charge + Volume\,charge$$
$$+ Quality\,charge$$
$$= JPY350\,for\,10\,m^3 + JPY16\,m^{-3}$$
$$\times volume\,more\,than\,10\,m^3$$
$$+ Quality\,rate\,m^{-3} \times volume$$

We used this equation to determine the sewer charge of combined treatment with discharge to the sewer pipe.

Case 3-1 assumes controlled discharge of sludge effluent into the sewer pipe, while Case 3-2 assumes direct discharge of sludge effluent without flow and concentration adjustment. The sewer charge was estimated to be JPY1,505 million for 20 years.

A comparison of the total costs of the individual treatment and combined treatment cases are shown in Figure 3, in which the ratio of cost to that of Case 1-1 as a reference is shown. It is clear that the total cost is much lower in all cases of combined treatment than the reference case (Case 1-1) of individual treatment. The highest cost among the combined treatment cases, in Case 2-2, arises from the use of fuel for sludge transportation by road tanker. It is also important to note that transportation by road emits more CO_2 than transportation by pipeline. The difference in cost between Cases 3-1 and 3-2 is due to the cost of constructing the storage tank for flow adjustment. The costs in Cases 3-1 and 3-2 are higher than in Case 2-1 mainly because of the high sewer charge. The total cost of Case 2-1 (67% of the total cost of individual treatment of Case 1-1 as a reference) was the lowest, followed by Case 3-2 (83%), Case 3-1 (87%), and Case 2-2 (93%).

The sewer charge of DWTP sludge for combined treatment was much lower than the additional construction cost for individual treatment. As a result of the construction of the dewatering facility and cake hopper and its associated labour cost, the individual treatment system is more costly than the combined treatment system, although some revenue from by-product cake, worth JPY10/t-DS, is obtained in Case 1-2. In economic terms,
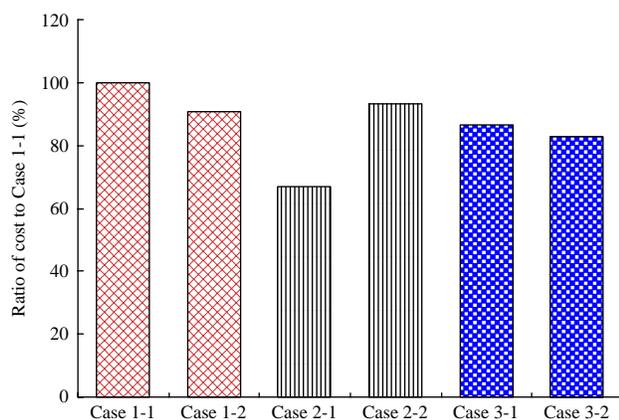
sludge transportation from DWTPs to SSTPs by pipeline (Cases 2-1, 3-1 and 3-2) is more attractive than individual treatment, although it requires the sludge liquor transport pipeline or sewer pipeline to be located close to the DWTP.

Sensitivity of sewer charges to the total cost

The total cost will vary depending on the given conditions and assumed unit costs. One of the most sensitive parameters is the sewer charge. Therefore, this section evaluates the effect of sewer charge on total cost.

The ratio of total cost of Cases 2-1 and 2-2 to the reference case (Case 1-1) is shown versus sludge treatment/processing rate as the sewer charge in Figure 4. It can be seen that the total cost is equal to that of Case 1-1, when the sludge rate of Cases 2-1 and 2-2 is JPY240,000 and 130,000/t-DS, respectively. The reasonable charge of JPY100,000/t-DS levied in Yokohama city is highly attractive to water supply works, because they do not have to undertake sewage sludge treatment. This means that the sewage works obtains more income by receiving DWTP sludge, while the water supply works succeeds in reducing the cost of sludge treatment.

