This is a review of the restoration and rehabilitation of sewer systems damaged by the Great East Japan Earthquake and Tsunami. The disaster caused serious damage to sewer systems, amounting to approximately 470 billion JPY. The damage was mainly caused by the tsunami, but the damage due to liquefaction was also serious. The tectonic activity caused additional discharge loads to municipalities in coastal areas. The nuclear accident at Fukushima Daiichi Nuclear Power Plant also affected sewer systems in such forms as radio-contamination of sewage sludge and reduction of power supplies. In addition, migration of users of sewer systems took place. In the restoration activities, sewage treatment plants (STPs) were restored step-by-step, and guidelines were developed to strengthen STPs against tsunamis. The effectiveness of different countermeasures against earthquakes and liquefaction were examined, and new countermeasures were proposed. Software measures such as the introduction of business continuity plans and information technologies are recognized as effective measures for overcoming disasters. In particular, the sewer systems in Sendai City have been successfully restored and rehabilitated after the disaster, with different hardware and software measures. In contrast, sewer systems in small municipalities seriously damaged by the tsunami are still taking time to rehabilitate.

**Key Words:** sewerage work, Great East Japan Earthquake and Tsunami, restoration and rehabilitation

1. **INTRODUCTION**

The Great East Japan Earthquake and Tsunami on March 11, 2011 caused serious damage to the sewer systems in the Tohoku and Kanto regions. In particular, it was the first disaster in the history of Japan, and most probably in the whole world, in which modern sewer systems were affected by a tsunami. The damage by the earthquake and tsunami to sewer systems was estimated to be around 470 billion JPY\(^1\). The recovery activities and the direction to strengthen sewer systems against tsunami were documented in detail in the final report by the Study Committee on Countermeasures in Sewerage against Earthquakes and Tsunamis (chaired by Masanori Hamada) set up by the Ministry of Land, Infrastructure, Transportation and Tourism (MLIT)\(^2\). The report is hereinafter referred to as the Earthquake and Tsunami Countermeasure Report.

The Earthquake and Tsunami Countermeasure Report\(^3\) covered in detail the damage caused to sewer systems by the tsunami and liquefaction. On top of that, there was damage caused by the accident at the Fukushima Daiichi Nuclear Power Plant, which brought about serious situations such as contamination of sewage sludge with radioactive substances and a reduction in electrical power-supply capacity. In addition, many people affected by the tsunami and the accident at the nuclear power plant had to move to safer places. This rapid migration of people was accompanied by a change in loading on the sewer systems. Furthermore, the earthquake on March 11, 2011 triggered tectonic movement; the surface level of the coastal line in the Tohoku region was reduced typically by 0.5 m – 1 m. Thus, it has become necessary for coastal cites to strengthen their capacities for dealing with stormwater discharge.

A fact of note is that the Japanese population has been in decline since the 2000s. Senno\(^3\) reports that 2011 may be the first year of consistent population reduction. This represents another challenge to sew-
verage works, because population reduction in the service area can result in a reduction of income, thereby challenging service sustainability. The population in the Tohoku region started to decrease around the year 2000, more rapidly than the national average. This means that population reduction is a threat to the sewerage service in the Tohoku region.

Here, I would like to briefly review the damage done to sewer systems by the Great East Japan Earthquake and Tsunami, as well as the subsequent restoration of those systems. Although many reports on such damage, restoration, and rehabilitation have been published in the academic literature and on local government websites, these were mostly written in Japanese. They also mostly focus on specific regions or aspects. I hope this review can help readers understand the whole picture of the damage done to sewer systems by the Great East Japan Earth-

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**Fig. 1** Locations of damaged wastewater treatment plants.  
Base map: GIS data from Geospatial Information Authority of Japan (GSI).  
Damaged STPs: Study Committee on Countermeasures in Sewerage against Earthquakes and Tsunamis.

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*STPs which stopped operation for a long period  
Partly damaged STPs  
STPs in the evacuation area*
2. SUMMARY OF DAMAGE DONE BY THE EARTHQUAKE AND TSUNAMI

Figure 1 shows wastewater treatment plants and sewer systems that were seriously damaged by the Great East Japan Earthquake and Tsunami. According to the Earthquake and Tsunami Countermeasure Report\(^2\), on March 16, 48 sewage treatment plants (STPs), 42 pumping stations for sewage and combined sewage, and 37 pumping stations for rainwater fully stopped functioning. In addition, the length of the damaged sewer extended to 642 km. Although about half of the fully stopped STPs recovered within several days, it took longer for others to recover, as shown in Table 1.

In addition to the Earthquake and Tsunami Countermeasure Report\(^2\), other reports on the damage have been published in English by Morita\(^5\) and Matsuhashi et al.\(^6\). In addition, different journals published special issues: “Restoration and Rehabilitation from Great East Japan Earthquake and Tsunami” in issue No. 585 (July 2011) of the Journal of Japan Sewage Works Association, “What we should learn from Great East Japan Earthquake and Tsunami” in the June 2011 issue of the Journal of Sewerage, Monthly, and the January 2012 issue of the Journal of Water and Waste.

The seismic loads and liquefaction caused the following damage:
- Sagging of sewers and detachment of connections
- Uplift of manholes and sewers
- Breakage of sewer pipes
- Disorder of sludge collectors in the settling tanks
- Increased intrusion of unknown water

The tsunami caused the following damage:
- Destruction due to the momentum of water and drifting debris: buildings and pipes on the surface, valve shafts, and basin covers were destroyed. Destruction of sewer bridges (in Kamaishi City) and electrical power-transmission towers (in Sendai City) were also reported.
- Destruction due to buoyancy: damage to gas holders, and damage to air pipes and ducts in the inundated areas.
- Inflow of debris and solids into buildings, basins, and basement facilities.
- Submergence of electrical and mechanical equipment.
- Submergence of documents.
- Loss of cars.

3. RESTORATION AND REHABILITATION IN TSUNAMI-AFFECTED AREAS

The tsunami affected the six prefectures of Aomori, Iwate, Miyagi, Fukushima, Ibaraki, and Chiba. The most seriously affected areas were from the southern part of Iwate Prefecture to the northern part of Fukushima Prefecture. Miyagi Prefecture was the most affected. In addition to the Earthquake and Tsunami Countermeasure Report\(^2\), the Construction Bureau of Sendai City and the Division of Sewerage of Miyagi Prefecture summarized their damage and published reports\(^7\)\(^,\)\(^8\).

