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Adaptation Pathways of Wastewater Treatment Plants to  
Sea Level Rise  
(海面上昇への下水処理場の適応策)

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ADAPTATION PATHWAYS OF WASTEWATER TREATMENT PLANTS TO SEA LEVEL RISE

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## ABSTRACT

Sea level rise (SLR) has been widely acknowledged as one of the most significant challenges that human beings will have to face in the course of the 21<sup>st</sup> century. Currently, the global mean sea level is rising at a rate of 3.2 mm per year. However, the rate of SLR is accelerating, shown in the increases in the upper range of SLR projections in the literature. Past studies have projected that global mean sea levels could be up to between 1m to 3m higher than at present. Such changes in sea level could seriously affect Wastewater Treatment Plants (WWTPs), a type of infrastructure that is critical to support human life, which is usually located in low-lying areas near the coastline to utilize the gravity for sewage transportation and to discharge the effluent into large water bodies.

Several studies have investigated the vulnerability of WWTPs to SLR, which indicated that many such installations around the world are at high risk. Also, under the same SLR scenario, the number of population that is exposed to the risk of direct flooding is projected to be many times smaller than the number of population that is exposed to the loss of sanitary service. However, there is a limited number of studies that focuses on the vulnerability and adaptation of WWTPs to SLR. Existing literature heavily focused on identifying the exposure of WWTPs to SLR using the elevation of the whole WWTP, which ignores the complexity of different levels of its components. Past studies only theoretically discussed the range of SLR impacts on WWTPs using a modeling approach combining with local SLR. There is

generally a lack of detailed and comprehensive discussion on how SLR can affect the operation or maintenance of WWTPs.

Thus, the present thesis aims to deliver a comprehensive analysis of the dynamic of SLR related issues on WWTPs near the coastline and how these can adapt to sea level rise by using land subsidence as a proxy. The author investigated three significant WWTPs in the Tohoku region in northern Japan, which experienced severe land subsidence up to 1.14 m in Ishinomaki city after the *2011 Tohoku Earthquake*. The authors conducted in-depth interviews with staff from the WWTPs in the area, with the aim to elucidate the effects that land subsidence had on their operations, and how they could adapt to an increase in land subsidence or SLR.

The results suggest that under SLR of + 0.53 m, the case study WWTPs were considered to be able to operate normally without undertaking any significant adaptation actions, even though the discharge culvert was frequently occupied with seawater and there was an increasing amount of groundwater entering the sewage pipes. Global warming projections based on current climatic policy suggested SLR by the end of this century is very likely to be higher than 0.53 m. Therefore, coastal WWTPs may have to start planning for SLR adaptation from around the middle of this century.

The author identified critical levels from components of the WWTPs that influence the vulnerability and adaptation strategies of WWTPs to SLR. These crucial levels lead to three types of SLR – induced floods that are coastal flooding, discharge flooding, and groundwater inundation. The impacts of these

types of flooding on the WWTPs and possible countermeasures were also discussed in detail. WWTPs in the coastal areas should identify their vulnerability and plan for adaptation according to these three types of SLR – induced flooding.

Finally, the author proposed a general process of constructing SLR scenario dependent adaptation pathways for WWTPs in low-lying coastal areas as a long-term and flexible adaptation guideline, with a sequence of possible countermeasures and timeline of actions that should take place. The methods were applied for the case study WWTPs, with the land subsidence being reflective of future SLR. The countermeasure sequences and timing for adaptation actions to be in place varies depending on the topography and design of each WWTP. The author also discussed the applications of the proposed adaptation pathways to the different context of Tokyo and Ho Chi Minh City. Different socio-economic contexts in these cities lead to different ways of applying the proposed adaptation pathways.

(689 words)

**Key words:** Wastewater treatment plants, Sea level rise, Adaptation, Land subsidence, Adaptation pathways

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## DEDICATION

To my beloved grandma and grandpa

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## LIST OF ABBREVIATIONS

GMSL	Global Mean Sea Level
HWL	High Water Level
IPCC	Intergovernmental Panel on Climate Change
RCP	Representative Concentration Pathway
SLR	Sea Level Rise
T.P.	Tokyo Peil
WPC	Water Purification Center
WWTP	Wastewater Treatment Plant

## LIST OF UNITS OF MEASUREMENT

$\text{kg m}^{-3}$	kilogram per cubic meter
$\text{m}$	meter
$\text{m d}^{-1}$	meter per day
$\text{m}^2 \text{d}^{-1}$	square meter per day



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## **CHAPTER 1. Introduction**

### **1.1 Problem statement**

#### **1.1.1 Sea level rise projections**

Sea level refers to the height of the ocean surface relative to the surface of the solid earth (Church et al., 2013). Sea level has been rising for centuries. Reconstructions of the sea levels during past warming periods of several hundred thousand years (roughly 125,000 and 400,000 years ago) and the Pliocene suggested that even with low level of global warming and a few degree warming at the pole, global mean sea level (GMSL) was 6 m higher than at present (Dutton et al., 2015). Many processes can cause these fluctuations in sea level (including melting of ice caps and glaciers), with increases in global temperatures causing an increase in the global ocean mass and its volume (Church et al., 2013).

Attributes of sea level rise (SLR) during the 20th and 21st century include thermal expansion, melting of glaciers, Greenland and Antarctic ice-sheets mass loss, and water storage on land, though thermal expansion contributes the most to the total, with the loss of glacier masses representing the second highest contribution (Church et al., 2013).

Existing methods for attempting to predict future SLR include process-based approaches (Church et al., 2013), semi-empirical approaches (Vermeer & Rahmstorf, 2009; Rahmstorf et al., 2012a), and expert assessment approaches (Horton et al., 2014).

The Intergovernmental Panel on Climate Change 5th Assessment Report (IPCC AR5) used a

process-based approach, which includes various sea level, land and ices models, to compute a sum of individual contributions to global mean sea level rise (Church et al., 2013). The contribution of Antarctic ice sheet mass loss was included in the 5th report (as opposed to the 4<sup>th</sup> report, which did not include it) and could contribute a significant amount to the global mean SLR. The results suggested that GMSL in 2100 could be 0.98 m higher than the present. However, the process-based approach did not include non-linear Antarctic ice sheet mass loss, which could dramatically increase the estimates of GMSL by the end of this century. To fill in that gap, Le Bars et al. (2017) captured the correlation between non-linear ice sheet mass changes and the global temperature changes. Moreover, the authors included the newly updated projections of the Antarctic ice sheet mass loss, with the results suggesting that GMSL by the end of this century could be 2.92 m higher than at present for the worst scenario, RCP 8.5.

Another approach for predicting future sea level under the context of global warming is the semi-empirical approach, which uses the observed statistics on GMSL change in history to develop models with parameters to predict the future SLR based on the relationship between the observed GMSL and the global mean temperature (Vermeer & Rahmstorf, 2009). This approach assumes that the trend in SLR will remain the same patterns as past sea level changes. The projected SLR in 2100 could be 1.79 m above 1990 levels (Vermeer & Rahmstorf, 2009). The semi-empirical approach has been demonstrated to be robust under different datasets and statistical techniques (Rahmstorf et al., 2012b) and considered to be useful for long-term projections of SLR comparing to a process-based approach, as process-based

approaches only compute the known attributes of SLR. There are still uncertainties and understanding in the SLR process, and it is not known whether all contributions have been taken into account.

Furthermore, climate projections regarding SLR like such in IPCC reports have underestimated past SLR when compared to observed statistical data (Rahmstorf et al., 2012a).

As different methods to develop future SLR projections result in different values due to the insufficient understanding of the dynamic of the systems that contribute to SLR and uncertainties or limitations in current models, Horton et al. (2014) conducted an expert assessment of future SLR with 90 experts who have published (as both authors and co-authors) in peer-reviewed journals regarding the topic of sea level rise. These experts expect future SLR to be higher than the of projections in the IPCC AR5. The median value of SLR under RCP 8.5 would be 1 m by 2100. After 2100, experts' opinions suggested that stringent emission strategies can keep SLR under 1 m in 2300, while a lack in emissions mitigation actions would cause several meters of SLR in 2300 (Horton et al., 2014).

#### 1.1.2 Wastewater Treatment Plants

It is widely acknowledged that SLR will be one of the most challenging barriers to the long-term development of human beings. Such changes in the sea level could put coastal communities and infrastructure at high risk. One of the critical infrastructures in the coastal areas that can be affected by the impacts of SLR is Wastewater Treatment Plants (WWTPs).

WWTPs collect wastewater from either residential households or factories and treat it with purification technologies such as biological and biochemical processes (Figure 1.1). WWTPs can use either a combined sewage system, where the inflow contains rainwater and wastewater, or a separated sewage system, in which only the wastewater is collected and treated at the WWTPs.



Figure 1.1. Wastewater Treatment Plants in coastal areas

In a sewage management system, the WWTPs are at the end of the process. A WWTP usual includes an inflow pumping station, which elevates the collected wastewater from the sources to the WWTPs. The treatment technology at WWTPs varies, though one of the most common processes is the activated sludge process, in which the main basic processes include removing solid waste in grit chamber, primary settlement, biological treatment in aeration tank, secondary settlement and disinfection.

Historically, WWTPs have been situated at low-lying areas, closer to the waterfront to utilize the gravity for transporting the sewage from sources far away to the WWTPs, and for the convenience of

discharging into large water bodies (Hummel et al., 2018). Therefore, WWTPs in coastal areas are highly susceptible to the future impacts of SLR.

## **1.2 Literature review**

### **1.2.1 Vulnerability of Wastewater Treatment Plants to sea level rise**

Several past studies have provided assessments regarding the vulnerability of WWTPs to SLR (County, 2008; Blumenau et al., 2011; Friedrich & Kretzinger, 2012; Hummel et al., 2018).

The Wastewater Treatment Division, Department of Natural Resources and Parks in King County (2008) looked at adaptation processes by identifying which WWTPs are at risk through a simple evaluation of the elevation of WWTPs against projected SLR and water levels from historical storm events. The results indicated that for the more extreme SLR more than 30 sewer facilities would be flooded even in no storm conditions (County, 2008).

Blumenau et al. (2011) proposed a risk and impact assessment method for coastal WWTPs against the impacts of SLR and applied the methods for the case of Massachusetts. The parameters included in the assessment method are past flooding events and locations of the WWTPs referring to 100 – year flood plains. As a result, out of 18 wastewater facilities in Massachusetts, three facilities are under high risk of flooding while seven facilities are at medium risk.

Friedrich & Kretzinger (2012) conducted a vulnerability assessment of the wastewater collection

and disposal facilities to SLR using Geographic Information System, which considered the position and elevation of the WWTPs and position of the outlet pipes as parameters for the assessment. The results suggested that WWTPs in South Africa might be able to operate as usual during the next few decades (the first stages of SLR). However, past events suggested that the WWTPs would experience inefficient operation due to the damage caused by strong waves for those WWTPs located close to the coastline (Friedrich & Kretzinger, 2012), which would be exacerbated under future SLR.

Hummel et al. (2018) conducted a national scale analysis on the exposure of WWTPs on the US coast to SLR flooding under different scenarios of SLR, and estimated the population that could be affected by the disruptions. The results indicated that 162 WWTPs could be exposed to flooding for a SLR of 1 m, and 394 WWTPs are at risk for 1.8 m of SLR. The projected population that would be suffering from losing sanitary service is six times larger than that of the population that would be affected by direct flooding under 1.8 m of SLR. The study also demonstrated how SLR – induced groundwater inundation could have a substantial impact on the WWTPs in San Francisco Bay.

#### 1.2.2 Impacts of sea level rise on Wastewater Treatment Plants and adaptation

De Almeida & Mostafavi (2016) analyzed 47 documents, including journal papers and national report and documents, and provided a systemic literature review on the impacts of SLR on coastal infrastructure, which included wastewater facilities and possible countermeasures. The synthesized results

showed that the impacts of SLR include coastal flooding, the major issue that all existing studies have focused on, sewage overflow in combined sewage systems, and degradation of the underground facilities.

Existing studies have suggested possible countermeasures for WWTPs to adapt to the impacts of SLR, including constructing dikes or seawalls to protect the plants from direct flooding (de Almeida & Mostafavi, 2016, Hummel et al., 2018), using pumps to increase the water head of the plants comparing to the sea level (Friedrich & Kretzinger, 2012), elevating the whole WWTPs (de Almeida & Mostafavi, 2016), and relocating the treatment plants further away from the coastline (Friedrich & Kretzinger, 2012).

### 1.2.3 Research gap

To date, most studies have just focused on identifying exposure or hypothesizing the range of impacts that can be expected, and no actual action has been taken to outline how existing WWTPs could potentially adapt to SLR (Revi et al., 2014). Some cities have discussed possible adaptation based on local SLR projections, yet most are still at the planning stage (Rosenzweig et al., 2011). Nevertheless, it is worth noting how some countries have taken a more proactive approach to these problems. In this sense, the Netherlands constitutes a special case, where water management boards have been dealing with SLR related issues for centuries (de Jonge, 2009).

Past literature that has attempted to understand SLR and its effect on WWTPs has used digital elevation models to discuss possible adaptation strategies, though such studies are based on a single



criterion: ground elevation. Such approaches are overly simplistic and ignore the complex nature of these types of installations and the geography in which they are situated.

### **1.3 Research Objectives**

Thus, the present study aims to provide an in-depth analysis on how WWTPs that are situated on coastal areas can adapt to SLR by looking at a number of installations that have been affected by land subsidence.

The research aim is elaborated further through three major objectives, together with the research questions outlined below:

- ① Clarify the impacts of SLR on WWTPs
  - What are the issues that the WWTPs experienced due to land subsidence?
  - Which of the issues experiences can be interpreted or confirmed as potential impacts of future SLR?
- ② Identify critical factors that determine the vulnerability and adaptation of WWTPs to SLR
  - How is SLR – induced flooding linked to different components or design levels in the WWTPs?
  - What are the countermeasures for SLR – induced flooding?

③ Develop SLR scenario dependent adaptation pathways with plausible implementation timing

- What would be the sequence of SLR countermeasures for WWTPs?
- When would such countermeasures be implemented?

#### **1.4 Approach**

The approach taken for the present study is using the experience of land subsidence to study SLR.

When the land subsides, for example, 1 m, the height difference between the ground level and the sea level decreases 1 m, which is similar to the case in which the ground level remains constant and the sea level rises 1 m (see Figure 1.2). Using land subsidence as a proxy for SLR allows for an understanding of the real types of adaptation strategies that could be adopted to deal with rising water levels in the future (Takagi et al., 2016, Jamero et al., 2017). All case study WWTPs are located in the Tohoku region in northern Japan, where land subsidence took place as a result of the 2011 Tohoku Earthquake. This essentially allows for land subsidence to be used as a proxy to study SLR, and be able to draw lessons from how the plants adapted to the higher (relative) water levels. Essentially, the experiences of these WWTPs provide a high degree of confidence on the extent of future impacts of SLR and the types of countermeasures that could be employed, rather than the conjectural and hypothetical approaches of other studies.