The ratio of total cost of Cases 3-1 and 3-2 to the reference case is shown versus sewer volume charge in Figure 5. The total cost of Case 3-1 is equal to that of Case 1-1 when the volume unit charge is increased from JPY16 to $45\,m^{-3}$. Case 3-2 is advantageous until the volume unit charge exceeds $JPY52\,m^{-3}$. Based on this sensitivity analysis, the sludge treatment/processing cost and sewer

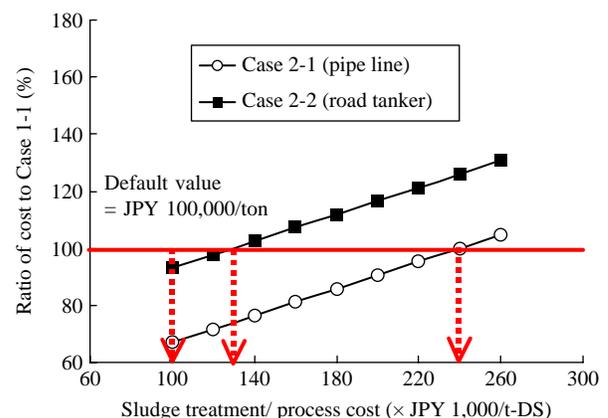**Figure 3** │ Cost comparison among the six cases of sludge treatment.

Figure 4 │ Effect of sludge treatment/processing charge on total cost.
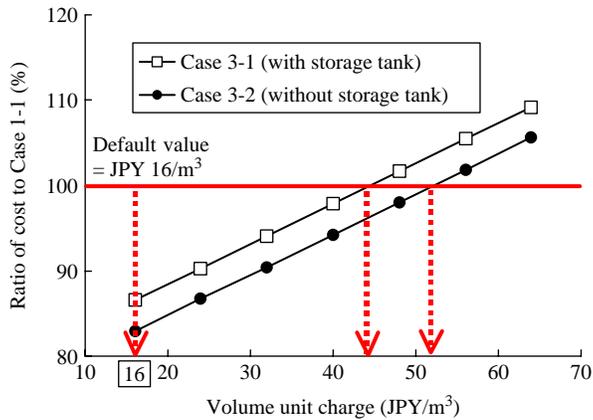
Figure 5 | Effect of volume unit charge on total cost.

charge are the crucial factors for applying combined treatment to manage DWTP sludge.

Sensitivity of physical relationship between DWTP and sewerage pipe to the total cost

As stated previously, it is assumed that the DWPT is located 1 km away from the sludge liquor transportation pipeline or sewer pipeline. As the distance between the DWTP and the pipeline increases, so too does the total cost of Case 2-1 and Cases 3-1 and 3-2. As shown in Figure 6, the total cost of Case 2-1 is the same as the reference Case 1-1 when the distance is 12 km. Case 3-1 and Case 3-2 are advantageous compared with Case 1-1 until the distance from the DWTP to the sewer pipeline exceeds 6 km and 7 km, respectively. It must be noted that the distance from the DWTP to the
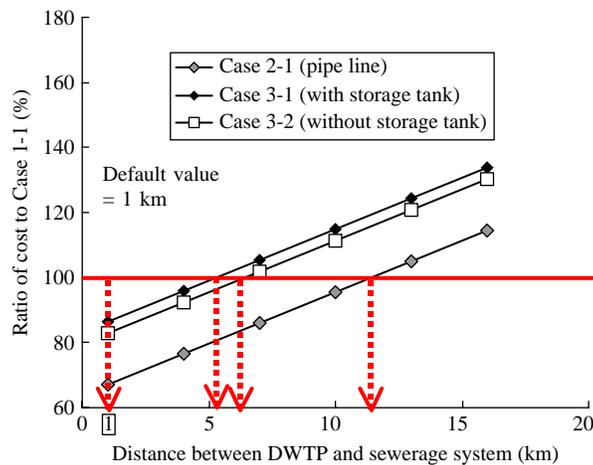
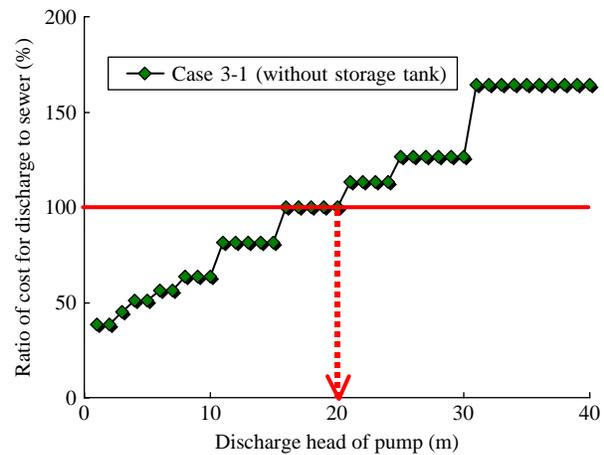**Figure 6** | Effect of distance between DWTP and sewerage system on total cost.