(1) Basic policy for restoration

The restoration of the STPs damaged by the tsunami was implemented based on the proposals published on April 12, May 24, and July 19, 2011 by the Study Committee on Countermeasures in Sewerage against Earthquakes and Tsunamis. The plan was to restore sewage treatment within two years through the following steps:
- Securing the discharge of collected sewage
- Restoring primary settling and the disinfection and handling of sludge
- Introducing temporary biological treatment
- Restoring treatment with activated sludge.

In the emergency response, securing the discharge of sewage without backup was the first goal. Then, primary treatment with disinfection was introduced to satisfy national discharge standards, particularly a biochemical oxygen demand (BOD) of 160 mg/L with a daily average of 120 mg/L, and a daily average coliform count of 3,000 cfu/mL in the Water Pollution Control Law. In the temporary biological treatment, the goal was set at different levels to further reduce the BOD.

The committee’s third proposal was to prioritize the facilities of STPs and protect them according to the assigned priorities. The recommendations were as follows:
- Facilities to be secured even when inundated by a tsunami: sewage inflow facilities, pumping functions, gates to discharge treated water, bypass lines to discharge sewage without primary or secondary treatment, administration building, emergency generators, and electrical facilities such as transformers.
- Facilities that should be restored within a week or so: primary treatment facilities, disinfection facilities, sludge dewatering facilities, and grit chambers. Facilities that should be restored within six months or so: other facilities such as for secondary and higher treatment.
Waterproofing facilities use methods such as elevating them or installing waterproof walls. Buildings can be waterproofed by methods such as waterproofing doors, eliminating windows, and raising vents. The key points of the third proposal are covered by Matsuhashi et al.6).

Different journals published special issues about efforts toward restoring and rehabilitating sewer systems and STPs: Nos. 599 (September 2012), 609 (July 2013), 621 (July 2014), and 635 (September 2015) of the Journal of Japan Sewage Works Association; Vol. 18, Is sue 4 of Journal of EICA (2014); and Nos. 148 (2012), 152 (2013), and 164 (2016) of Mizu-sumashi, the periodical of the Japan Sewage Works Agency.

The restoration and rehabilitation of the sewer systems damaged by the tsunami followed the proposed basic policies, although each case had its own characteristics. Some of these are explained in the following sections.

(2) Sanriku Region

a) Outline of Sanriku Region

Sanriku Region is a part of Tohoku Region and is situated in its northeastern part. The coastal line of the Sanriku Region is best described as saw-toothed: it is complicated, with mountains that are connected by the surrounding sea without any intervening plains. Towns expand on the narrow plains along the coastal lines. Kamaishi City has a steel industry, but the main industry of the Sanriku Region is fisheries and fish processing. In addition, the scenic geography attracts people for sightseeing.

Because the region is mountainous and its industries are not particularly strong, the population in this region is relatively small. The larger cities are Kuji (population around 35,000), Miyako (55,000), Kamaishi (36,000), Ofunato (38,000), and Kesen-numa (66,000). Nevertheless, the populations in those cities are much smaller than in Hachinohe (230,000) and Ishinomaki (146,000) located at the northern and southern ends of Sanriku Region. The population in the coastal areas of Sanriku Region peaked around 1980, and is now estimated to have decreased by more than 30%.

The coastline of Sanriku Region has been affected by tsunami every few decades: Meiji Sanriku Tsunami (1896), Showa Sanriku Tsunami (1933), Tsunami in the Great Chilean Earthquake (1960), and the present Heisei Sanriku Tsunami (2011). Even a tsunami on the opposite side of the earth has caused serious tsunami damage in this region. The

| No. | Municipality | Name | Installation | Process | Daily average inflow in dry weather (m³/d) | Dist. from coast (km) | Elevation (m) | Restoration of secondary treatment |
|-----|--------------|------|--------------|---------|------------------------------------------|----------------------|-------------|-----------------------------------|
| 1   | Noda V.      | Noda WPC | 2002         | AOB     | 266                                      | 0.2                  | 5           | restored Nov. 2012                 |
| 2   | Miyako C.    | Taro WPC | 2001         | AOB     | 483                                      | 0.5                  | 8           | restored March 2013                |
| 3   | Yamada T.    | Creapure Funakoshi | 2000 | AOB     | 523                                      | 0.1                  | 20          | no damage, no inflow, restored Sep. 2014 |
| 4   | Otsuchi T.   | Otsuchi WPC | 1999 | OD      | 1,400                                    | 1.4                  | 5           | restored February 2012             |
| 5   | Kamasaki C.  | Odara STP | 1950         | CAS     | 15,000                                   | 0                    | 8           | restored March 2014                |
| 6   | Ofunato C.   | Ofunato WPC | 1994 | EAS     | 2,400                                    | 0.4                  | 4           | restored March 2013                |
| 7   | Rikuzen-Takata C. | Rikuzen-Takata WPC | 1999 | DN      | 1,500                                    | 0.5                  | 4           | restored May 2014                  |
| 8   | Kesen-Numa C. | Kesen-numa STP | 1984 | AO      | 7,500                                    | 0.2                  | 3           | restored Jan. 2014                 |
| 9   | Tsuyamachi WPC | 1982 | AO      | 180      | 0.2                                      | 1.7                  | 5           | restored May 2013                  |
| 10  | Minami-Sanriku T. | Utatsu WPC | 2002 | AOB     | 150                                      | 1                    | 19          | no damage, restored 2011           |
| 11  | Minami-Sanriku T. | Shidugawa WPC | 2004 | AOB     | 340                                      | 0.9                  | 31          | no damage, demolished              |
| 12  | Ishinomaki C. | Kitakami WPC | 2002 | OD      | 1,200                                    | 4                    | 6           | restored March 2013                |
| 13  | Ogasu WPC    | 2006      | AOB     | 200      | 0.5                                      | 20                   | demolished                          |
| 14  | Lower Kitakami River East BSS | Ishinomaki-tobu WPC | 1981 | DOS     | 12,000                                   | 0.2                  | 1           | restored March 2013                |
| 15  | Senen BSS   | Senen WPC | 1978      | DOS, A2O | 101,000                                  | 1.3                  | 5           | restored March 2013                |
| 16  | Sendai C.    | Minami-Gamo WPC | 1964 | CAS     | 287,000                                  | 0.2                  | 2           | restored March 2016                |
| 17  | Lower Abukuma River BSS | Kennan WPC | 1985 | CAS     | 88,000                                   | 0.3                  | 2           | restored March 2013                |
| 18  | Yamamoto T.  | Yamamoto WPC | 1993 | OD      | 2,200                                    | 0.8                  | 2           | restored March 2013                |
| 19  | Shiri T.     | Shiri WPC | 2000      | OD      | 650                                      | 0.2                  | 1           | restored March 2013                |
| 20  | Souma C.     | Souma STP | 1990      | CAS     | 4,900                                    | 1.6                  | 4           | restored July 2012                 |
| 21  | Minami-Souma C. | Kaahmin WPC | 2000 | OD      | 600                                      | 1.9                  | 4           | restored March 2016                |
| 22  | Hokusen WPC | 1993      | OD      | 50       | 0.2                                      | 7                    | demolished                          |
| 23  | Namie T.     | Namie WPC | 1991      | OD      | 2,000                                    | 0.2                  | 1          | restored March 2016                |
| 24  | Futaba T.   | Futaba WPC | 1989 | OD      | 1,600                                    | 0.2                  | 5          | restored March 2016                |
| 25  | Okuma T.    | Shinmachi WPC | 1997 | OD      | 1,300                                    | 0.3                  | 7          | unknown                            |
| 26  | Tomioka T.   | Hohoyasu WPC | 1989 | OD      | 170                                      | 0.2                  | 4           | restoration in progress            |
| 27  | Naraha T.    | Tomika WPC | 1992 | SBR     | 2,800                                    | 0.2                  | 10         | restored Aug. 2014                 |
| 28  | Kita-chiku T. | Kita-chiku WPC | 2005 | OD      | 750                                      | 0.1                  | 10         | restored June 2014                 |
| 29  | Minami-chiku WPC | 1994 | OD      | 900      | 0.1                                      | 4                    | 3           | restored March 2013                |
| 30  | Hirono T.    | Hirono WPC | 1993      | OD      | 950                                      | 0.1                  | 3           | restored March 2013                |