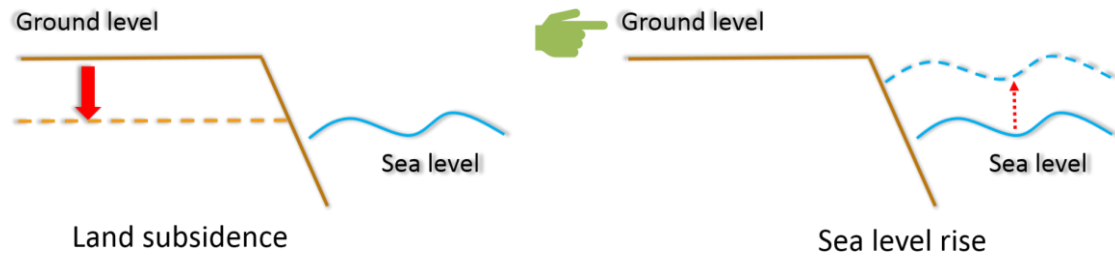


Figure 1.2. Land subsidence as a proxy for sea level rise

### 1.5 Structure of the present thesis

In the present thesis, the first chapter provides the background of this study regarding SLR and the methods for deriving their projections, WWTPs and how they can be vulnerable to the impacts of SLR. This section also includes a literature review on the vulnerability and adaptation of WWTPs in coastal areas to SLR, regarding what have been done and the gaps in literature. Chapter 2 describes in detail the case study WWTPs and the interviews conducted during the field trips. Chapter 3 elaborates the interview results (3.1.), the critical levels that influences the vulnerability and adaptation of WWTPs to SLR identified from the discussion with the interviewees (3.2.), and analysis results, which is the proposed adaptation pathways for similar WWTPs to adapt to future SLR (3.3.). Chapter 4 discusses the applications of the proposed adaptation pathways (as described in 3.3.) to different contexts of Tokyo and Ho Chi Minh City, suggesting how to effectively adapt to SLR for WWTPs in these cities. Finally, Chapter 5 summarizes the key findings of the present research and suggests directions for future studies.

## CHAPTER 2. Methods

The author conducted in-depth interviews and site visits at three WWTPs in Miyagi Prefecture as the land subsidence took place in this area after the 2011 Tohoku Earthquake (see Figure 2.1 and Figure 2.2). At one location, namely Ishinomaki city, land subsidence was up to - 1.14 m (Imakiire & Koarai, 2012). The surveyed WWTPs are Minami-Gamo Water Purification Center (WPC), Sen-en WPC, and Ishinomaki-Tobu WPC. The following section summarizes the characteristics of these WWTPs.

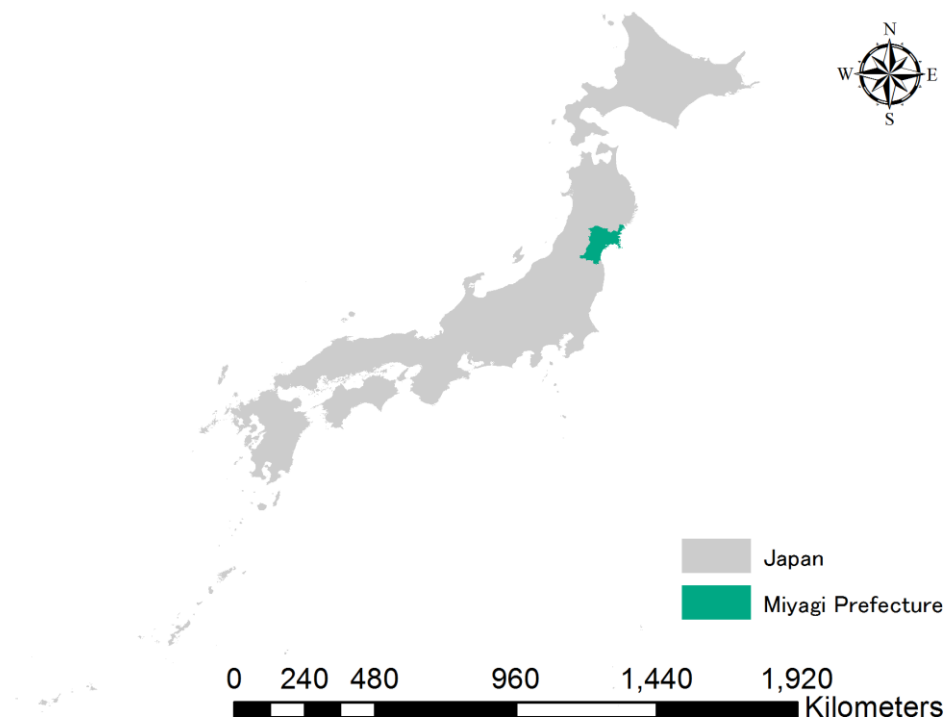


Figure 2.1. Location of Miyagi Prefecture, Japan\*

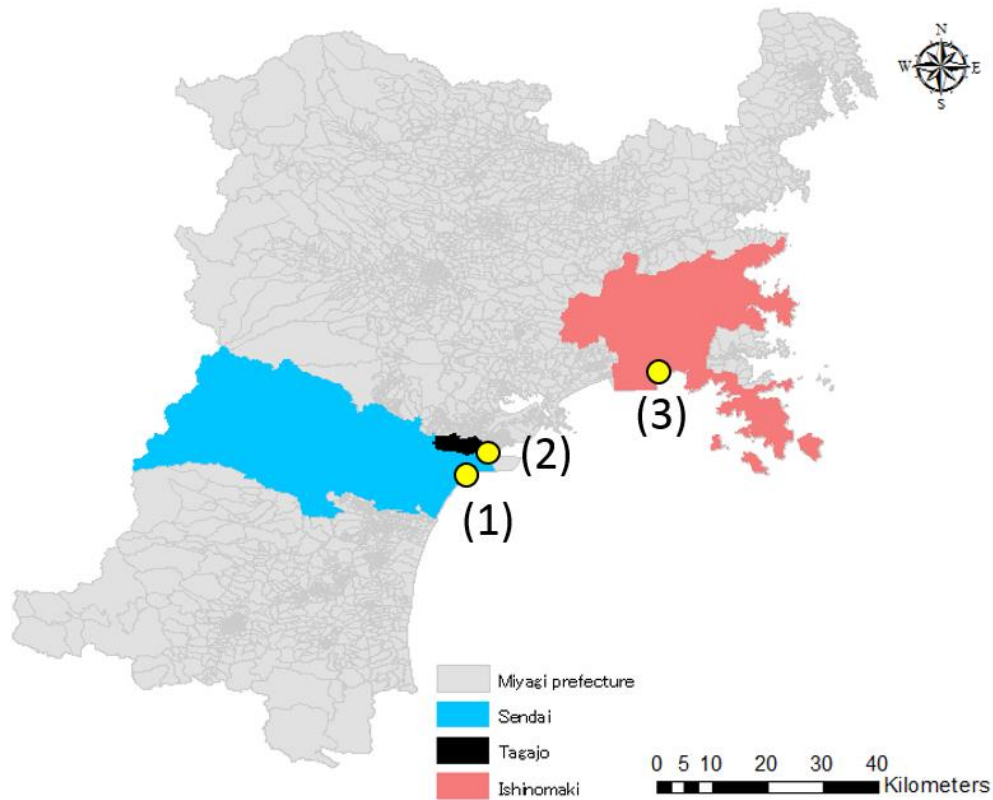


Figure 2.2. Locations of case study WWTPs in Miyagi Prefecture: (1) Minami-Gamo WPC, (2) Sen-en WPC, and (3) Ishinomaki-Tobu WPC\*

## 2.1 Cases studies description

- Minami-Gamo WPC (see Figure 2.3) is located in Sendai City, Miyagi Prefecture, 200 m away from the coastline (Satoh, 2017). The WWTP receives and treat the domestic wastewater from households in the city, and is under the management of Sendai city government. The treatment plant processing capacity is 433,000 m<sup>3</sup>/day. It discharges its effluent directly into the Pacific

Ocean. This treatment plant uses a Combined Sewage Overflows system, treating both storm water and wastewater. During heavy rains, the rainwater inflow into the WWTP is controlled by pumps, and any overflow is discharged to the river.



Figure 2.3. Minami-Gamo WPC as after 2011 Tohoku Earthquake

- Sen-en WPC (see Figure 2.4) has a capacity of 222,000 m<sup>3</sup>/day. The WWTP is situated in a residential area and is operated by Miyagi Prefecture government. According to Satoh (2017), this WWTP receives inflow from multiple municipalities and discharges its outflow to Sunaoshi-Teizan canal. In contrast to Minami-Gamo WPC, this WWTP uses a separated sewage system, which means only wastewater is treated in this plant.



Figure 2.4. Sen-en WPC as after 2011 Tohoku Earthquake  
(Source: Google Earth)

- Ishinomaki-Tobu WPC (see Figure 2.5) is located at 200 m away from the coastline, receiving roughly 12,000 m<sup>3</sup>/day of sewage from Ishinomaki city (Sato, 2017). Similar to Sen-en WPC, this WWTP is a separated sewage system.





Figure 2.5. Ishinomaki-Tobu WPC as after 2011 Tohoku Earthquake (Source: Google Earth)

After the *2011 Tohoku Earthquake and Tsunami*, Minami-Gamo and Ishinomaki-Tobu WPC were severely damaged. However, analyzing such damage and the recovery (including the construction of new tsunami countermeasures) are outside of the scope of the present thesis. Thus, the author focuses solely on analyzing the impacts of land subsidence and how the WWTPs adapted to its consequences.

## 2.2 Interviews

Interviews were in Japanese with staff members of the WWTPs, each lasting for approximately an hour and a half. In total, two different rounds of interviews were conducted, as two different instances of fieldworks were undertaken.

The first fieldwork was in March 2018. During the interviews, the author first asked about the



experience of the WWTPs with land subsidence, focusing on its impacts and the countermeasures that were implemented. Then, questions about the technical, economic, and social aspects of implementing the countermeasures were asked, in order to discuss the feasibility of adaptation strategies. During the interviews, the levels of critical components of the WWTPs that would be susceptible to SLR-induced flooding were identified. Finally, the author discussed the possible impacts of different future SLR scenarios and adaptation strategies, given the experience of these WWTPs with land subsidence. For example, the author asked what would happen if the SLR is 1 m higher than at present, and how they would address any problems that would arise from it. Initial interview questions were used to prompt the interviewees to start discussing. Follow-up questions were then asked to obtain a more detailed and comprehensive picture of the situation at each plant.

The author revisited the same WWTPs one year after the first fieldwork. At this point, the results of the first fieldwork had been analyzed and written in the form of a draft journal paper. The purposes of this second fieldwork were (1) to present the results and analysis of the first fieldwork, in order to obtain a consensus regarding their accuracy, (2) to clarify any uncertain aspects that required further discussion, and (3) to collect any missing data.

In the first field work interviewees were solely the staff members of the WWTPs. However, in the second fieldwork they included officers from Miyagi Prefecture government as well to obtain the government consensus on knowledge dissemination.

### 2.3 Sea level rise scenarios

Considering different SLR scenarios is essential to anticipate how WWTPs can adapt to SLR. The author selected SLR scenarios based on existing studies in the literature, Scenario 1 and 2 were retrieved from global mean SLR projections from the IPCC AR5 (2013), where Scenario 1 is median value for Representative Concentration Pathway<sup>1</sup> (RCP) 4.5, and Scenario 2 represent the upper range value for RCP 8.5. These projections indicate that global mean SLR by 2100 would be 0.53 m and 0.98 m for Scenario 1 and Scenario 2, respectively. The projections for RCP 2.6 were not considered, as the observed global mean SLR is rising at an accelerating rate (Weeman & Lynch, 2018), and the author felt they would likely be exceeded.

Scenario 3 was based on global mean SLR projections from Le Bars et al. (2017), which were derived using a probabilistic process-based approach that considered the temperature dependent Antarctic ice mass loss and uncertainties from previous climate models. Scenario 3 was taken from the upper range of global mean SLR in RCP 8.5 in this high-end SLR projection, which indicates that SLR by 2100 could be 2.92 m higher than pre-industrial levels.

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<sup>1</sup> Green House Gases and aerosols emission scenario including land use or land cover data that indicates one chosen pathway highlighting long-term concentration and trajectory leading to the outcomes (Moss et al., 2010)

## CHAPTER 3. Results and Discussion

### 3.1 Interviews results

Table 3.1 shows some of the key design parameters of the WWTPs surveyed, which were obtained during the interviews or from design diagrams of the plants (which were provided by the interviewees).

These are discussed in more detail in the subsections below.

Table 3.1. Parameters of the surveyed WWTPs

	Pre-2011 Ground level (m)	Pre-2011 Discharge level (m)	Pre-2011 High water level (m)	Land subsidence level after the 2011 Tohoku tsunami (m)
Minami-Gamo WPC	+3.00	+3.64	+2.68	-0.65
Sen-en WPC	+3.00	+2.07	+2.00	-0.48
Ishinomaki WPC	+2.13	+2.59	+1.29	-0.67

Notes:

- (1) All of the levels in Table 1 are to Tokyo Peil level (T.P. levels). Tokyo Peil, also known as Japanese Datum of levelling. T.P. = 0 m is determined according to the observed average tide level at Reigan-Jima in Tokyo Bay (Ministry of Infrastructure, Land, Transport and Tourism, n.d. a).
- (2) High water level (HWL), also known as sakubou-heikin-manchoui in Japanese, is defined as the average highest high tide levels observed within two days before and four days after the new moon or full moon of each month (Ministry of Infrastructure, Land, Transport and Tourism, n.d. b).

### 3.1.1 Minami-Gamo WPC

The 2011 tsunami destroyed most of the facilities at Minami-Gamo WPC, with the earthquake also lowering the land at this point by 0.65 m. As a result, the plant took five years to fully recover. Before land subsidence took place elevation of the discharge point was at T.P. +3.64 m, the design high-water level was at T.P. +2.68 m, and the ground level was T.P. +3.00 m. After the 2011 Tohoku Earthquake Tsunami, due to serious destruction, some treatment buildings were reconstructed (with the ground level being the same as the original elevation).