Figure 7 | Effect of pump head from DWTP and sewer pipe on pumping cost.

sewer pipeline is more critical than the distance from the DWTP to the sludge liquor pipeline. If a small wastewater treatment plant does not have a sludge treatment facility and has to transport its sludge to a central sludge treatment plant, the pipeline network can be designed considering the location of surrounding DWTPs.

When DWTP sludge is discharged to a sludge liquor pipeline or sewer pipeline, the pumping elevation has an effect on the pumping cost. Figure 7 shows the ratio of the cost for sludge transportation by pump as a function of discharge head for Case 3-1. This graph is regarded as a representative example, because the tendency for Case 2-1 and Case 3-2 is similar.

The default value of pumping elevation was 20 m. The range of pumping elevation of 1 to 40 m was used for the sensitivity analysis. It was found that the ratio of pumping cost for sludge discharge decreased to about 40% of the reference value. When the pumping elevation increased to 40 m, the ratio of pumping cost increased to 160%. The stepwise shift of pumping cost is due to the step change in the number of pumps or step change in pump capacity in response to increasing pump head.

CONCLUSIONS

The economic cost for treating DWTP sludge by the individual system and by the combined system was evaluated. In the individual treatment scenario, the DWTP

treats the sludge using its own facilities, while DWTP sludge is discharged or transported to the sewerage system in the combined treatment scenario. The construction cost was much lower in the combined treatment scenario than in the individual treatment scenario, while the operation cost was higher in the combined system due to the existence of a sewer charge. However, the additional sewer charge is less than the increase in construction cost for individual treatment. The individual treatment system is more costly owing to the need to construct a dewatering facility and cake hopper, with associated labour cost. Although sludge recycling generates revenue in the individual system, it is not sufficiently large at present to offset the higher labour cost.

In the combined treatment system, sludge must be transported from the DWTP to the SSTP. The cost analysis revealed that sludge transportation by road is less beneficial and emits more CO_2 than by using the pipeline in the sewerage system. In this study, two possible pipelines for transporting sludge from DWTP to SSTP were discussed, considering the existing systems in Yokohama and Kyoto where sludge effluent is discharged to sludge liquor pipe and sewer pipe, respectively. Considering the existing sewer charge system, effluent from the DWTP should be regarded as normal wastewater to sewage treatment plants. Therefore, the sewer charge based on volume is much higher than the special sludge processing cost based on dry solids. In economic terms, the combined treatment case with sludge liquor pipeline (Case 2-1) is the most advantageous of all the cases.

The total cost will depend on the given conditions and assumed unit costs. Sensitive parameters are the sewer charge and distance between the DWTP and sewerage system such as a sewer pipe. The results of the sensitivity analysis showed that the sludge treatment/processing cost and sewer unit charge are the crucial factors for applying combined treatment to manage DWTP sludge. It was also found that the distance between the DWTP and sewer pipeline or sludge liquor pipeline is sensitive. Therefore, the pipeline network could be designed by considering the location of surrounding DWTPs in the future. Although pumping indirectly emits CO_2 through electric power utilization, it has less impact on the total cost estimation.

It is concluded that the combined treatment system is more beneficial economically. To assess the feasibility of the combined treatment scenario, the effect of the above-mentioned parameters should be determined and criteria for judging whether to introduce the system should be developed. It is also very important to hold discussions between the sewage and water supply works, especially for new sludge management in urban regions. It might be possible to establish a new charge system for sludge effluent from DWTPs. Cooperation between the water supply and sewage works is essential to mitigate sludge management problems, to develop more economical and advantageous sludge treatment systems, and to reduce the environmental impact in future.

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