V.: village, T.: town, C.: city, BSS: basemide sewer system, WPC: water purification center, STP: sewage treatment plant
AOB: anaerobic aerobic biological bed, OD: oxidation ditch, CAS: conventional activated sludge (AS), EAS: extended aeration AS, DOS: pure oxygen AS
AO: anaerobic aerobic AS, DN: denitrification-nitrification AS, A2O: anaerobic anoxic aerobic AS, SBR: sequencing batch reactor AS
STPs that stopped operation for a significant length of time.
STPs that confirmed restoration operations for a significant length of time.
Distribution from the coast.
saw-toothed geography of the region effectively focuses the tsunami energy to the deepest ends of the bays alongside which the fishery towns are located and where many people live. In response to repeated tsunamis, some villages have moved to higher and safer locations, and some cities installed high sea-walls. In spite of the danger, many people want to continue to live there because of the attractive fishery sites and the sociological relationships that people have established over time.

b) Sewer systems in Sanriku Region

Many of the sewer systems on the Sanriku coast were installed after the 2000s. As the population in these regions was lower, the needs for sewerage were less. However, the region wished to attract a younger generation by having sewer systems and more comfortable toilets and wanted to protect the water environment for better fisheries and tourism. With the policy of the central government to construct sewer systems in local cities, these sewer systems were installed.

Although some of the treatment plants are located close to the coast, others are located inland at higher elevations. These latter treatment plants are relatively new: suitable sites could not be found on the densely populated plain, and there was concern about the possibility of tsunami damage. It is also noted that the newly built STPs introduced anaerobic–aerobic biological beds, which are cheaper and easier to operate.

c) Damage to STPs and sewer systems

The damage done to the STPs in the Great East Japan Earthquake and Tsunami can be placed into one of two categories: 1) those that are located on the plain and were damaged directly by the tsunami, and 2) those that were damaged either less or not at all, but the pumping facilities on the plain and in the service area were seriously damaged. Figure 2 shows the case of Kesennuma STP as an example of the former case, and Fig. 3 shows the case of Shizugawa Water Purification Center (WPC, which is another name for STP) in Minami-Sanriku Town as an example of the latter case.

Many of the damaged STPs in Sanriku Region were restored within two years, as shown in Table 1, but restoration took longer in other cases. As an example of the latter, I would like to explain the case of Kesennuma STP, which was documented by Yoshida.

One of the reasons for the delay in restoring Kesennuma STP was the reduction of elevation of the region by about 0.75 m. Because of this, during a high tide, the area around the plant would become inundated by seawater. Removing debris and elevating the roads to ensure safe transportation took almost two months. In addition, once the roads had been elevated, the manholes for accessing the sewers were buried underground. This situation made inspecting the sewer damage more difficult. Moreover, the plant is located at the end of a peninsula, and the industrial and residential zones closer to the base of the peninsula were determined to be elevated by piling soil on the land. These situations made it very difficult to set up a restoration plan.

Because the main sewer in the peninsula was seriously damaged, transporting wastewater through it to the treatment plant could not be considered. Instead, they installed three small temporary treatment facilities with which to treat domestic sewage.

Nevertheless, the Kesennuma STP was also receiving wastewater from fishery facilities and fish processing factories. To help industry to recover, they also installed temporary treatment facilities for industrial wastewater to help rehabilitate the most important industries of the city.

Restoration work at the Kesennuma STP started in 2012, the sludge treatment facility was restored in May 2013, and the biological treatment facility was restored in January 2014. Furthermore, the sludge carbonization facility was restored in March 2015, and the reconstruction of the administration building designed to be tsunami-proof was mostly finished in November 2015. The new administration building has a facility for receiving high-voltage power and an emergency generator on the third floor, and a low-voltage power-receiving facility and a control room on the fourth floor. In addition, the pumping building for the inflow has been made waterproof with watertight doors and no windows.

Although Kesennuma STP has now been completely restored, the restoration of the surrounding areas and main sewers are still underway. The elevating work is nearing the final stage, and is expected to be finished by March 2017 in most of the areas, and by March 2018 for the others.

Finally, in Table 1, it is also noted that Shizugawa WPC of Minami-Sanriku Town was demolished without being restored, even thought it was not damaged. Whereas Kesennuma and Rikuzen-Takata Cities decided to elevate their land, Minami-Sanriku Town decided to relocate the residential areas to higher places. The difference in response is due to geography: the mountains in Sanriku Region are steeper in the north and more gentle in the south. In the relocated residential areas, the Johkasou system (a sewage treatment facility for an individual house) has been introduced.

(3) Sendai Plain

From Ishinomaki to the south through Sendai to Souma, the coastline is characterized by flatlands of the delta of Old Kitakami River and the delta of
Fig. 2 Downtown district of Kesen-numa City and related STPs. Base map prepared with data from GSI \(^{86}\) (DEM: 10m, 2009, buildings and water area: 2014, 2015 or 2016). Temporary treatment plants and sites to be elevated are approximated from Yoshida \(^{10}\) and Kesennuma City \(^{87}\), respectively.