During the recovery period (between 2011 and 2016), seawater often come into the discharge channel during high tides (see Figure 3.1 and Figure 3.2). However, thanks to an adequate height difference between the discharge culvert and the disinfection tank (the last stage in sewage treatment before discharge), the plant was still able to discharge its effluent without major problems.



Figure 3.1. Discharge channel of Minami-Gamo WPC that connects to the Pacific Ocean



Figure 3.2. Discharge channel of Minami-Gamo WPC to the Pacific Ocean

From the discussion with staff at the plant, if land subsidence had not taken place, for a SLR of up to +0.65 m there would have been little need for the plant to take any adaptation action (as this was the same as the land subsidence that took place, and they did not experience any significant problems). Despite the occasional seawater intrusion into the discharge channel, the plant was still able to operate, indicating that for low levels of SLR the adaptation requirements for WWTPs with similar topography and design in other locations would be minimal. When the HWL rises higher than the discharge level of the disinfection tank, the staff think that it would be necessary for an additional pump to discharge the treated wastewater. For SLR greater than 2 m the staff believed that the entire plant would become submerged if no adaptation measures were taken and that in such an event adaptation would involve elevating a large stretch of land in combination with coastal protective structures.

An issue regarding the possible impact of future SLR on the plant that was mentioned by staff is that if the groundwater table rises, water will be able to penetrate the sewage pipe, increasing the inflow into the treatment plant. In that case, the capacity of the plant would be reduced, which would further compound the problems they are already experiencing during rainy days.

### 3.1.2 Sen-en WPC

Sen-en WPC is located at T.P. +3.00 m. The discharge point of the plant is at T.P. +2.07 m, and the design HWL is at T.P. +2.00 m (see Figure 3.3). The plant experienced -0.48 m of land subsidence,

though according to the interviewees it did not suffer from sewage discharge issues. However, after the land subsidence took place, the plant experienced an increase in the amount of groundwater entering the sewage pipe, which could exacerbate the process of pipe corrosion.



Figure 3.3. Discharge channel of Sen-en WPC to Sunaoshi-Teizan canal

For a SLR of between 0.48 m to 2 m, the ability to discharge treated water by gravity would depend on tidal cycles. When the tides are higher than the discharge level, a discharge pump would be necessary. However, for a SLR higher than 2 m, an additional discharge pump would be necessary all the time, which could increase the total energy consumption of the plant by up to up 10%. For more extreme SLR scenarios, raising the ground level of the whole plant was considered to be technically difficult and extremely costly.

### 3.1.3 Ishinomaki-Tobu WPC

Land subsided by -0.67 m around Ishinomaki-Tobu WPC. The plant is located 200m away from the ocean, and its discharge level is at T.P +2.59 m (see Figure 3.4 and Figure 3.5), while the high water level is at T.P. +1.29 m. As a result, the plant did not experience any significant problems to discharge treated water. However, during periods of heavy rain or the passage of typhoons, the plant had to use sandbags to prevent the water from entering the building housing critical electric facilities (see Figure 3.6).



Figure 3.4. Discharge channel of Ishinomaki-Tobu WPC that connects to the water body





Figure 3.5. Discharge channel of Ishinomaki-Tobu WPC to the water body



Figure 3.6. Sand bags used in Ishinomaki-Tobu WPC to prevent flooding inside the buildings

For higher water levels, the staff believe that there would be an increase in groundwater intrusion into the sewage pipe, which could lead to exacerbated corrosion. If the SLR is higher than 1m, a temporary discharge pump would be necessary, as the difference between the discharge level and the HWL is around 1m. In the long run, all the staff agreed that constructing new treatment facilities at higher elevations and then demolishing the old facilities represented a plausible plan to adapt.

### **3.2 Critical levels from a technical perspective**

A WWTP usually include several types of equipment to treat the wastewater, through a variety of different processes. Among these components of the treatment plant, several design water levels are critical when considering the vulnerability and adaptation strategies that they can implement with regards to SLR. Based on the discussions with staff from the surveyed WWTPs, these critical design levels were identified as the ground level, the discharge level, and the groundwater level (see Figure 3.7). These critical levels links to three types of SLR – induced flooding: coastal flooding, discharge flooding, and groundwater inundation.

The following section analyzes how these levels can affect the impacts that SLR can have and what countermeasures can be taken to handle each impact.

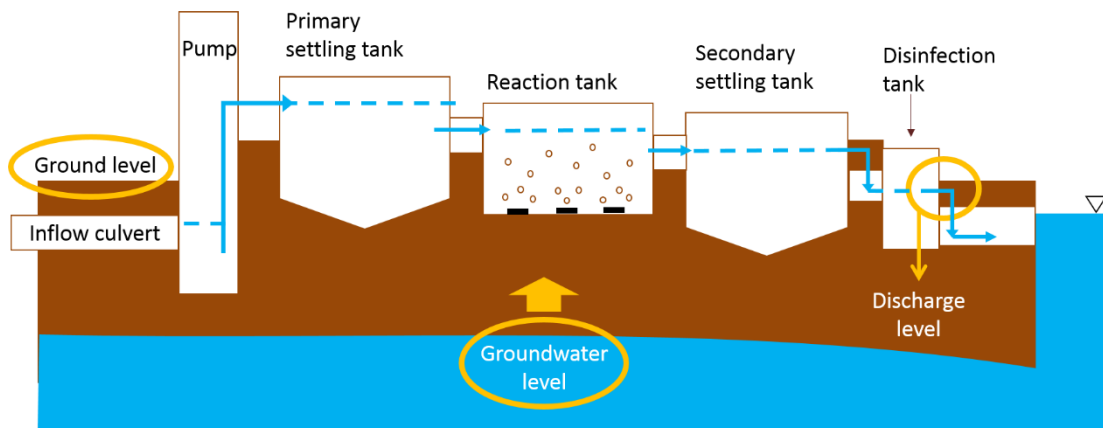


Figure 3.7. Simplified diagram of a WWTTP, showing critical levels that determine the vulnerability and adaptation to SLR (ground level, discharge level, and groundwater level)

### 3.2.1 Ground level and coastal flooding

In this study, the ground level is defined as the overall elevation of the WWTTP. When the HWL is higher than the ground level, the entire facility can be flooded several times during a day (see Figure 3.8), with this problem being accentuated during spring tides or storm surges. As sea levels keep rising, the frequency of coastal flooding will also increase. The impact of this flooding on the plant will depend on the level of flooding, potentially affecting access to the plants and maintenance. Saltwater will also corrode equipment, aside from waves being able to destroy the facilities physically. If the flood level is high enough to reach the electricity control infrastructure, the plant can suffer a loss of electricity, rendering it unable to operate.

Countermeasures against coastal flooding include building coastal protection structures such as seawalls, dikes, and levees or elevating important facilities such as the pump, electricity generation

center, and the control center (see Figure 3.8). Elevating the level of the ground is possible yet can be costly, though it has been attempted along hundreds of kilometers of the Japanese coastline (following the *2011 Tohoku Earthquake and Tsunami*, in order to improve the resilience of coastal communities against such events, Esteban et al. 2015).

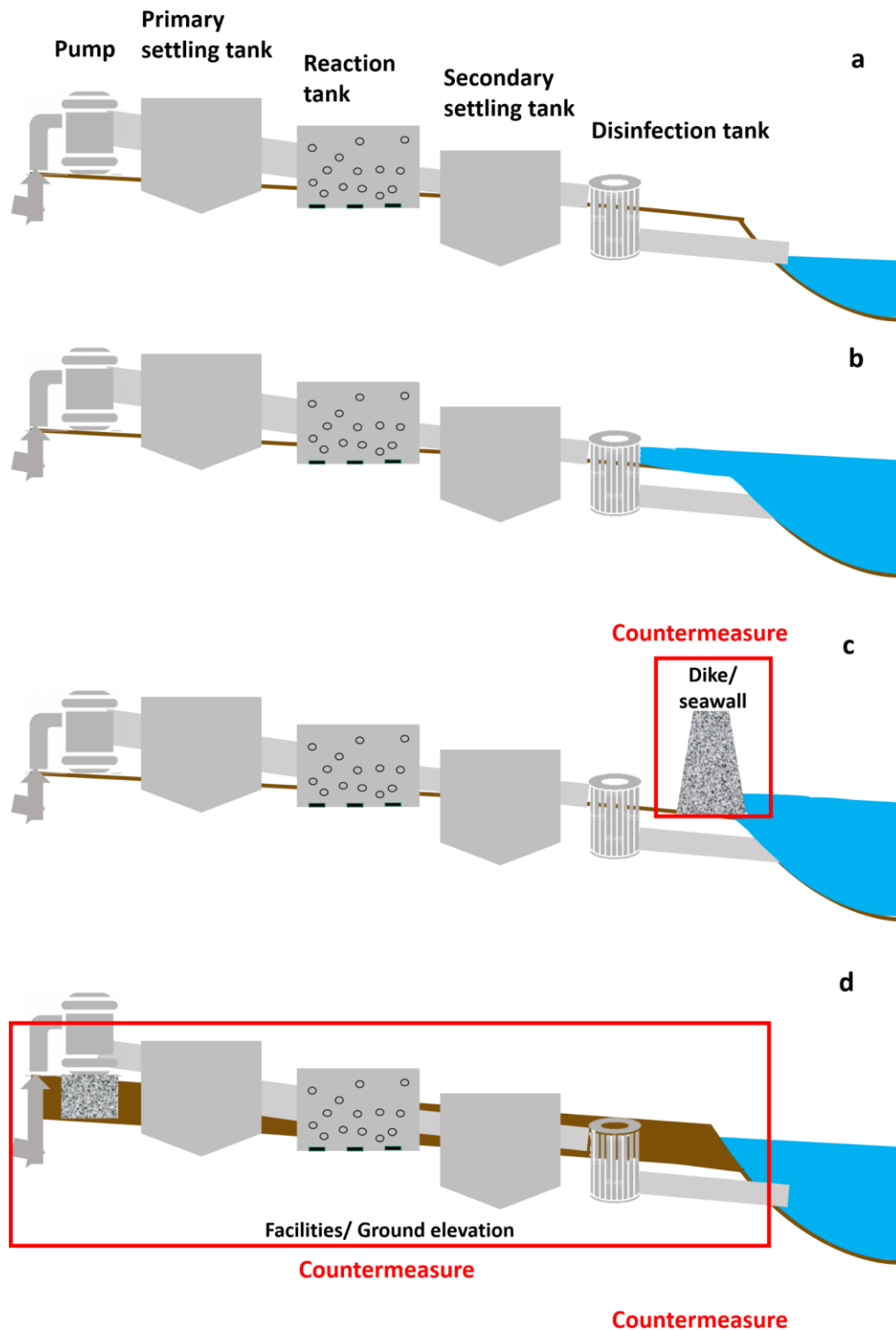


Figure 3.8. Coastal flooding and possible countermeasures. **(a)** When the WWTP operates as usual, a simplified set of components in a WWTP includes pump, treatment facility, and disinfection tank before discharge, **(b)** coastal flooding occurs due to SLR, possible countermeasures include **(c)** coastal protection and **(d)** facilities or ground elevation

At the bare minimum, crucial facilities such as the pump station and electricity control center should have flood-proof systems to prevent the buildings from being flooded, and be elevated to a higher level (such as the second floor of the same building) whenever possible (see Figure 3.9 and Figure 3.10).



Figure 3.9. Pumping facilities of Sen-en WPC



Figure 3.10. Electricity generation center of Sen-en WPC, showing flood prevention structures surrounding the facility

### 3.2.2 Discharge level and discharge flooding

In WWTPs, the critical discharge level is usually the water level at the disinfection tank (before the treated water enters the final discharge pipe). Therefore, in this study, the discharge level was taken to mean the level of the disinfection tank. When the sea level is higher than the discharge level, the treated wastewater cannot be discharged into the larger water body, which will be referred to as discharge flooding in this study (see Figure 3.11). The treated outflow instead accumulates in the sewage pipes, potentially even flowing back into the treatment tanks. This accumulation in the system would prevent the plants from treating any additional inflow sewage. Therefore, the staff would usually stop the pumping

station from sending inflow sewage into the treatment plant. As a result, sewage would probably cause backflow and flooding at low elevation areas near the plant (potentially even flowing back to the cities, spilling over onto roads through manholes or into households via sinks and toilets) (see Figure 3.12). In that case, not only the sanitary function of the plant would be stopped, but the public would be potentially exposed to raw sewage, with the consequent risks of infection due to pathogens. Besides, pollutants such as organic matters, heavy metals, nitrogen, or phosphorus would invade the surrounding environment.

Saltwater can also intrude the treatment system when the sea level is higher than the discharge level. Critical facilities in WWTPs like pump motors or aeration tanks are not typically designed to cope with high salinity water. Therefore, these facilities can corrode, which would hinder their long-term operations.

From the interview results, it would appear that a measure that can be effective to address such discharge issues would be adding a pump station or temporary pump (see Figure 3.11), especially for the cases of plants with a relatively small capacity, like Ishinomaki-Tobu WPC. To prevent saltwater intrusion, Ishinomaki-Tobu WPC implemented a gate at the discharge channel, which opens when discharge using gravity is possible and closes when the tide level is higher than the discharge pipe (see Figure 3.13). The author recommends the other two WWTPs to use such an installation.



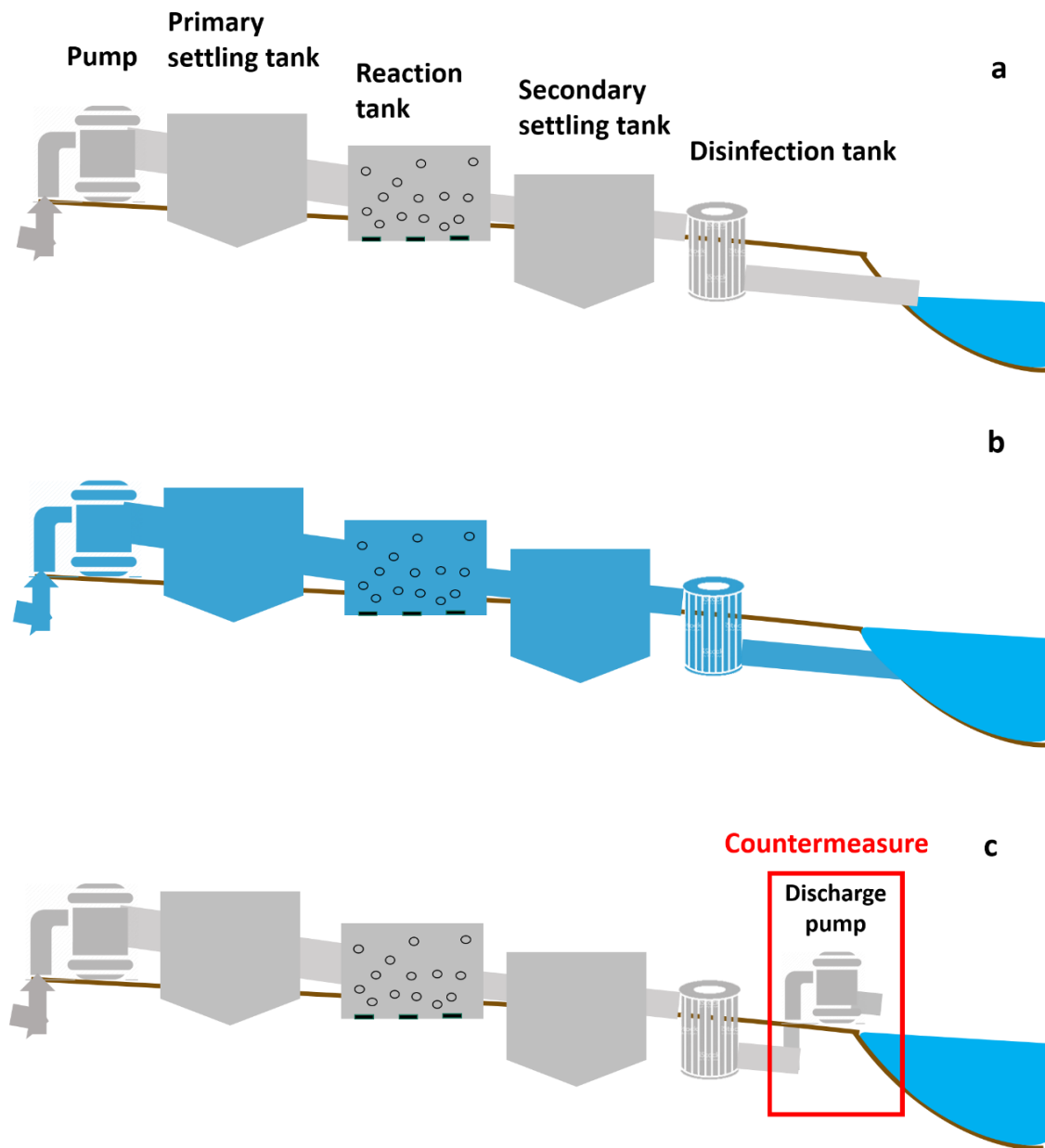


Figure 3.11. Discharge flooding and a possible countermeasure. **(a)** a simplified set of components in a WWTP including pump, treatment facilities, and disinfection tank before discharge, **(b)** discharge flooding occurs when SLR is higher than the discharge level, and an effective possible countermeasure is **(c)** discharge pump

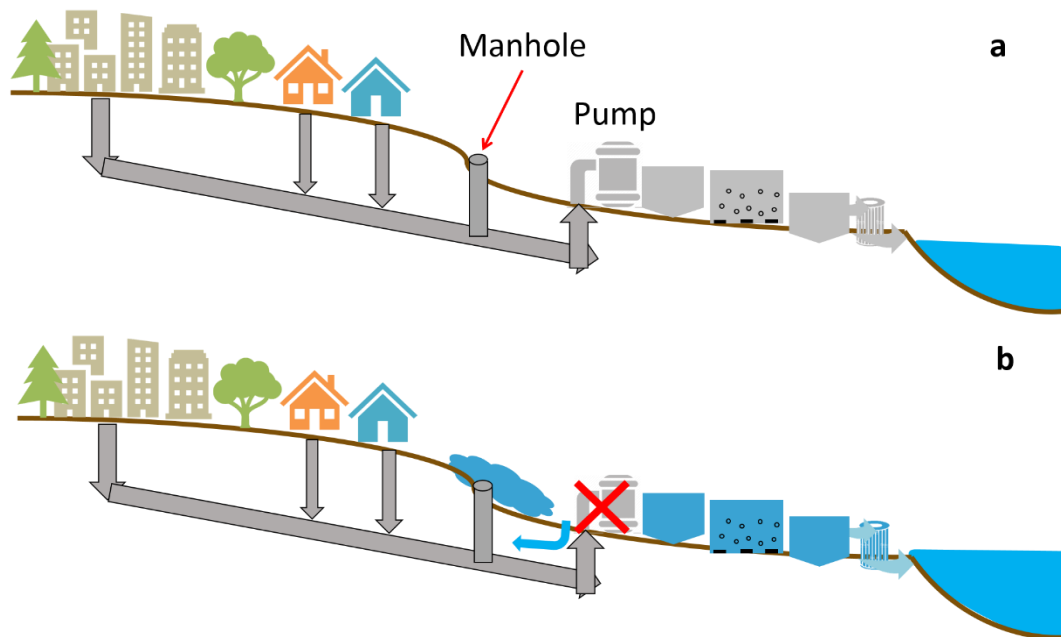


Figure 3.12. Flooding caused by the termination of pumping inflow to the WWTP. **(a)** When the WWTP operate as usual. **(b)** When the WWTP cannot discharge, and the inflow exceeds the plant capacity, the staff usually will stop the pump station.



Figure 3.13. Discharge gate at Ishinomaki-Tobu WPC discharge channel. The gate can be closed to prevent seawater intrusion into the pipes.

### 3.2.3 Groundwater level and groundwater inundation

When sea level rises, coastal groundwater levels also rise (Bjerklie et al., 2012), as the coastal groundwater table is usually above the sea level (Habel et al., 2017). Groundwater inundation happens when the groundwater table rise and breaks through the ground surface and causes flooding at the WWTP (see Figure 3.14). In areas with high groundwater level, the design of WWTPs usually takes the buoyant force of this water into account. However, in areas where the groundwater level was originally not high, SLR can eventually bring it in contact with underground facilities. If these facilities have not been designed to take this into account, they can end up floating on the water table, breaking pipes with adjacent facilities and possibly resulting in the spillage of sewage into the groundwater.

In areas with high groundwater level, WWTPs are vulnerable to SLR – induced groundwater inundation. Studies conducted in Hawaii have pointed out that the rising water table can increase the floods risks to coastal areas up to 10% when comparing to excluding its impacts (Rotzoll & Fletcher, 2012).

Rising groundwater table can also exacerbate the problem of inflow into the treatment plants, which contributes to the phenomenon of unknown water. Unknown water is a common phenomenon that can be caused by various reasons, such as groundwater that penetrates the sewage pipes, or rainwater infiltration into sewage pipes (Association of Water and Sewerage Works Consultants Japan, n.d.). This phenomenon may result in the plant's capacity being exceeded or increased corrosion to various elements such as the

sewage pipes of treatment equipment. Possible countermeasures include flood-proof structures surrounding the crucial building, usage of pumps to drain water, and the effective maintenance of facilities to ensure no unknown inflows (see Figure 3.14).

In this section, the author identified three critical levels that leads to three types of SLR – induced flooding, which are coastal flooding, discharge flooding, and groundwater inundation. The impacts of these types of flooding on WWTPs and possible adaptation measures are summarized in Table 3.2.

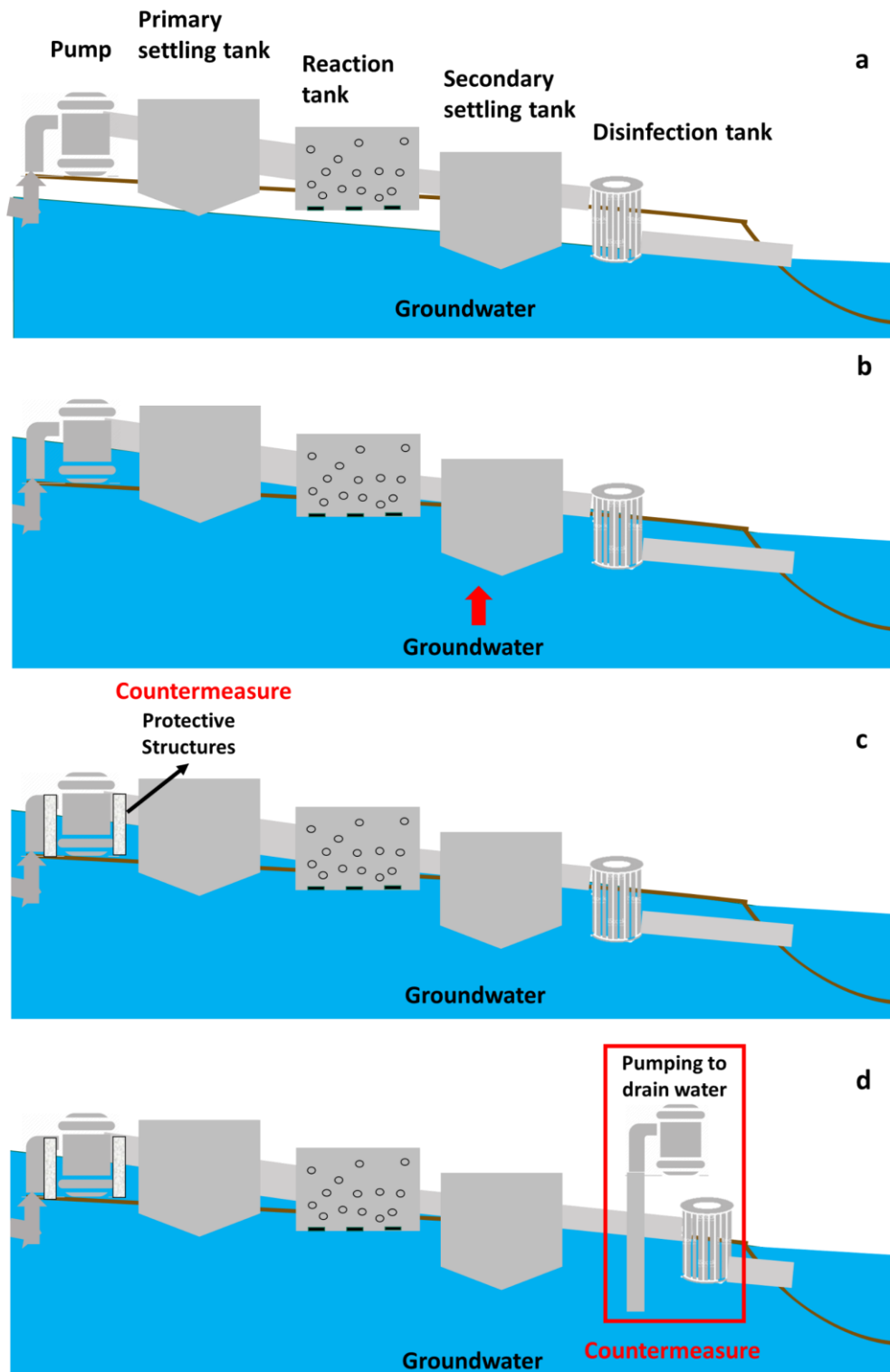


Figure 3.14. Groundwater inundation and possible countermeasures. **(a)** coastal groundwater table is usually higher than the sea level, **(b)** SLR – induced groundwater inundation occurs when the groundwater breaks through the ground surface, possible countermeasures include **(c)** protective structures surrounding crucial facilities and **(d)** pumping to keep the area dry

Table 3.2. Summary of impacts of SLR – induced flooding on WWTPs and countermeasures

SLR – induced flooding	Possible issues	Possible impacts on WWTPs	Countermeasures
Coastal flooding	Flooding at the entire WWTP	<ul style="list-style-type: none"> <li>● Hinder access to the WWTP and maintenance</li> <li>● Equipment corrodes when comes into contact with saltwater</li> <li>● Physical damage from strong waves</li> <li>● Loss of electricity during high level of flooding, which eventually leads to termination of the WWTP</li> </ul>	<ul style="list-style-type: none"> <li>● Coastal protection such as seawalls, dikes, and levees</li> <li>● Flood-proof systems or elevation of crucial facilities such as the pump, electricity control center</li> <li>● Elevation of the ground level</li> </ul>
Discharge flooding	Inability to discharge treated water	<ul style="list-style-type: none"> <li>● Sewage backflow potentially causes flooding at low-lying surroundings</li> <li>● Loss of sanitary service</li> <li>● Potential raw sewage leaks to the environment, which put public health in high risk</li> <li>● Saltwater intrusion to the treatment system, which exacerbates corrosion of the facilities</li> </ul>	<ul style="list-style-type: none"> <li>● Pumping station before discharge</li> <li>● Gate installed inside the discharge channel to prevent saltwater intrusion</li> </ul>
Groundwater inundation	<ul style="list-style-type: none"> <li>● Buoyancy of underground facilities</li> <li>● Flooding at the surroundings of the WWTP</li> </ul>	<ul style="list-style-type: none"> <li>● Damage to sewage pipe due to the buoyancy of treatment tanks</li> <li>● Exacerbate the impacts of coastal flooding</li> <li>● Groundwater entering the sewage pipe, which lowers the efficiency of the WWTP regarding its capacity and corrosion of sewage pipes</li> </ul>	<ul style="list-style-type: none"> <li>● Flood-proof structures surrounding the crucial building</li> <li>● Usage of pumps to drain water</li> <li>● Effective maintenance to prevent leakages in sewer pipes</li> </ul>

### **3.3 SLR scenario dependent adaptation pathways**

#### **3.3.1 The concept**

The various issues outlined in the previous section would start to manifest themselves as SLR reaches different thresholds. To attempt to foresee the sequence and timing of the interventions that would eventually be required, the authors thus developed SLR scenario dependent adaptation pathways for WWTPs that have similar design and topography to each of the plants considered earlier. While other WWTPs in the world will not necessarily be identical to them, looking at this case study approach can still inform about the type of countermeasures and timing of interventions elsewhere.

The shift in perceptions of climate change adaptation both in practice and research developed the concept of adaptation pathways throughout the literature. The perception of adaptation has shifted from considering climate change as a threat to development to a driver of change and co-evolution in socio-ecological systems (Wise et al., 2014). The perspective on adaptation has developed from a single strategy to a dynamic system approach of long-term planning (Maru & Smith, 2014). Adaptation pathways, which are used as a metaphor to illustrate the adaptation, are defined as sequences of actions for systems to cope with changes in the environment or society (Hassnoot et al., 2012). The approach of building adaptation pathways to support decision-makers have been applied expansively to the water management sector regarding fluvial and pluvial flooding in delta areas (Haasnoot et al., 2012; Manocha & Babovi, 2017) and coastal flooding due to SLR (Lin et al., 2017; Stephens et al., 2018, 9). Existing

case studies have mainly from developed countries such as The Netherlands, UK, US, and Australia (Haasnoot et al., 2015; Kingsborough et al., 2016; de Ruig et al., 2019; Ramm et al., 2018a, Ramm et al., 2018b). Some studies also examined the application of adaptation pathways to developing countries such as Indonesia (Butler et al., 2016a; Butler et al., 2016b) and Vietnam (Scussolini et al., 2017). However, to the author's knowledge, no studies have attempted to apply the concept of adaptation pathways to wastewater management either in developed or developing countries.