Fig. 3 Minami-Sanriku Town and its STPs. Base map prepared with data from GSI \(^{86}\) (DEM: 10m, 2009, buildings and water area: 2014, 2015 or 2016). Tsunami-inundated areas and elevated housing sites are approximated from GSI \(^{86}\) and Minami-Sanriku Town \(^{89}\), respectively.
Abukuma River. These areas form the wider Sendai Plain. Despite these areas having repeatedly experienced strong earthquakes for which the collective name is the “Off-shore Miyagi Prefecture Earthquakes,” damage by tsunamis has scarcely been reported. The Jogan Earthquake and Tsunami in 869 was a historic event that brought tsunami debris several kilometers inland of this area.[2]

When the distribution of buildings is plotted, it is seen that Ishinomaki City has many buildings in low places and in the coastal area (Fig. 4). In contrast, there are fewer buildings in the coastal area of Higashi-Matsushima City. Around Sendai City (Fig. 5), there are many buildings in the coastal areas of Shiogama City, Tagajo City, and the harbor area of Sendai City. However, there are far fewer buildings in the other coastal areas; most buildings are located in the highlands.

a) Ishinomaki

In Ishinomaki City, fisheries, fish processing, and pulp and paper industries are the major industries and are located along the coast. There were many households close to the industrial sites. They were seriously damaged by the tsunami. Also seriously damaged was Ishinomaki-tobu WPC of the Lower Kitakami River East Basinwide Sewer System, located close to the harbor. Restoration of the center was completed in March 2013[9]. In contrast, another STP in the city, Ishinomaki WPC of the Kitakami River Basinwide Sewer System, was located inland and was not affected by the tsunami. This center immediately resumed treatment and also served as a center for volunteer restoration activities. Nevertheless, the sewer system of Ishinomaki City is still suffering from lowered elevation caused by the tectonic change. It should be noted that the main sewer and the STPs (Ishinomaki-Tobu and Ishinomaki WPCs) are operated by Miyagi Prefecture, whereas the branch sewers and sewers for storm water are operated by Ishinomaki City.

b) Around Sendai

Around Sendai City, there are three large STPs: Senen WPC (100,000 m³/d from 300,000 PE), Minami-Gamo WPC (290,000 m³/d from 700,000 PE), and Kennan WPC (88,000 m³/d from 260,000 PE). While Senen and Kennan WPCs are operated by Miyagi Prefecture and are responsible for treating sewage from multiple municipalities (for Senen, sewage from places such as Sendai, Tagajo, and Shiogama; for Kennan, sewage from places such as Sendai, Natori, and Iwanuma), Minami-Gamo WPC is operated by Sendai City and treats sewage from Sendai City only.

Minami-Gamo and Kennan WPCs are located along the coast, and were exposed to the momentum of the tsunami wave. In contrast, Senen WPC was located more inland, and damage was caused more by inundation.

c) Minami-Gamo WPC

The damage and immediate responses at Minami-Gamo WPC has been reported by the Bureau of Construction of Sendai City[3], by Hamamoto[13], and by Qi et al.[14]. This WPC collects and treats sewage from the central part of Sendai City that is located higher than 20 m. The sewer system was designed so that collected sewage can be discharged gravimetrically if biological treatment is omitted. Thus, on March 12, the day after the tsunami inundation, they squeezed open the gate by about 10 cm, and on March 17 they destroyed the wall of the conduit to enable discharge of sewage.

They started disinfection with solid calcium hypochlorite on March 18, and then with liquid sodium hypochlorite on April 14. They also restored the sludge dewatering machines by the end of May and the primary settling tanks by the end of July. By this time, collected sludge was being stored temporarily in the secondary settling tanks. The stored sludge was dewatered and sent out to the disposal site. From September, dewatered sludge was incinerated at the Matsumori Cleaning Plant, an incineration plant for municipal solid waste.

In 2012, they gradually introduced the “swim-bed” process, a biological treatment process for middle-grade treatment[15]. Effluent BOD in the latter half of 2012 ranged around 60 mg/L –70 mg/L, close to the target of 60 mg/L. On June 12, the special high-voltage supply was restored, and then incineration was started. It took more than a year to restore the power supply because the plant was in a remote location and damaged power-transmission towers dedicated for the plant had to be restored. However, at Minami-Gamo WPC, instead of restoration, they decided to reconstruct the whole facility in September 2011. The economic analysis showed that reconstruction would be cheaper than restoration, partly because the level of the foundations was seriously affected by the tectonic movement, and partly because measures against tsunamis needed to be introduced.

In the reconstruction of the Minami-Gamo WPC, the whole wastewater treatment facility was packed in a building with multiple layers and a smaller footprint to allow it to withstand a tsunami inundation[7]. The reconstruction work took five years and was completed in March 2016[15].

d) Senen WPC

Whereas the areas around Minami-Gamo and Kennan WPCs are sparsely populated and the treated water is discharged to the Pacific Ocean, Senen WPC is located close to a residential area and the treated water is discharged to the Sunaoshi-Teizan
Fig. 4 Downtown of Ishinomaki and its surrounding areas. Base map prepared with data from GSI (DEM: 10m, 2009, buildings and water area: 2014, 2015, or 2016). Tsunami-damaged areas are approximated from GSI.

Fig. 5 Coastal areas around Sendai City. Base map prepared with data from GSI (DEM: 10m, 2009, buildings and water area: 2014, 2015, or 2016).
In the emergency response, restoring the sewage discharge capability was the first thing to do. Whereas collected sewage could be discharged by gravity at Minami-Gamo WPC, pumping was needed to discharge the sewage at Senen WPC of the Senen Basinwide Sewer System. However, both the pumps and the electrical power were damaged in the tsunami. Thus, after the tsunami, temporary power generators and pumps were employed to ensure sewage discharge. Barely enough fuel could be supplied for the temporary generators. However, as the water supply recovered, backup of sewage occurred at manholes in the lowlands. To reduce the hydraulic load on the Senen WPC, temporary pumps were installed at upstream locations with temporary settling basins that were disinfected using solid calcium hypochlorite.

Temporary sludge dewatering machines and aeration of sewage (without activated sludge) were introduced in June 2011. However, the dewatering machines that were introduced initially were found to be not as effective, and effective dewatering was started in October 2011. Treatment by the activated sludge process was resumed in August 2012 for half of the inflow, and in December 2012, the activated sludge process was fully restored. The incinerators and the gasholders were restored by March 2013. The effluent BOD was around 200 mg/L before the introduction of aeration; after the introduction of aeration and sludge removal, it was reduced to around 100 mg/L. As activated sludge process was restored, in August 2012, the BOD was reduced to around 30 mg/L. Coliform counts were higher than the target of 3,000 cfu/mL by a multiplicative factor of about 100, but after August 2011 the target was mostly achieved. The quality of the discharged water and the receiving water bodies was published on the internet[16].

Odor from sludge was another problem that Senen WPC had to address. They had to take care of three types of sludge: sludge that had been brought into the basins and basement facilities by the tsunami, sewage sludge at the temporary settling basin, and sewage sludge generated in the plant. They found that odor was emitted when sludge was mixed. Thus, when they had to mix sludge for such reasons as to add chemicals or to transport to another place, they communicated with the surrounding local communities and explained the situations repeatedly. At the same time, they tried different measures to reduce the emission of odors: addition of a masking reagent, deodorant, a sulfate reduction suppressor, and a solidifying reagent. Of course, covering was also effective. Their efforts have been reported by the Division of Sewerage, Department of Civil Engineering, Miyagi Prefecture[9] and by Ito[17].

(4) In the evacuation-order area of the nuclear power plant accident

Eight STPs are located in the evacuation-order (exclusion) zone for the accident at the Fukushima Daiichi Nuclear Power Plant. After the disaster, the situation of those treatment plants remained unknown. Once the distribution of radioactivity had been assessed and some parts of the area had been classified as preparation zones for termination of the order, the STPs were inspected and restored to prepare for the day when people would come back to start their lives again. Minami-chiku WPC and Kita-chiku WPC in Naraha Town were restored in June and August 2014, respectively, and the evacuation order in Naraha Town was terminated in February 2015. Similarly, Namie WPC and Shinji WPC located on the coast were inundated by the tsunami. Hokusen WPC, a very small STP located on the coast, was seriously damaged, and was demolished because its service area was seriously damaged by the tsunami and there was no inflow to the plant.

In these areas, rehabilitation of the municipalities and the lives of local people are major challenges. Many of the people have more or less established their lives in their temporary residences that could extend for years. Meanwhile, life back in their hometown poses a lot of uncertainties: although the
infrastructure has been restored, significant efforts are required to restore their homes, and their working environments have changed significantly.

4. REDUCTION OF ELEVATION

The tectonic activity caused the coastline of Tohoku Region to drop. This amounted to 50 cm –100 cm in the region from the coast of Sanriku Region down to Fukushima Prefecture. Thus, restoration work at Kesennuma STP was hindered, as discussed previously. The drop also made discharge of rainwater more difficult in cities such as Ishinomaki, Higashi-Matsushima, Shiogama, and Iwanuma.

The most seriously affected of these cities was Ishinomaki, because its industrial zone and downtown are spread over the lowland of the Old Kitakami River, as shown in Fig. 4. Discharge of rainwater with gravity was found not to be feasible for the whole downtown area. In June 2014, Ishinomaki City established a master plan for stormwater management, which included construction of stormwater pipes and construction/renovation of pumping stations at a cost of 80 billion JPY. The rehabilitation work is planned to be completed by the end of FY2020.

There is one contradictory issue between the stormwater management plan and the housing plan for the disaster evacuees. The residential areas close to the coast were seriously damaged by the tsunami; the most seriously damaged area has been categorized as a disaster hazard zone. To accommodate evacuees, the city planned to construct new residential areas inland. Some of the sites were paddy fields that accommodated rainwater. Constructing the residential area on soil elevated by about 1 m led to the reduction of rainwater storage capacity.

Fortunately, a rebound in the drop has been reported: every year, the elevation of the area increases by a couple of centimeters. However, once the whole city has been surrounded by a wall, stormwater will have to be discharged by pumping.

Stormwater management countermeasures have also been reported in relation to Iwanuma City.

5. DAMAGE TO SEWAGE COLLECTION SYSTEMS

This section reviews damage to sewage collection systems caused mainly by liquefaction.

(1) History

Historically, in the Hanshin Great Earthquake (also known as the Kobe Earthquake) in 1995, Higashi-nada STP was seriously damaged by liquefaction of its foundations, and connections of the main sewer lines were destroyed. Another striking type of damage by liquefaction was reported in the Chuetsu Earthquake of 2004: the backfill soil of sewers and manholes was liquefied. This led to many manholes being uplifted and many sewers sagging. Surface traffic was hindered by the uplifted manholes and the cracked road surfaces on top of the sagged sewers. This then hindered the emergency response activities and made the disaster worse.

(2) Countermeasures against liquefaction of backfill soil

In 2006, the Japan Sewage Works Association published guidelines on the countermeasures to prevent damage to sewer systems by liquefaction. These included different methods of backfilling: compacting backfill soil, using pebbles, and solidification by mixing cement. These countermeasures were implemented in Kurihara City and in Higashi-Matsushima City. Both of these cities (but especially Kurihara City) have repeatedly experienced strong earthquakes. In the Great East Japan Earthquake, the countermeasures were tested, and the results have been reported in the Earthquake and Tsunami Countermeasure Report. They have also been summarized in English by Morita and Matsushashi et al. According to these reports, backfilling with pebbles and solidification with cement both proved very effective.

As for the uplift of manholes during liquefaction, more measures have been developed and are being implemented. These include putting weights on the manhole at its top or bottom to anchor it to a stable and hard foundation, and installing manholes that contain special holes to allow liquefied water to flow inside.

(3) Liquefaction of the surrounding foundation in residential areas

The Great East Japan Earthquake caused serious damage to sewer systems in Kanto Region in another way: underground facilities in residential areas were seriously damaged by the liquefaction of the surrounding foundations. Residential areas on old river basins or landfill sites without proper anti-liquefaction measures were seriously affected. Utility poles sank and overhead power cables sagged, levels of houses and roads were disordered, underground pipelines were destroyed, and liquefied sand filled the damaged pipes. The sewer system damage amounted to 11 billion JPY for Urayasu City, which was the most seriously affected by liq-
uefaction. The solids removed from the damaged sewers amounted to more than 70,000 t.

Sewer system damage caused by liquefaction in Kanto Region has been reported variously: Tsuruta\(^{29}\) summarized the liquefaction damage in Chiba Prefecture, Horii\(^{30}, 31\) reported liquefaction specifically in Urayasu City, Fukatani \textit{et al.}\(^{32}\) reported surfacing of sewers in Itako City, and Hashimoto \textit{et al.}\(^{33}\) reported liquefaction damage in Kamisu City.