According to Maru & Smith (2014), adaptation pathways have been informed by at least four strands of research, sustainability and development, deep uncertainties in long-term changes, depth of changes that need to be taken, and detailed causal understanding of climate change impacts on systems. This study falls under the context of the second strand, deep uncertainties, and several studies have demonstrated how adaptation pathways are useful for raising awareness, informing and mobilizing policymakers in adaptation planning (Haasnoot et al., 2015; Bloemen et al., 2018).

### 3.3.2 Methods

Theoretically, the process of building adaptation pathways is flexible and can be customized for an individual case study. The general steps of constructing a map of adaptation pathways can include defining objectives and uncertainties (such as sea level rise, increased precipitation), identify possible options to achieve the objectives, determine the condition to implement or use-by time of each option



(adaptation tipping point), and scope out the pathways (Kwadijk et al., 2010; Haasnoot et al., 2015; Ramm et al., 2018b).

Throughout the literature, several studies have attempted to improve the methodology of creating adaptation pathways. Haasnoot et al. (2013) combined adaptation pathways with adaptive policy making to propose “dynamic adaptive policy pathways”, which utilized strengths from both approaches, namely adaptation tipping points and signposts or triggers for adaptation. Transient scenarios and robust decision-making were demonstrated to be useful in methods for building adaptation pathways (Haasnoot et al., 2013; Ramm et al., 2018a). Barnett et al. (2014) developed locally and socially accepted adaptation pathways and demonstrated that the concept could be applied to local contexts. Bosomworth et al. (2017) analyzed a problem – structured approach to improving the applications of adaptation pathways to natural resource management. Other studies further advanced the methodology of adaptation pathways through an in-depth analysis on the monitoring process, introducing the concept of coping capacity to delay the timing of adaptation tipping points, and developing signals and timing to trigger adaptation (Hermans et al., 2017; Radhakrishnan et al., 2018; Stephens et al., 2018, 9).

The core of the methodology to construct a map of adaptation pathways is the adaptation tipping point or thresholds, at which the current strategies or measures fail to meet the objectives of the systems (Kwadijk et al., 2010). The adaptation thresholds can be determined using impact assessment against adaptation objectives and a set of simple rules that involves the external factors that relate to the change

in values in the systems (Ramm et al., 2018b). For example, in the case of coastal flooding induced by SLR, one simple rule is when sea level (an external factor) is higher than the ground level, coastal flooding happens (a change in a value of the system) and countermeasures should be implemented. Such a set of rules can be retrieved from expert judgment, prior knowledge, and scientific models (Ramm et al., 2018b). Existing studies have heavily focused on using scientific models to derive the conditions leading to adaptation tipping points. In this study, rather than using scientific modeling, the author used expert judgments and knowledge of experience with land subsidence to identify thresholds that required adaptation actions to be taken. Figure 3.15 shows the steps of creating the SLR scenario-dependent adaptation pathways that were used in the present study.

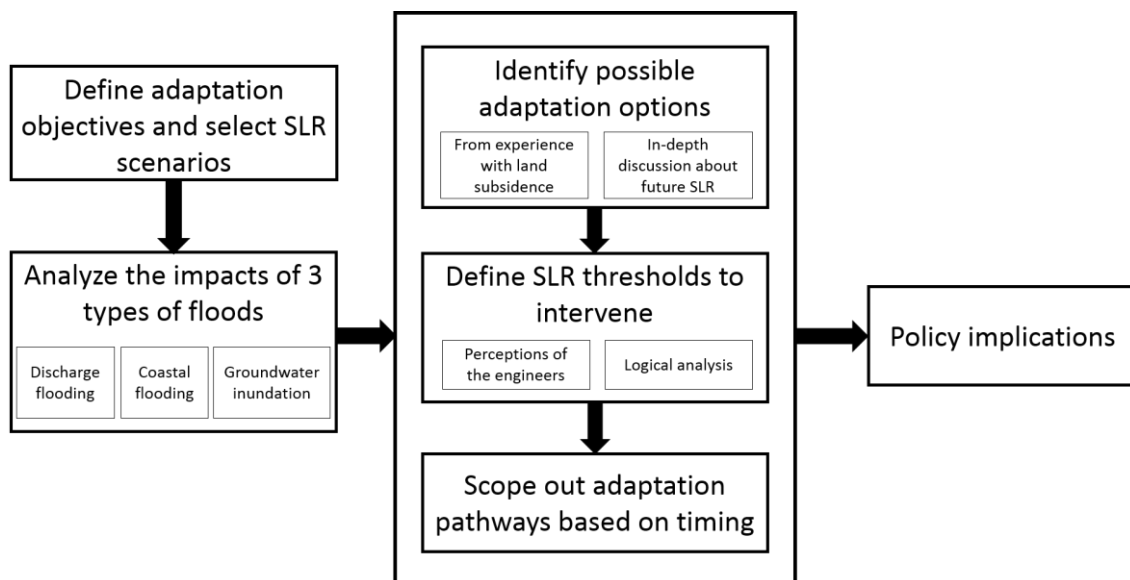


Figure 3.15. Process for building SLR scenario dependent adaptation pathways

The ultimate objective of the adaptation strategies is for the WWTP to continue to be able to operate as usual. The parameters used in this theoretical analysis include the ground level and discharge level of the treatment plants, plus the HWL and groundwater level (both of which are affected by SLR). The authors defined three different types of SLR – induced flooding:

- Coastal flooding: When the HWL is higher than ground level.
- Discharge flooding: When the HWL is higher than the discharge level.
- Groundwater inundation: When the groundwater level rises and breaches the ground surface.

Possible adaptation options were identified based on the plants' experience with land subsidence, as derived through discussions with their staff there regarding how they could hypothetically adapt to further subsidence/SLR. The thresholds to start to take action were determined based on the perceptions of the staff at the plants, plus logical analysis and expert engineering judgment by the authors based on the elevations of vulnerable technical components and design levels (as described in the previous section) in the plants. These sequences of interventions were then set against the expected rates of increase in SLR outlined in the scenarios presented earlier.

### 3.3.3 SLR scenario dependent adaptation pathways

In this section, scenario-dependent adaptation pathways were applied to Minami-Gamo, Sen-en, and Ishinomaki-Tobu WPCs, as they were before the land subsidence took place in 2011, in order to serve as examples to inform possible policy for other similar treatment plants elsewhere around the planet. All parameters used in the analysis were provided during the interviews or through the plants' design diagrams, except for the groundwater level. Groundwater levels at Minami-Gamo and Sen-en WPC were calculated using the Glover equation (Rotzoll & Fletcher, 2013), which assumed a temporarily constant condition of the groundwater level:

$$h = \sqrt{\frac{2(\rho_s - \rho_f)qx}{\rho_s K}} \quad (1)$$

where  $h$  (m) is the level of the groundwater, which depends on the distance to the coastline  $x$  (m),  $\rho_s$  is the saltwater density ( $\text{kg m}^{-3}$ ),  $\rho_f$  is the freshwater density ( $\text{kg m}^{-3}$ ), and  $q$  is the freshwater flow per unit length of shoreline ( $\text{m}^2 \text{d}^{-1}$ ), and  $K$  represents a hydraulic – conductivity estimate ( $\text{m d}^{-1}$ ).

Table 3.3 shows the calculated groundwater levels at Minami-Gamo and Sen-en WPC. The level of the groundwater at a well in the Sendai coast was extracted from the Miyagi Prefecture website (2017a), and the distance from that location to the coastline was estimated by using Google Maps (see Figure 3.16). The distance from Minami-Gamo WPC and Sen-en WPC to the coastline were extracted from Satoh (2017), and thus the calculated maximum groundwater level at Minami-Gamo WPC was T.P. +0.31

m, and at Sen-en WPC T.P. +0.79 m.

Table 3.3. Calculated groundwater levels at Miami-Gamo and Sen-en WPC as before 2011

	Groundwater measuring well in Ogimachi, Sendai	Minami-Gamo WPC	Sen-en WPC
Distance to coastline (m)	5770	200	1300
Maximum groundwater level (pre-2011) (m)	T. P. + 1.67	T. P. + 0.31	T. P. + 0.79

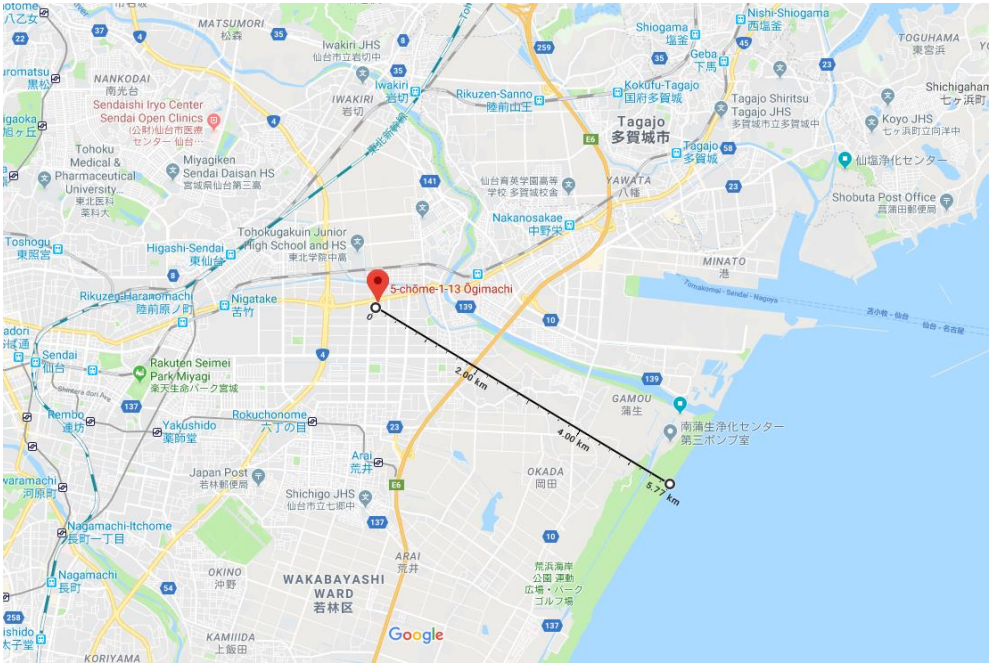


Figure 3.16. Distance from a groundwater measuring well to the coastline in Sendai City. Location of the well was retrieved from Miyagi Prefecture (n.d.). (Source: Google Maps)

For the case of Ishinomaki-Tobu WPC, there is a well nearby, and there was no need to calculate the groundwater level (it has a maximum level of T.P. +1.2 m, Miyagi Prefecture, 2017b). The authors

assumed the ratio of SLR to water table rise to be based on the monitored results from Habel et al. (2017)

in order to forecast the maximum impact of SLR-induced groundwater inundation.

Table 3.4 shows the proposed countermeasures against the impacts of SLR on a WWTP that has similar design and topography to Minami-Gamo WPC (as it was before the earthquake took place in 2011), and the thresholds to intervene. According to the interview results, no significant intervention was required for -0.65 m of land subsidence (equivalent to 0.65 m of future SLR), even though the plant may have experienced occasional seawater intrusion into the discharge pipe. This essentially means that it is possible to “do-nothing” up to this point.

For SLR higher than 0.65 m, occasional coastal flooding will start to occur. At this point, the plant should start constructing coastal protection structures to protect the facilities from being flooded during high tides.

When SLR is higher than 0.96 m, the plant would start to be unable to discharge the treated water to the ocean, given the height difference between the discharge level and HWL at that time. Therefore, adding one pump station at the point where the water is discharged would be fundamental for the plant to remain operational. As SLR continues to increase, coastal flooding during high tides or storm surges will occur more frequently. Coastal protective structures such as seawall or a dike should eventually be put in place. According to the interview results, for a SLR over 2 m, the HWL will reach more than T.P. +4.68 m, resulting in the entire area of the plant being flooded unless significant interventions are made. In this

case, apart from options such as building significant coastal protection structures and pump stations, the elevation of crucial facilities such as the pump and electricity generation center or power backup plant would be necessary.

When SLR exceeds 2.69 m, groundwater inundation will start to occur, as the maximum groundwater level at the plant is T. P. +0.31 m, and the ground level is T.P. +3.00 m. Possible countermeasures will include pumping the water out of inundated areas and the construction of protective structures surrounding essential buildings.

Table 3.4. Countermeasures and SLR thresholds to intervene for a WWTP that is similar to Minami-Gamo WPC (as before the land subsidence took place in 2011)

SLR Thresholds to intervene (m)	Issues	Countermeasures
0.65	<ul style="list-style-type: none"> <li>Occasional coastal floods</li> </ul>	<ul style="list-style-type: none"> <li>Coastal protection</li> </ul>
0.96	<ul style="list-style-type: none"> <li>Occasional discharge issues</li> <li>Frequent and higher magnitude coastal flooding</li> </ul>	<ul style="list-style-type: none"> <li>Discharge pump station</li> <li>Seawall/ dike</li> </ul>
2	<ul style="list-style-type: none"> <li>More frequent and higher magnitude coastal flooding</li> </ul>	<ul style="list-style-type: none"> <li>Elevation of facilities</li> </ul>
2.69	<ul style="list-style-type: none"> <li>Groundwater inundation</li> </ul>	<ul style="list-style-type: none"> <li>Pumping water out to prevent inundation</li> <li>Protection structures to surround critical facilities</li> </ul>

Figure 3.17 describes what would be the possible adaptation pathways of a WWTP similar to Minami-Gamo WPC to SLR, according to the three different scenarios outlined earlier. The adaptation

pathways outlined assume that SLR would start at present and that the plant had not suffered any prior land subsidence (in essence, it represents Minami-Gamo before the 2011 subsidence took place, to see how another WWTP would adapt to SLR from now). As explained earlier, the range of adaptation strategies includes “do-nothing” (at first), the construction of coastal defenses, adding a discharge pump, and finally the elevation of all facilities. All these measures are assumed to take place sequentially, as explained earlier. The dashed line marking a SLR of 0.65 m indicates a high degree of confidence on the countermeasures for WWTPs to adapt (as they are essentially the same as the land subsidence that took place). In scenario 1, the WWTP that is similar to Minami-Gamo WPC that was not affected by land subsidence and would be able to “do nothing” until 2100, without significantly suffering from the consequences of SLR. Essentially, in this scenario, the extent of SLR would be within the range the plant endured as a result of the 2011 subsidence, for which it did not have to implement any countermeasures. In scenario 2, the plant would have to start constructing low scale coastal protection from 2079. Towards the end of the century, the plant would face effluent discharge problems, at which time a discharge pump should be installed. In scenario 3, where the speed of sea level rise is the fastest, the treatment plant should have in place coastal protection from 2065. A discharge pump station and higher coastal protection (such as a seawall or dike) would be essential from 2074. Elevating a significant part of the facilities would be necessary by 2091. Finally, countermeasures for groundwater inundation would have to be implemented from 2097.



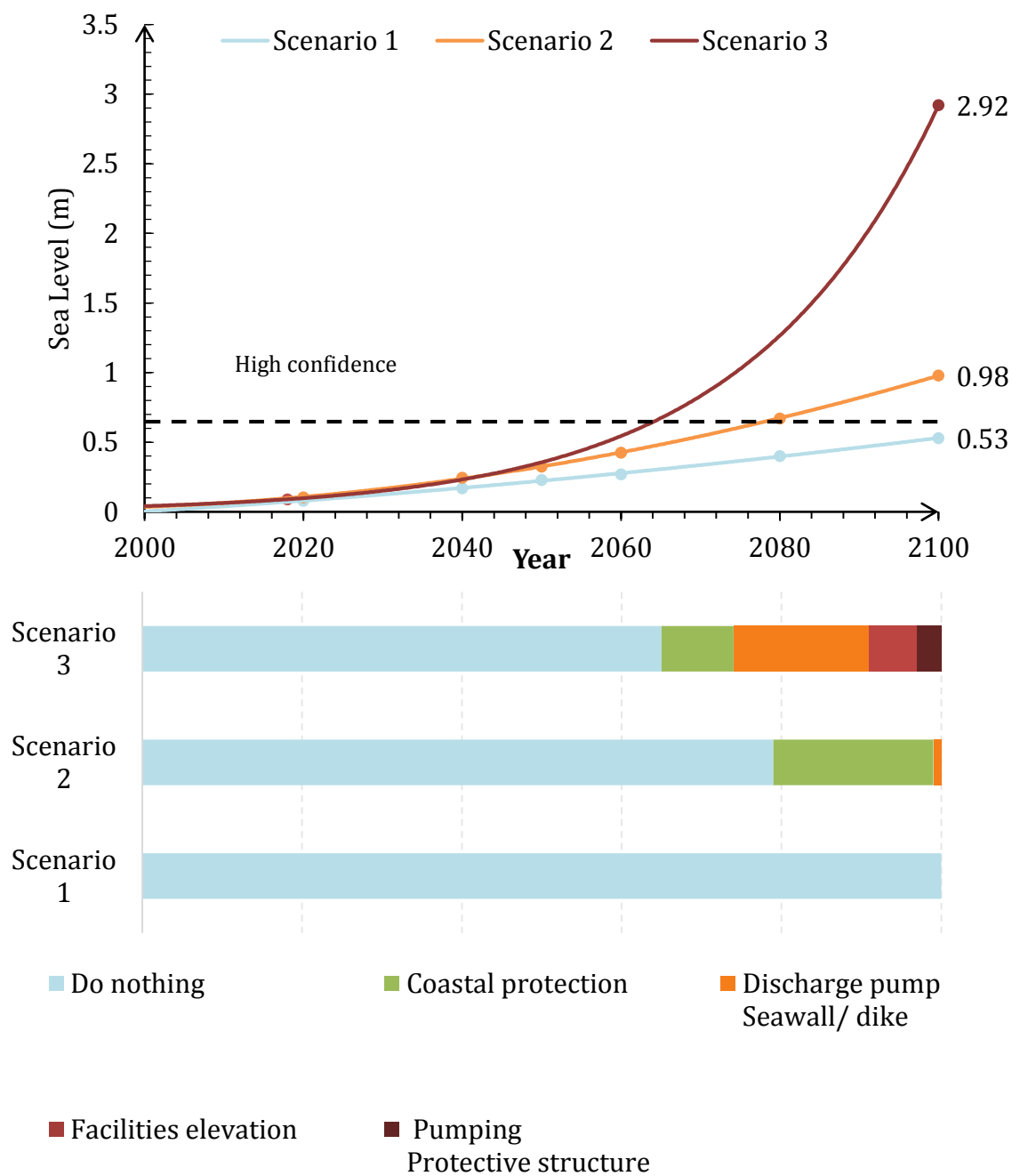


Figure 3.17. SLR scenario dependent adaptation pathways for a WWTP that is similar to Minami-Gamo WPC (as before land subsidence took place in 2011) until 2100. The dashed line indicates the level of land subsidence that Minami-Gamo WPC experienced in 2011

Similarly, Table 3.5 shows the proposed possible countermeasures for SLR impacts on a WWTP that has similar design and topography to Sen-en WPC and SLR thresholds to implement. Then, Figure 3.18 demonstrates the proposed SLR scenario dependent adaptation pathways for a WWTP that has similar design and topography to Sen-en WPC to adapt to SLR from the present.

Table 3.5. Countermeasures and SLR thresholds to intervene for a WWTP that is similar to Sen-en WPC (as before land subsidence took place in 2011)

SLR thresholds to intervene (m)	Issues	Countermeasures
0.48	<ul style="list-style-type: none"> <li>No significant issue</li> </ul>	<ul style="list-style-type: none"> <li>Do-nothing</li> </ul>
1.0	<ul style="list-style-type: none"> <li>Occasional coastal flooding</li> <li>Occasional discharge flooding</li> </ul>	<ul style="list-style-type: none"> <li>Small coastal protection</li> <li>Temporary discharge pump</li> </ul>
2.0	<ul style="list-style-type: none"> <li>Unable to discharge water</li> <li>Higher level of coastal flooding</li> </ul>	<ul style="list-style-type: none"> <li>Discharge pump at all time</li> <li>Seawall/ dike</li> </ul>
2.21	<ul style="list-style-type: none"> <li>Groundwater inundation</li> </ul>	<ul style="list-style-type: none"> <li>Pumping to drain water</li> <li>Protective structures for crucial facilities</li> </ul>

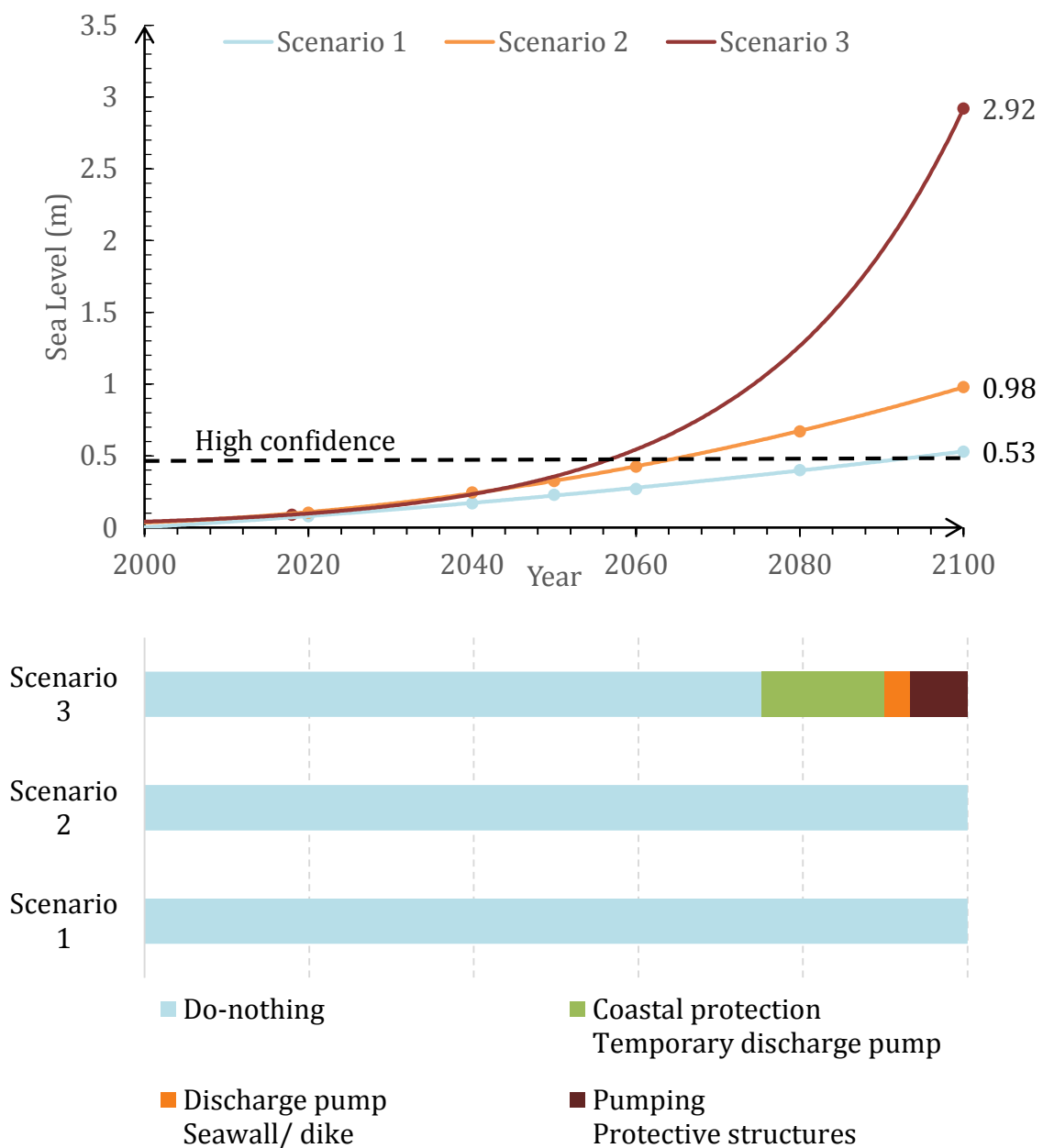


Figure 3.18. SLR scenario dependent adaptation pathways for a WWTP that is similar to Sen-en WPC (as before land subsidence took place in 2011) until 2100. The dashed line indicates the level of land subsidence that Sen-en WPC experienced in 2011.

A WWTP that is similar to Sen-en WPC (as before 2011) would face no significant challenges for a SLR of up to 1 m, given the high level of the discharge point (compared to the HWL of the canal). The plant would have to cope with groundwater inundation problems shortly after it is permanently unable to discharge.

Table 3.6 shows the proposed countermeasures for the impacts of SLR on a WWTP that is similar to Ishinomaki-Tobu WPC (as before the land subsidence took place in 2011) and the threshold to implement.

Figure 3.19 illustrates the SLR scenario dependent adaptation pathways for a WWTP that has a similar design and topography to Ishinomaki-Tobu WPC (as before the land subsidence happened in 2011). The dashed line indicates the land subsidence level that Ishinomaki-Tobu WPC experienced in 2011.

Table 3.6. Countermeasures and SLR thresholds to intervene for a WWTP that is similar to Ishinomaki-Tobu WPC (as before the land subsidence took place in 2011)

SLR thresholds to intervene (m)	Issues	Countermeasures
0.67	No significant issue	Do-nothing
0.84	• Frequent coastal flooding	• Small coastal protection
0.93	• Groundwater inundation	• Pumping to drain water • Protective structures surrounding crucial facilities
1.30	• Occasional discharge difficulty	• Temporary discharge pump
2.59	• Permanent discharge flooding • Severe coastal flooding	• Discharge pump at all time • Seawall/ dike

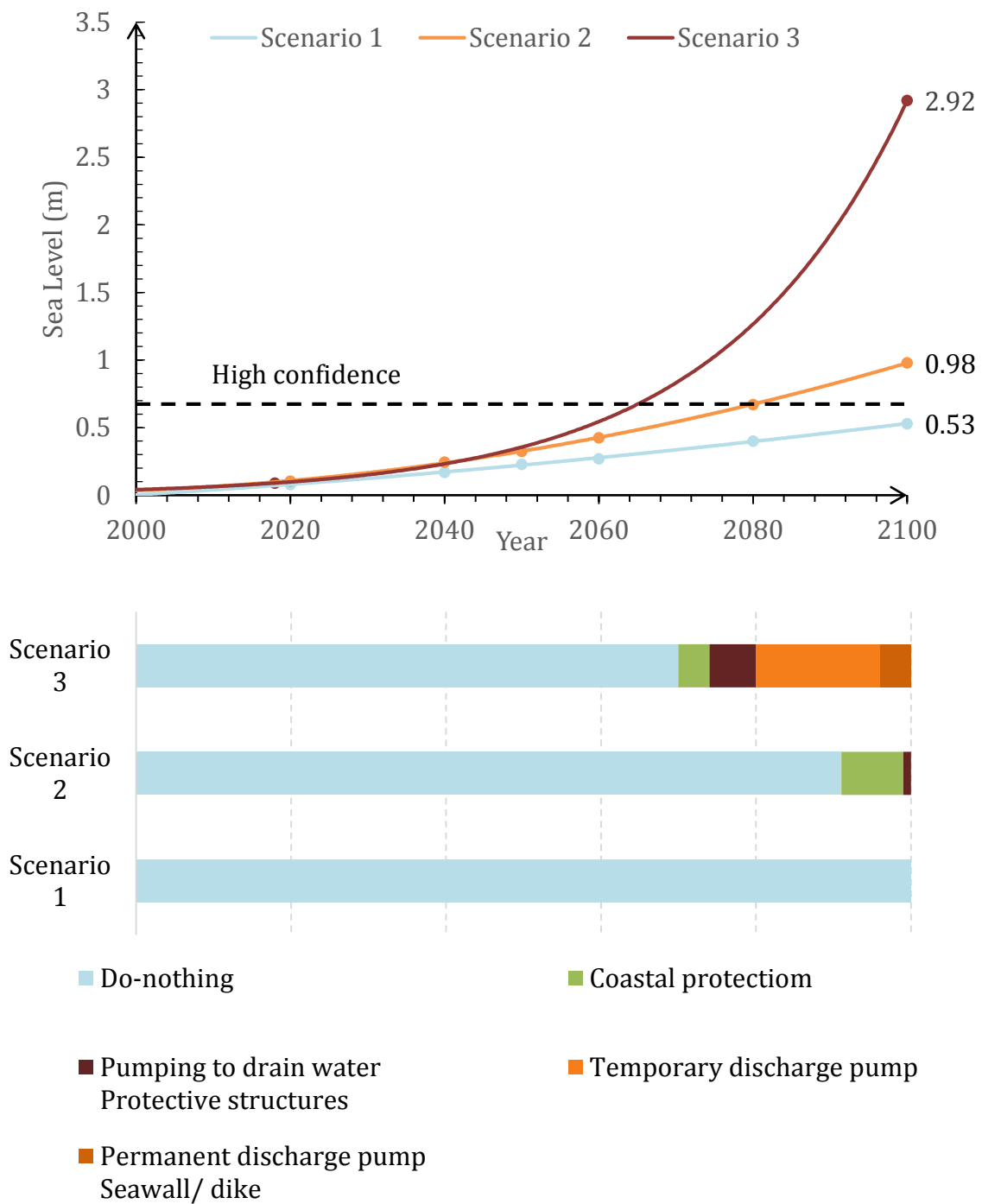


Figure 3.19. SLR scenario dependent adaptation pathways for a WWTP similar to Ishinomaki-Tobu WPC (as before the land subsidence took place in 2011) until 2100. The dashed line indicates the land subsidence level that Ishinomaki-Tobu WPC experienced in 2011

Comparing to the other WWTPs analyzed in the present work, Ishinomaki-Tobu WPC is situated on lower ground, though it has a lower HWL and higher groundwater level. Therefore, the plant (as it was before 2011) would have to construct coastal defenses for a SLR of merely 0.84 m. Also, the plant would have to cope with groundwater inundation by using a pump and construct protective structures surrounding critical facilities for a SLR of 0.93 or higher. As SLR continues after that point, groundwater inundation would become more severe and require the strengthening of the measures described above. Besides, the discharge channel would occasionally get flooded, and thus a pump would be needed to discharge during high tides when the SLR is higher than 1.3 m. When SLR reaches 2.59 m, the plant would need this pump to be in constant use, as the discharge level would be lower than the tide at any point in the day.