Tsuruta\(^{29}\) discussed countermeasures against the liquefaction of foundations. The necessity of deploying countermeasures for the whole foundation has been reported. Also reported was the necessity of introducing countermeasures for sewers constructed by the pipe-jacking method by using heavier segments with shorter spans. Mayama\(^{34}\) reported on the reconstruction by the pipe-jacking method of sewers damaged in liquefaction.

(4) Other issues

I would like to add the following issues that could not be covered along with the previous items.

- The inspection of a damaged sewer starts by opening the lid of a manhole. From a practical point of view, opening manhole lids are often difficult and problematic. Fujiwara reported such cases and proposed improvements\(^{35}\).

- In this earthquake, uplift of manholes was reported even where liquefaction was not observed\(^{36}\), although the number of such cases was limited.

- In Kesennuma City, manhole lids were blasted off by the tsunami pressure applied in the sewer. This means that even if the seawall stops the tsunami, the backpressure due to the tsunami has to be prevented.

In addition, the damage of sewer systems resulted in the increase of unknown inflow. This increase was greater in tsunami-affected areas where surface structures were destroyed together with the inlet facilities of sewers, and the elevation was lowered. Many tsunami-affected areas also experienced liquefaction. The unexpected increase of inflow of unknown water may exceed the design capacity of the bypass discharge line of an STP for a separated sewer system, although luckily such a situation did not happen in the recovery process. However, an increase in unknown water is surely an increased burden on the economy. As an attempt to clarify the effect of unknown water, Fukase and colleagues studied the relationship between precipitation and inflow into STPs\(^{37}, 38\).

6. OTHER DAMAGE

(1) Damage caused by the accident at the nuclear power plant

The accident at the Fukushima Daiichi Nuclear Power Plant affected sewage works in two ways: the accumulation of radioactivity in sewage sludge, and the need to reduce power consumption in response to the reduction of the grid power-supply capacity.

a) Contamination of sewage sludge with radioactive substances

Radioactive substances released from the Fukushima Daiichi Nuclear Power Plant precipitated on urban surfaces, flowed into sewers with the rain, and concentrated in sewage sludge, especially that of combined sewer systems. According to the regulations, waste with a radioactivity of less than 100 Bq/kg can be recycled, that with a radioactivity of less than 8,000 Bq/kg can be safely disposed, and that with a radioactivity exceeding 8,000 Bq/kg is categorized as radioactive waste and cannot be disposed by the usual measures\(^{39}\).

Kamei-Ishikawa \textit{et al.}\(^{40}\) studied the mass balance of radioactive cesium around an STP in Iwate Prefecture. They concluded that roughly 10% of the cesium entering the plant was condensed in sewage sludge. This cesium was then maintained without loss in thickening, dewatering, and incineration. The MLIT set up the Study Committee on Countermeasures against Radioactive Substances in Sewage Works (chaired by Tetsuya Kusuda). Its interim report summarizes issues such as the accumulation of radio-contaminated sewage sludge and guidelines on safe storage, and a mass-balance study at selected STPs\(^{41}\). A summary has been reported by Iwasaki\(^{42}\). In his report summary, Iwasaki\(^{42}\) concluded that a significant part of the cesium inflow was accumulated in sewage sludge. Furthermore, Tsushima \textit{et al.}\(^{43}, 44\) experimentally evaluated the possibility of radio-cesium leakage when contaminated sludge (ash or dried sludge) is landfilled. They reported that leaks were negligible during their 64-d elution experiment, except for ash solidified with cement.

Radio-contaminated sewage sludge has to be stored onsite at each individual STP, basically until an intermediate storage site for radioactive waste is ready.

One of the most seriously affected treatment plants was Horikawa-cho STP in Fukushima City. It accumulated dewatered sludge amounting to 7,726 t. To reduce its volume and to reduce the storage amount at the intermediate storage site, a technology was introduced to dry and granulate the sewage sludge\(^{45}, 46\). From April 2013, two years after the disaster, the drying and granulation plant started...
operation. In December 2015, the operation was completed and the plant was dismantled safely. The weight and volume were reduced by about 80%, and now the dried sludge is being transferred to the intermediate storage site.

Other studies were conducted. The Study Committee on Countermeasures against Radioactive Substances in Sewerage Works evaluated three technologies for separating radioactive substances from contaminated sludge and one technology to safely demolish radio-contaminated sludge treatment facility in its 6th committee meeting.

It should be noted that the management of radio-contaminated sludge is a sensitive issue, and thus authorities made the monitoring results open to local residents. For example, Fukushima Prefecture publishes the monitoring results of the treatment plants under its responsibility, and MLIT compiles information from different STPs and publishes reports.48)

b) Shortage of grid power-supply capacity

Another effect of the nuclear accident was the shortage of grid power-supply capacity in two ways: the short-term shortage immediately after the accident, and the chronic shortage due to the cessation of all nuclear power plant operations in Japan.

Rotational blackouts were implemented in the grid of Tokyo Electric Power Company from March 14 for about two weeks. The affected STPs operated emergency generators to overcome the situation49).

The shortage of grid power-supply capacity became worse as the safety of nuclear power plants was questioned: some plants were forced to stop operation because of serious questions of safety, and others could not resume operation after they were stopped for regular maintenance and inspection. In May 2012, all nuclear power plants in Japan stopped operation.

In the summer of 2011, based on Article 27 “Restriction of Use of Energy” of the Electricity Business Act, an order was issued for industries with contracts of more than 500 kW to reduce power consumption by 15% (or 5% for medical, elderly welfare, and public health including water supply and sewerage works) in areas where the power was supplied by the Tokyo Electric Power Company and Tohoku Electric Power Company. The efforts of sewerage administrations in different municipalities were reported in the December issue of the Journal of the Japan Sewage Works Association (Vol. 48, No. 590), which specialized on energy saving in sewerage works: Tokyo Metropolitan Government50, Kanagawa Prefecture51, Yokohama City52, and Kawasaki City53. They reduced power consumption during the hours of peak demand for electrical power by stopping the operation of pumps (sewage was held in the sewers instead), reducing aeration, shifting of sludge treatment works, and power generation with biogas. As a result, Kawasaki City achieved a 29% reduction during peak hours and 16% for the whole day, for example. In addition, Nagoya City54 and Osaka City55, to which the reduction order did not apply, also formulated plans for power savings and peak cuts, and implemented them.