Amongst the three types of flooding identified, it is clear that all three WWTPs would first face the threat of coastal flooding. However, while Minami-Gamo and Sen-en WPCs would have to cope with the effluent discharge problem next, Ishinomaki-Tobu WPC would have to deal with the impacts of groundwater inundation. Thus, the analysis conducted highlights that the same method of creating adaptation pathways can be applied to different WWTPs. Even with the same methodology, the countermeasures suitable for each plant and timing for implementation vary depending in the design of different critical water levels inside the WWTPs and their topography.

#### 3.3.4 Assumptions and limitations

In the present thesis, the author used land subsidence as a proxy to study SLR. The experiences of the case study WWTPs were used to create SLR adaptation pathways for similar WWTPs elsewhere. Therefore, the levels of land subsidence that took place at the surveyed WWTPs are reflective of the future SLR that can take place in the proposed adaptation pathways.

The data used to map out adaptation pathways were mostly obtained from either the interview results or documents provided by the staff at WWTPs, such as the designs and water level diagrams of the WWTPs. However, it was not possible to obtain data for the groundwater levels at Minami-Gamo and Sen-en WPCs. Thus, the author calculated the relative groundwater levels at these plants by using the Grover equation (1) and data of groundwater level measuring by a well nearby. Equation (1) assumes the groundwater table is at a constant, unchanging state. Moreover, the maximum value of the measured groundwater level was selected for the calculation to project the worst scenario of groundwater inundation that could happen. Furthermore, the literature regarding the simulation of SLR – induced groundwater inundation is limited. The ratio of groundwater level rises to SLR may vary depending on the topography of the areas. Therefore, the estimation of groundwater inundation in the present study should be treated with caution, and more research should be conducted in this area.

In the proposed adaptation pathways, the author considers global mean SLR scenarios that retrieved from existing literature. Hence, the proposed adaptation pathways do not consider water level changes

during extreme events, which might shorten the timing for the threshold to arrive. In essence, if future global climate change changes the frequency and intensity of tropical cyclones or flooding then the WWTPs analyzed might have to adapt to flooding before the timing projected in the proposed adaptation pathways.



## **CHAPTER 4. Applications and recommendations for WWTPs**

### **4.1 Tokyo**

#### **4.1.1 Wastewater management in Tokyo**

Tokyo is one of the most populated coastal cities in the world, being home to almost 13.5 million people (estimated in 2015, Tokyo Metropolitan Government, n.d.) (see Figure 4.1 for the location of the city). The city can be divided into two major areas: Tama region and Ward region. The Tama area is a mountainous area that covers the west side of the city, whereas the ward area is the highly populated area surrounding the watershed of the rivers and Tokyo Bay. In this section, the author will focus only on the Ward area, as it is a coastal area that includes the below - sea - level areas comprising Edogawa Ward and Koto Ward.

The author went through documents available on the official website of Tokyo Metropolitan Government on Sewerage, interviewed the officers working in the Sewerage Department, and visited Kiba Pumping Station and Sunamachi Water Reclamation Center (WRC) to get a state-of-the-art overview on the wastewater management in Tokyo. Both Kiba Pumping Station and Sunamachi WRC are situated in Koto Ward, which is below sea level due to land subsidence that took place in the 1940s – 1970s period due to large-scale groundwater extraction activities (Sato et al., 2006).

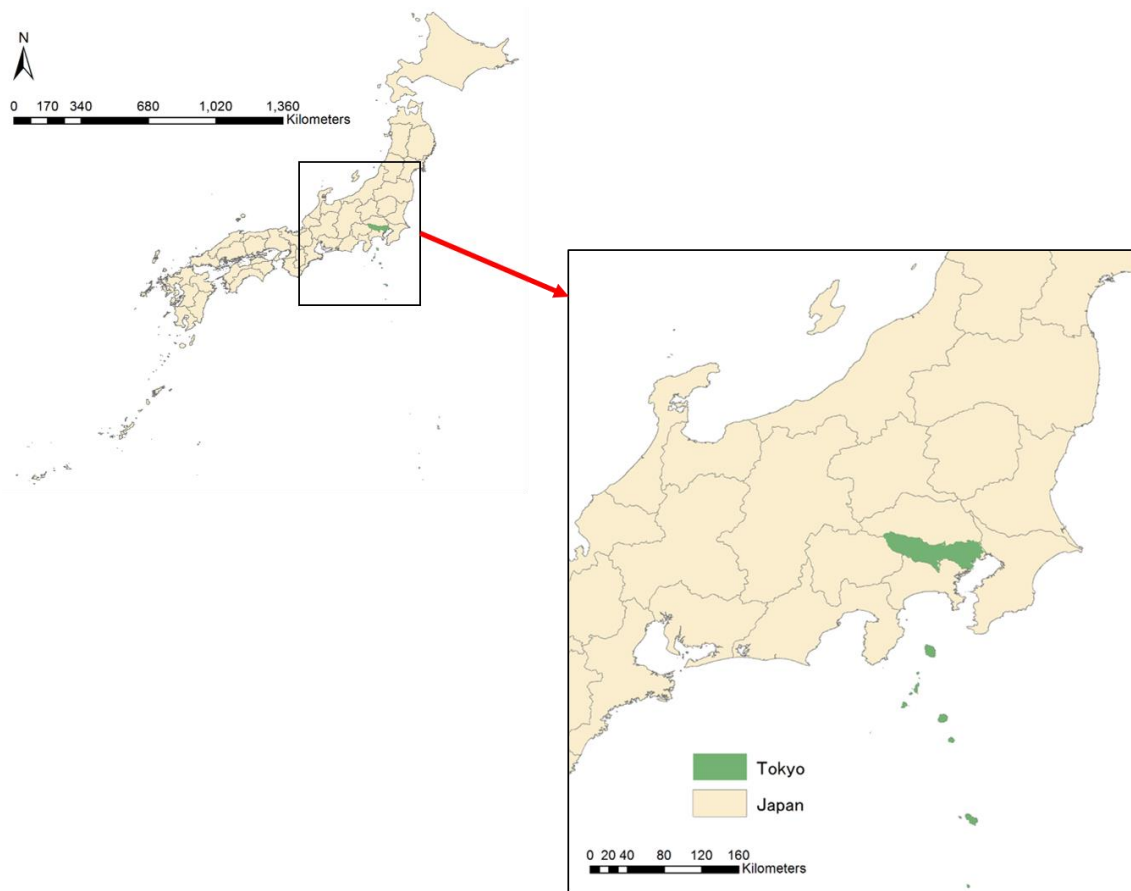


Figure 4.1. Location of Tokyo, Japan

In total, 84 pumping stations and 13 WWTPs are responsible for managing 4.51 million cubic meters of sewage in 23 wards, for a population of approximately 8.7 million people (Bureau of Sewerage, 2017). Figure 4.2 describes all the pumping stations and WWTPs in the Tokyo ward area. The sewerage systems in the ward area covers 100% of the population since March 1995 (Bureau of Sewerage, 2017).



Figure 4.2. Overall planning for Sewerage System in the Ward Area, Tokyo. (Source: Tokyo Bureau of Sewerage, 2017)

#### 4.1.2 Implementation of countermeasures to identified SLR- induced flooding

- Coastal flooding

Tokyo is originally in the downstream of Tonegawa (Tone river). However, in 1594 Shogun Ieyasu Tokugawa initiated the project of altering the direction of Tonegawa, which resulted in increasing the risk of flooding to Tokyo, as the area remained at a low elevation (Tsuchiya, 2014). The city then attempted to implement flooding countermeasures, heavily focusing on coastal protection schemes such as river embankment, dikes, and elevating the ground due to the nature of its topography. These countermeasures can also protect the WWTPs from coastal flooding.

Tokyo is also exposed to the risk of storm surges during typhoons. One of the worst events to affect the country was typhoon Vera (also known as Isewan Typhoon, which struck the Kansai Region in September 1959) (Tsuchiya, 2014). The maximum flood level caused by this typhoon (T.P. +2.61 m) was chosen as the standard design level for flooding countermeasures in Tokyo Bay. Therefore, most wastewater management facilities in Tokyo, such as Kiba pumping station have flooding countermeasures against this level of flooding. Essentially, a combination of raising the ground and using flood-proof structures at the entrance of the building was implemented to cope with such a high water level (see Figure 4.3 and Figure 4.4).



Figure 4.3. Elevated monitoring center at Kiba Pumping Station



Figure 4.4. Countermeasures to prevent water intrusion into building, designed against the storm surge expected for an event similar to Typhoon Vera (T.P. +2.61 m) in Kiba Pumping Station

Some WWTPs are situated in newly reclaimed areas (Ariake, Koto Ward), which were built to a level of T.P. +5.00 m high, which is considered safe from coastal flooding. Given that such newly reclaimed areas are situated in front of the lower lands, they also act as a barrier to protect the older areas.

- Discharge flooding

Most of the WWTPs in Tokyo are using gravity to discharge the treated water, except for three WWTPs, which use pumps to discharge. These WWTPs were installed with the discharge pump from the beginning of their operation.

As mentioned above, all WWTPs in the area were designed to withstand a storm surge similar to that caused by Typhoon Vera, which was T.P. +2.61 m. As a consequence, the level of the discharge point of most WWTPs in the Bay is around T.P. +3.00 m.

Most WWTPs have flap valves installed in their discharge pipes to prevent seawater intrusion during high tides.

- Groundwater inundation

Regarding the groundwater inundation issue, the government has so far not investigated its impacts. However, they can see the possible negative impacts that this can have, such as buoyancy or damage to underground facilities. However, in some important points countermeasures (such as using elastic materials for connecting points and pressure control inside the manholes) have already been implemented (see Figure 4.5).

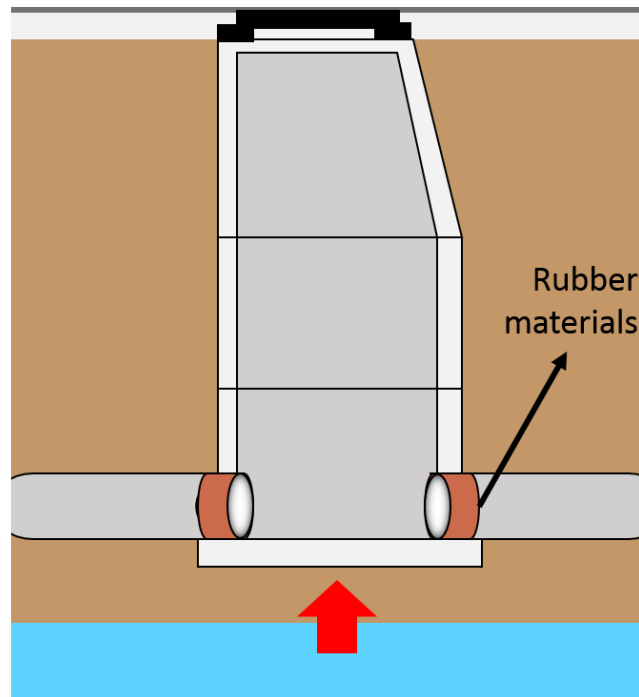


Figure 4.5. Rubber materials installed at the connecting points of major sewage pipelines to prevent damage due to buoyant force (adapted from Bureau of Sewerage, 2017)

The case of Tokyo demonstrates that the SLR countermeasures described in the proposed adaptation pathways are not just hypothetical, as they have indeed been implemented in many WWTPs.

Regarding the application of the proposed adaptation pathways, Tokyo does not face any significant financial obstacles (though these measures are nevertheless costly). Elevating parts or the entire extent of WWTPs would be highly effective against both coastal flooding and discharge flooding. However, this would be costly and require a long time to complete. Besides, the treatment plants have to operate 24 hours every day, and attempting to elevate them while maintaining service would be difficult, particularly in the Tokyo area, where there is limited space for infrastructure development.

The typical life cycle of a WWTP is around 60 to 80 years. After this period, the WWTP should be

rebuilt or replaced with new facilities. Therefore, the author suggests that Tokyo should incorporate additional adaptation measures when the time comes to renovate existing WWTPs.

Moreover, SLR can exacerbate the consequences of extreme disasters such as storm surges and tsunamis, which can then result in higher damage to WWTPs. WWTPs in Tokyo should consider such impacts when planning to adapt to extreme events such as storm surges and tsunami.

## **4.2 Ho Chi Minh City**

### **4.2.1 Wastewater management in Ho Chi Minh City**

Ho Chi Minh City (HCMC) is the largest industrial city in Vietnam, with its economy and population continuing to expand rapidly (see Figure 4.6 for the location of the city). The city is home to almost 8.4 million people (as estimated in 2019, Population Stat, 2019). This densely populated city is only situated around 1.5 m above sea level, and it is projected to be one of the most vulnerable cities to SLR in the future (Revi et al., 2014). Currently, HCMC is already suffering from frequent flooding every year.