(2) Migration of population

In the Great East Japan Earthquake and Tsunami, the number of evacuees reached as many as 470,000 right after the disaster, and it was still more than 170,000 as of March 201656. Before the disaster, the number of migrations from Iwate, Miyagi, and Fukushima Prefectures was around 10,000 every year before 2010, but in 2011, as many as 40,000 people migrated to other prefectures57. Within a prefecture, migrations were observed from coastal areas to inland or to major cities such as Sendai58. Similarly, within the same municipality, people moved from coastal areas to inland. The number of temporary dwellings constructed by the government was almost 50,00059. Of course, the migration of people was accompanied by a migration of sources of sewage.

If a temporary housing complex was constructed in a sewer-serviced area, then the sewage was discharged to the sewers. For those complexes not located in a sewer-serviced area, sewage was treated by Johkasou facilities sized typically for 50–100 households. An outline of the sewage management systems in temporary housing complexes with Johkasou systems has been reported by Niki et al.60.

(3) Toilet issues

There has been a significant demand for improved toilet facilities in a disaster. Historically, very serious toilet situations were first reported in the early restoration phase following the Kobe Earthquake in 1995. In that disaster, a violent earthquake and fires seriously damaged the city. Many people had to evacuate to shelters, where within a short period of time toilets became a serious issue. Flushing toilets could not be used because the water supply was not operating. Delivery of temporary toilets was not effective because of the lack of information and the bad traffic conditions. The traffic conditions also delayed the removal of excreta from the temporary toilets. For evacuees who had to struggle for restoration, toilet issues posed serious stress.

In the Great East Japan Earthquake and Tsunami, while many people lost their houses, toilet issues were not emphasized as much. One of the reasons...
was that the damage was less in tsunami-unaffected areas, and the water supply was more rapidly restored. In Urayasu City, which was seriously damaged by liquefaction, people could not use their toilets for weeks, and temporary toilets were installed in residential areas. However, because the structures of houses were mostly healthy, people could go back to their homes and used their toilets if equipped with bags containing solidifier. They then discharged the solidified excreta as solid waste.

In Higashi-Matsushima City, they utilized "manhole toilets" installed at shelter elementary schools. A manhole toilet facility is composed of sewer pipes with many openings (small manholes) as the underground structure, and temporary bowls and temporary covers as the surface items. The surface items are stored in a shelter. When the facility is used, lids of the manholes are opened; surface items are installed and served as toilets. Gate of the sewer is closed and water (from the swimming pool of the elementary school) is filled, toilets are used, and when excreta is accumulated, the gate is opened to flush the contents.

Kumai61) reported on the restoration of the sewer system in Ofunato City. He emphasized that officers in charge of sewerage should also take charge of toilet issues in a disaster. This is because when people have toilet-related problems, they usually consider that the sewerage section is in charge, regardless of the responsibility assignments in municipalities. Toilet issues in shelters are also reported in the Earthquake and Tsunami Countermeasure Report2).

(4) Comparison with Hurricane Sandy and funds for restoration

Nakazato et al. compared the damage done to STPs by the storm surge from Hurricane Sandy in October 2012 with that done by the tsunami from the Great East Japan Earthquake and Tsunami62). In Hurricane Sandy, most of the STPs submerged by the storm surge were restored within less than one month. Because the degree of physical damage in the tsunami was much more serious, restoration times in these two events could not easily be compared.

Nevertheless, Nakazato et al.62) identified that differences in funding for restoration is one of the key issues. That is, in the United States, they utilized the government-operated flood insurance program under the Federal Emergency Management Agency, and the assessment of damage was conducted by private insurance companies. In contrast, in Japan, damage assessment is performed by central government. As the extent of damage was huge, it took until almost the end of 2011 to complete the assessment, and the restoration of damaged facilities could not be started before the damage was assessed.

7. DEVELOPMENTS IN TECHNOLOGY AND MANAGEMENT

(1) Wastewater treatment and water quality management

In the disaster, while sewerage works were seriously damaged, different technologies to reduce damage were also invented and evaluated.

The efficiency of temporary biological treatment processes was examined at different wastewater treatment plants in the course of restoration. At Rikuzen-Takata City, a portable membrane bioreactor was introduced to treat sewage from 410 households2). At Senen WPC, the effluent BOD was reduced from around 200 mg/L to 120 mg/L by the introduction of sewage aeration without the addition of activated sludge. Contact oxidation with an attached medium (swim-bed process) successfully reduced the BOD to around 60 mg/L–70 mg/L. These attempts are reported in detail in the reports by Miyagi Prefecture8) and the National Institute for Land and Infrastructure Management63).

The effects on the water environment of the discharge of effluents with only temporary treatment were also of concern. In view of the control of health-related microorganisms, Tanaka et al.64) conducted an extensive study on the effectiveness of different disinfection methods on sewage at different treatment levels and the distribution of indicator microorganisms in receiving water bodies. Hata et al. reported on the distribution of enteric and indicator viruses in Ishinomaki coast65). While these results showed the effectiveness of chlorination in controlling pathogenic bacteria, they also showed that disinfection of viruses by chlorination was less effective.

(2) Sewer systems for more efficient use of resources

The energy crisis after the nuclear accident accelerated the recovery of energy resources from sewage and the use of renewable energy, such as the recovery of sewage heat, biomass energy (in such forms as methane), and solar power and heating at STPs.

At Sendai, a feasibility study was conducted in using the heat energy in sewage. The studied plan employed rehabilitation of an aged sewer by the SPR method (sewage pipe renewal method by lining the pipe surface with a spiral profile) with a heat exchange system. Thus, installation of a heat exchanger and rehabilitation of the aged sewer can be
done simultaneously. The studied plan was implemented in 2013\(^{66}, 67\).

At Kesennuma City, a feasibility study was conducted to recover biomass energy by accepting not only sewage but also garbage and industrial food processing waste to anaerobic digesters\(^{21,68}\). The studied plan included efficient solid removal from sewage and wastewater by upflow filtration through plastic media to recover biomass without loss by oxidation. Unfortunately, this plan was not implemented because the city had to give the highest priority to the speed of restoration.

Nevertheless, the use of energy and resources collected from sewer systems is now attracting the interest of sewerage businesses. In January 2015, MLIT revised the “Guideline and Commentary for Mater Planning Investigation on Sewerage in Individual Basin”\(^{69}\). In that document, the effective use of resources from sewage has been added as a new goal of sewer planning in river basins, in addition to the original goal of achieving environmental water quality standards.

In addition, some researchers have proposed ideas to utilize the ability of microorganisms to absorb organic pollutants without consumption of oxygen to improve the energy efficiency of sewage treatment.

One of the ideas is the peak-shifting of aeration energy consumption by removing organic pollutants at peak hours by utilizing the absorption capability of microorganisms. Absorbed organic pollutants can later be oxidized by supplying surplus air during off-peak hours of power demand\(^{70}\). Together with the peak-shifting measures implemented in the summer of 2011 mentioned in 6.(1).b), this technology is of interest not only to overcome the energy crisis but also to optimize energy consumption at STPs, which will be supported by solar and wind power in the future.

Another is to promote purification of sewage in sewers: an attached medium is installed in a sewer to sustain the growth of microorganisms, and the medium is in contact with sewage and air alternatively by utilizing the change of flow rate in the sewer. Microorganisms absorb organic pollutants when they contact with sewage, and oxidize the absorbed pollutants when they are exposed to air. A preliminary study demonstrated promising performance of purification\(^{71}\). As the proposed in-sewer treatment does not require mechanical energy, it can save electrical power consumption and can work even when the power supply is down.

(3) Collection systems

With regard to technologies for reducing the damage to collection systems, the effectiveness of anti-liquefaction measures for backfill soil was confirmed, as has been mentioned before\(^{2}, 5, 6, 72\). In addition, the following rehabilitation measures were found not to have been damaged in the disaster: the FRP inner-wall mending method\(^{73}\), and the SPR method, and the omega liner method\(^{74}\). In addition, vacuum sewer systems with polyethylene pipes were scarcely affected in the disaster\(^{75}, 76\).

As another important aspect, Ishizaki reported the recycling of waste pipes made of polyvinylchloride collected in the restoration work\(^{77}\).

(4) Management systems

In the Great East Japan Earthquake and Tsunami, it was found very important to have a business continuity plan (BCP), to have agreements for mutual assistance between different municipalities and stakeholders in a wider area, and to have asset information that is sharable with the assistant team from other authorities. In March 2011, Sendai City was in the middle of preparing its BCP, and was able to take proper measures in the emergency response\(^{77}, 78\). The necessity to formulate alliances on a wider scale has been recognized and implemented even before 2011, and it is being further strengthened, as can be seen in the special issue of the *Journal of Japan Sewage Works Association* entitled “Expanding and Networking Sewerage Works–Business Alliances” (Vol. 49, No. 601, 2012). The merits of having a BCP were also analyzed in the *Earthquake and Tsunami Countermeasure Report*\(^{2}\).

In addition, the merit of managing assets electronically is being increasingly recognized. It makes daily asset-management work easier, and in disasters when partners come to help, information on assets can be shared easily. The *Journal of Japan Sewage Works Association* has a special issue on the “Use of ICT (Information and Communication Technology) for Higher-Level Sewerage Works” (Vol. 50, No. 613, 2013). Honma\(^{79}\) reported on the Study Committee to Promote Use of ICT in Sewerage Works established in MLIT, and Komatsu\(^{80}\) reported on the promotion of ICT in different facets of sewerage, such as asset management, risk management, and task management.

8. FUTURE OF SEWER SYSTEMS IN RURAL CITIES

The restoration and rehabilitation of the sewer systems in Sendai City was mostly completed by the reconstruction of the Minami-Gamo Water Purification Center in March 2016. Sendai City has established their BCP based on their experience accumu-
lated over repeated earthquakes. They are now intensively introducing ICT to strengthen and improve their business. They are going further to more efficiently rehabilitate their aged sewers, and are also trying to utilize energy in sewage more efficiently. In addition, the population in Sendai is expected to increase by 2020, and population reduction is expected to start only after 2030\(^{11}\).

In contrast, the situations in rural areas and small cities outside commuting distance from Sendai is challenging, especially in the tsunami-affected areas.

In response to the reduction of national population, especially in rural areas, and the fact that coverage by sewer systems has reached almost 75%, three ministries related with domestic sewage management—MLIT, Ministry of Agriculture, Forestry and Fisheries (MAFF), and Ministry of the Environment (MoE)—started discussions in 2010. Here, MAFF is responsible for small-scale centralized sewer systems for agricultural and fishing communities and MoE for the Johkasou system. The Study Committee to Formulate Manual on Prefectural Wastewater Management Master Plan (chaired by Hiroaki Furumai) was established in the three ministries, and the manual was published in January 2014\(^{52}\).

The most important issue in the manual is the request to local governments to mostly complete covering domestic wastewater either by sewer systems or by Johkasou systems within basically 10 years. As of 2014, the plans local governments had were typically based on the growing scenario of the communities based on the future projection made in the late 20th century, and the growing population was planned to be covered typically by centralized sewer systems. The manual prompts local governments to review their plan in view of the reality of population reduction by reducing areas planned to be covered by sewer systems. In addition, to reduce costs, the manual recommends the merging of small sewer systems into bigger ones to reduce reconstruction and operation costs.

Miyagi Prefecture revised its domestic-wastewater management plan in response to the manual, and published a revised plan in June 2016\(^{53}\). In the revised plan, many tsunami-damaged areas have been removed from sewer-planned areas.

9. CONCLUDING REMARKS

As has been reviewed, the Great East Japan Earthquake and Tsunami caused serious damage to sewer systems, and different countermeasures were implemented or proposed. Japan is located on plate boundaries, and is destined to have many earthquakes and tsunami. One of the most important lessons learned was the necessity of prioritization, as was mentioned by the Study Committee on Countermeasures in Sewerage against Earthquake and Tsunami. It is vitally important to utilize the lessons to prepare against expected disasters, such as the projected Tokyo earthquake and Nankai/Tonankai/Tokai earthquake.

The sewer systems of Sendai City are now moving from the restoration/rehabilitation phase to the next phase. The challenge is to improve sustainability while utilizing the advantage of high population density. Rehabilitation of aged sewers, improving energy, and resource efficiency and the use of ICT are key issues.

In contrast, the situation regarding sewer systems in rural areas is more challenging. Population reduction is significant in rural areas in Tohoku, especially in tsunami-affected areas, and it is a major challenge to sustain the sewer infrastructure. Furthermore, some municipalities such as Kesennuma are still in restoration. It is reasonable that Miyagi Prefecture shrank its sewer-planned areas\(^{83}\). Yet, shrinking the service area does not necessarily mean reducing the role of sewerage works in the region. In the future, they may reconsider more active utilization of sewer systems, such as the biomass utilization project proposed for Kesennuma City\(^{2,68}\). This is because efficient use of biomass energy and the recycling of nutrients are theoretically easier and more attractive in rural areas. More efforts are needed to improve the sustainability of sewer systems.

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