HCMC urgently needs to expand its wastewater treatment facilities. In Vietnam, only 10% of the collected domestic wastewater is treated at WWTPs (World Bank, 2013) (see Figure 4.7). Furthermore, the rapid growth of urban population due to the development of the city will put higher pressure on its wastewater management.



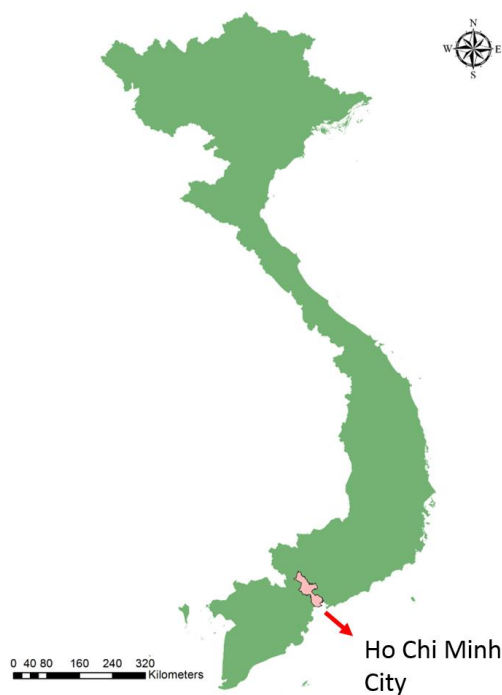


Figure 4.6. Location of Ho Chi Minh City, Vietnam\*\*

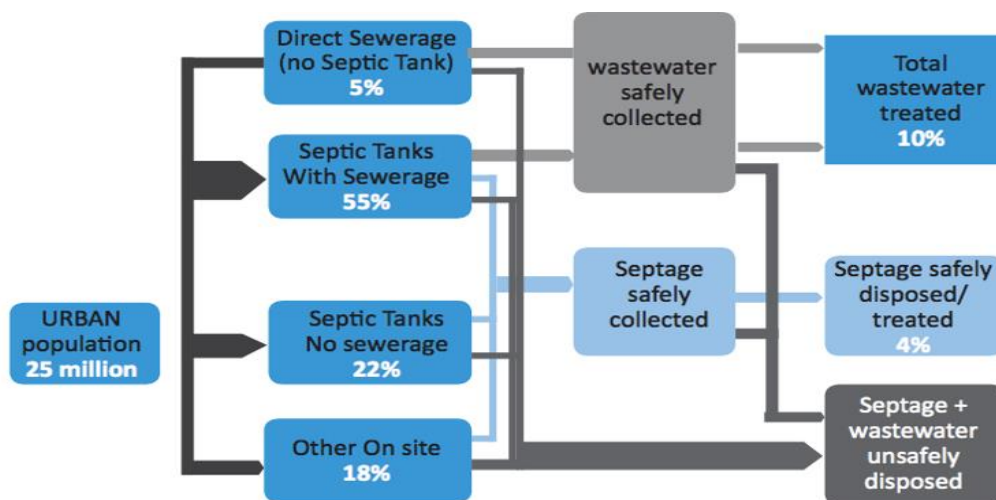


Figure 4.7. Status of urban wastewater treatment in Vietnam in 2013 (World Bank, 2013)

There are only 20 WWTPs in the whole of Vietnam, three of which are in HCMC, ( two of them are treating around 13% of the total amount of wastewater in the city and the other is still under testing before it can begin operation, see Figure 4.8). At the time of writing, another WWTP had just been constructed and would be entering operation (Nhan Dan, 2018).

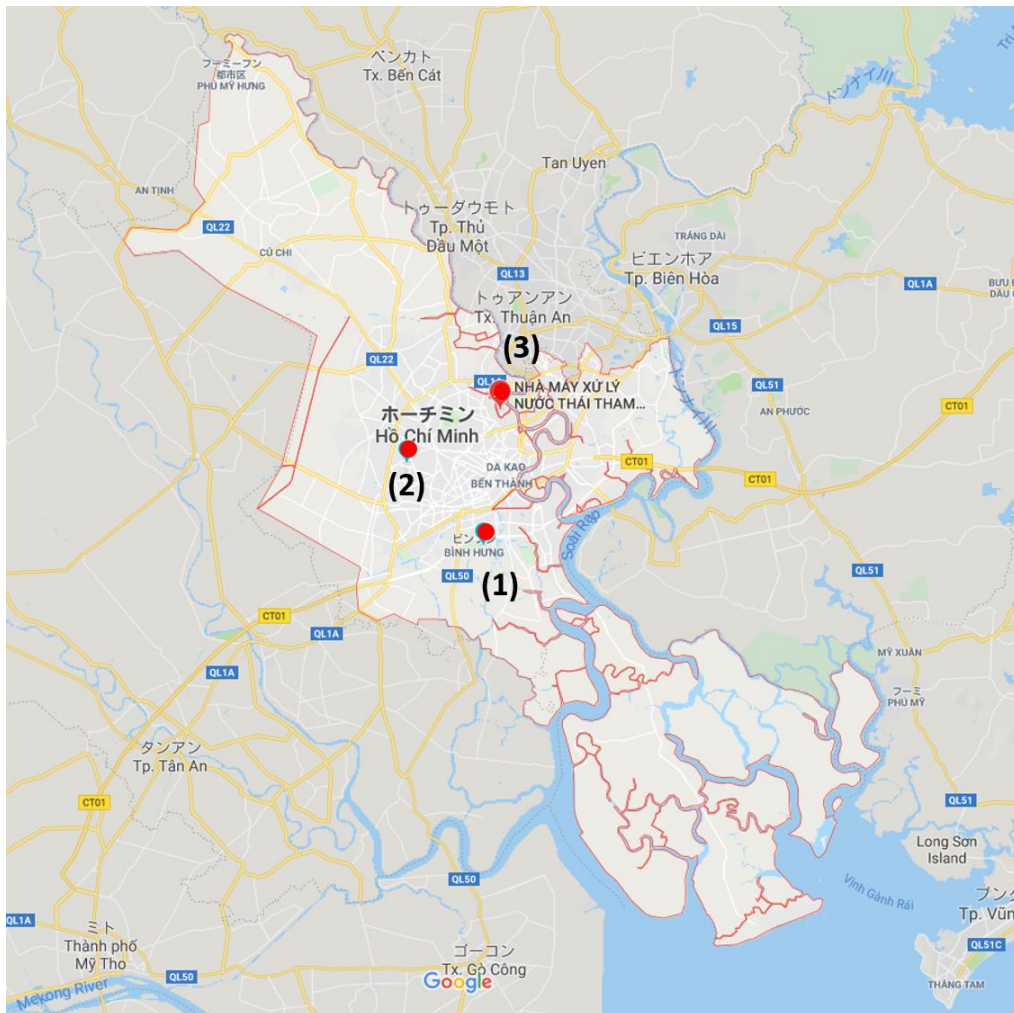


Figure 4.8. Operating Municipal WWTPs in HCMC (1) Binh Hung WWTP, (2) Binh Hung Hoa WWTP, and (3) Tham Luong – Ben Cat WWTP  
(Source: Google Maps)

#### 4.2.2 Application feasibility

Regarding the feasibility of the proposed adaptation pathways, HCMC seems to have many financial challenges. The city has received funding and investments from other countries, for example, Japan (Swing, n.d.) (see Figure 4.9). The government aims to being able to treat 80% of the domestic wastewater by HCMC in 2020. However, this currently appears to be too ambitious and the goal might not be realistic. Nevertheless, the city expects to finish constructing 12 WWTPs by 2025, which would cover 100% of the population. This plan might be unrealistic, and currently Ho Chi Minh City is calling for investors for 7 WWTPs, representing a total of almost 2 billion USD (Nhan Dan, 2018).



Figure 4.9. Ho Chi Minh WWTP constructed with funding from Japan ODA loan  
(Source: Swing, n.d.)

For vulnerable coastal cities in developing countries such as HCMC, the city should prioritize and foster the process of constructing new WWTPs to meet the demand for sewage treatment for the population. If the countermeasures are implemented from the beginning of construction of the WWTPs, it would be time-consuming and costly. According to Tokyo Metropolitan Government, a WWTP that is rigorously designed and constructed takes around 10 years to be finished and ready for operation. New York City, in its Wastewater Resiliency Plan, estimated the cost for protective measures for its 14 WWTPs to be US\$187 million (New York City, 2013). However, cities such as HCMC find it challenging just building WWTPs, and thus implementing countermeasures at present would represent an unnecessary extra cost.

Therefore, affordable countermeasures that can be implemented after WWTPs are built, such as a discharge pump and protective structures surrounding the plants are more feasible than elevating the ground of the components of the WWTPs. The author suggests that new WWTPs should be designed with adaptive capacity, which means that SLR – adaptive flooding countermeasures such as discharge pumps and concrete protective structures either surrounding the buildings of the WWTPs or at the coastline can be easily added after the construction of the WWTP is completed.

While Tokyo has implemented various flooding countermeasures already, many other vulnerable coastal cities such as Ho Chi Minh City still lack detailed and long-term adaptation for WWTPs. Hence, the proposed thinking of developing adaptation pathways is useful and applicable to such cases.

## **CHAPTER 5. Conclusion**

### **5.1 Key findings and implication for WWTPs**

In the present work, the author conducted in-depth interviews with staff from WWTPs in the Tohoku area in Japan to learn about possible future adaptation to SLR in these types of installations.

The results suggest that many WWTPs in Japan would be relatively unhindered by SLR of up to 0.53 m (scenario 1 in the present thesis, the median value of global mean SLR for RCP 4.5 scenario by the year 2100, according to the IPCC AR5, 2013). However, it should be noted that even for those levels, the surveyed treatment plants experienced seawater backflow into the discharge channel and an increased amount of “unknown water” entering the sewage pipes. Therefore, even a limited amount of SLR will also bring with it some minor problems, and hence the longer-term impacts of SLR on WWTPs will vary according to the design and topography of each plant.

According to Climate Action Tracker (2018), current policies are setting global warming on track for a 3.3 Celsius increase in temperatures by the end of this century, which would lead to a higher SLR scenario than RCP 6.0 (higher than RCP 4.5, which represents scenario 1 of the present thesis). Hence, according to Climate Action Tracker’s warming projection, it can be inferred that under current climate policy, global mean SLR by 2100 would be much higher than 0.53 m. In such a scenario, WWTPs in coastal areas might have to construct countermeasures before the end of this century. Considering that the process of planning and implementing adaptation actions is time-consuming, WWTPs might have to start

planning adaptation measures to SLR impacts towards the middle of this century.

The critical technical design parameters of WWTPs that influence their adaptation pathways to SLR are the ground level, discharge level, and groundwater level. These critical levels determine the vulnerabilities of any WWTP to SLR and lead to three types of flooding: coastal flooding, discharge flooding, and groundwater inundation. The impacts of these types of flooding on WWTPs and countermeasures were discussed in details.

Finally, the author proposed a general method of constructing adaptation pathways for vulnerable WWTPs based on the interview results and existing studies on adaptation pathways. Applications of the proposed methods to case studies WWTPs indicated that the adaptation measures and timing for taking actions vary depending on the design and topography of each WWTP.

The proposed SLR scenario dependent adaptation pathways can help policy-makers and planners to predict which type of flooding will have to be dealt with first and serve as a flexible guideline towards the adaptation sequence to SLR in the course of the 21<sup>st</sup> century.

## **5.2 Suggestions for future research**

In this study, the author identified three types of SLR – induced flooding, namely coastal flooding, discharge flooding, and groundwater inundation. Groundwater inundation can have severe impacts on WWTPs. However, there is a comparative lack of research or monitoring of the groundwater levels and

its impacts on wastewater management. Essentially, there is a need to understand the relationship between SLR and the changes in groundwater levels. Also, the impacts of SLR – induced groundwater inundation on a complicated installation such as the WWTP should be thoroughly modeled or simulated.

As mentioned above, water level changes during extreme events such as storm surges or tsunamis are out of the scope of the present work. Researchers are encouraged to include the impacts of such extreme events in the development of SLR adaptation pathways.

The proposed adaptation pathways not only provided sequences of countermeasures but also included timing for WWTPs to put those countermeasures in place. This timing was referred to as thresholds to intervene in the present work. However, there is still limited understanding or estimation of when to initiate the process of design and construction adaptation measures. The next step in adaptation research should focus on determining the signals from the stressors (such as SLR) that triggers the decision-making point in an adaptation process.

Finally, all case study WWTPs in the present thesis are located in Japan. The results obtained from these case study WWTP may depend on the socio-economic context of Japan. Therefore, the author suggests future research should investigate in WWTPs in other locations in the planet that have experienced land subsidence to increase the sample size and provide a variety of the local contexts.

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- \*\* Map created using ArcGIS tool and boundary data from Humanitarian Data Exchange. Retrieved from: [https://data.humdata.org/dataset/viet-nam-administrative-boundaries-polygon-polyline?fbclid=IwAR1efiZ8y3vY\\_ASugyJ3ffEEd4MBMBrtud9EcJvHHGLZ-h-yQQZhA318bJU](https://data.humdata.org/dataset/viet-nam-administrative-boundaries-polygon-polyline?fbclid=IwAR1efiZ8y3vY_ASugyJ3ffEEd4MBMBrtud9EcJvHHGLZ-h-yQQZhA318bJU)
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## APPENDIXES

### APPENDIX A

#### **Semi-structured interviews with staff from Wastewater Treatment Plants (WWTPs)**

Date:

Time started:

Time ended:

WWTP:

Number of interviewees:

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<Key interview questions>

1. What were the impacts of land subsidence on the WWTP?
2. How did the WWTP deal with land subsidence? What were the immediate actions and the long-term actions?
3. Were there any difficulties in implementing the countermeasures regarding financial support, technical limits and social acceptance?
4. Were the countermeasures cost-benefit?
5. What are the impacts of future sea level rise on the WWTP given its experience with land subsidence?

## APPENDIX B

### 宮城県仙台市・石巻市における下水処理施設訪問調査

日付：

時間：

開始時間：

終了時間：

下水処理場：

面談の人数：

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#### <面談の主な質問>

1. 下水処理場が地盤沈下に直面したとき、どのような影響を受けたか？
2. 下水処理場が地盤沈下に直面したとき、直後の応急的な対応策、および長期的な対応策としてどのような技術的対応策をとったか？
3. 上記の措置を講じた際に、財政面、技術面に何らかの困難があったか？ また、周辺住民との関係や社会的な制約など技術以外の面で何か課題があったか？
4. これらの対応策に実際にかかった費用と、その効用を比べたときに、費用対効果についてどう考えるか？
5. 地盤沈下の経験を考慮すると、将来の海面上昇が下水処理場に与える影響は何ですか？