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A quantitatively effectiveness of hybrid sewerage systems allowing rainwater flow into sewage facilities for disaster prevention of inland flooding

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A quantitatively effectiveness of hybrid sewerage systems allowing rainwater flow into sewage facilities for disaster prevention of inland flooding

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Abstract

In Japan, recent low birthrate and aging population have progressively led to a crisis for infrastructure. In particular, the quantity of drainage from homes and factories is remarkably decreasing, along with the decline of economic activity resulting from the overseas move of Japanese companies. As a result, a condition of overcapacity of sewage systems has arisen. On the other hand, the risks of natural disaster, such as damage from local flooding by heavy rain, are rapidly increasing. But the capacity of rainwater drainage systems remains chronically short. We suggest that underground space is not being used effectively in urban sewage systems.

In our study, which focused on the rainwater sewage systems and sewage systems of enormous social capital infrastructure, we commented on the conditions and problems of two systems. To improve the spatial conditions of the two systems, we suggested that space reallocation is required. As such, we proposed a framework of hybrid sewerage systems and showed its various benefits in terms of environmental issues and disaster prevention of inland flooding. Targeting a specific district in Japan, we estimated that the capacity of rainwater drainage systems would improve from 61.6mm/hr. to 65.0 mm/hr. by introducing hybrid usage of sewerage systems. As a result, the possibility of inland flooding damage in this district could be reduced up to 20.7%. Realizing hybrid sewerage systems would contribute greatly to appropriate reallocation policy for underground water system space, compared with the river reforming works and the rainwater drainage pipes' constructions.

Considering the problem from an institutional viewpoint, the sewage business is planned and operated based on the decisions of city planners, so in order to construct and perform hybrid sewerage systems, it is important to re-adjust the duties of various relevant authorities.

Considering the problem from a technical viewpoint, in order to allow rainwater into sewage facilities, it is important to devise rules for controlling rainfall inflow and outflow to and from sewage disposal plants. Namely, it is required that inflow loads are reduced at sewage disposal plants.

We approach the institutional and technical problems in carrying out hybrid sewerage systems, in two parts. 1) We suggest that rainwater drainage systems should be treated as a part of whole city systems, as opposed to separating rainwater drainage systems and sewage systems. 2) We construct the Intelligent Rainwater and Sewage Systems (IRSS) concept for handling environment issues and disaster prevention by fully utilizing the capacities of rainwater drainage systems and sewage systems.

Finally, we should still expect and be prepared for minimal damage such as local flooding, and should work for a sustainable life environment in the long term. To improve city planning in safety, relief and comfort, we hope IRSS can be included as a part of space reallocation policies by fully exploiting unused capacities.

Key words

Hybrid sewerage systems, Disaster prevention of inland flooding, Infrastructure management

1 Introduction

Due to the massive population increase and industrialization in the late 20th century, Japan built up its infrastructure. Today, however, the amount of sewage from homes and factories is rapidly decreasing, and the capital for infrastructure maintenance and renewal has dramatically declined due to the recent low birth rate, aging population, and Japanese companies moving overseas. [1] However, citizens still demand reliable sewer and rainwater drainage systems that meet or exceed the current level of service. These conditions have results in a sewer system that is expensive and not operating near its full capacity. Simultaneously, global climate change has increased the risk of a natural disaster, such as local flooding due to torrential rain. Unfortunately the capacity of the rainwater drainage system in Japan is insufficient. Thus, creative solutions are necessary to minimize the cost of infrastructure renewal and maintenance. [2] [3]

Our research indicates that urban sewer systems do not efficiently utilize underground space with respect to environmental issues and disaster prevention. Thus, we suggest the strategic implementation of a hybrid sewer system that can handle both sewage and rainwater drainage. Herein we develop a scheme where rainwater, which is polluted or exceeds the capacity of the rainwater drainage system, is directed into sewage treatment facilities, and quantitatively show the impact of a hybrid sewer system on environmental issues and disaster prevention.

The rest of this paper is organized as follows. Chapter 2 comments on the current conditions and problems of the sewer and rainwater drainage systems in the target area. We suggest reallocation is necessary to improve the spatial conditions. Chapter 3 proposes a framework for a hybrid sewer system, and shows the effects with respect to environmental issues and disaster prevention. Chapter 4 comments the circumstances and future prospects by conventional schemes reduced the inland flooding damage in Nagaokakyo City, while Chapter 5 quantitatively assesses the effectiveness of a

hybrid sewer system. Finally Chapter 6 summarizes the research results, addresses implementation hurdles, and provides suggestions to improve the sewer and rainwater drainage systems.

2 Conditions and Problems

2.1 Sewer system

In our study, the target area is Nagaokakyo city, which is located on flat protected lowland in the Kyoto Prefecture of Japan. The population density for inhabitable land is about 7,000 persons/km^2.

Nagaokakyo city began treating sewage in 1974. The diffusion rate of the sewer systems is 99.3% (April 1, 2013). Although the city's population now is comparable to that in 1974, the amount of drainage from homes and factories has drastically decreased due to a decline in economic activities and improvements in polluted water processing techniques. Consequently, the sewer system (both sewage pipes and disposal plants) is not operating near its designed capacity in the target area.

Figure 1: Location of the target area

2.2 Rainwater drainage system

In the target area, the probable maximum precipitation is 53.1 mm/hr. (return period: 5 years) and 61.6 mm/hr. (return period: 10 years). However, precipitation of 76.5 mm/hr. (July 2008) and 96.0 mm/hr. (August 2010) were reported. Thus, heavy rainfall can lead to inland flooding and damage in the target area. Additionally, global climate change has increased the risk of a natural disaster (e.g., local flooding due to torrential rain). However, the capacity of the rainwater drainage system remains insufficient due to the slow outflow from the flat protected lowland and difficulties improving the rainwater drainage system.

2.3 Spatial conditions of rainwater drainage and sewer systems

The previous two sections demonstrate that underground space is inefficiently utilized in urban sewer systems. Figure 2 shows the current utilization of underground space for sewage and drainage. Reallocation of this space could greatly improve the spatial conditions of the rainwater drainage and sewer systems.

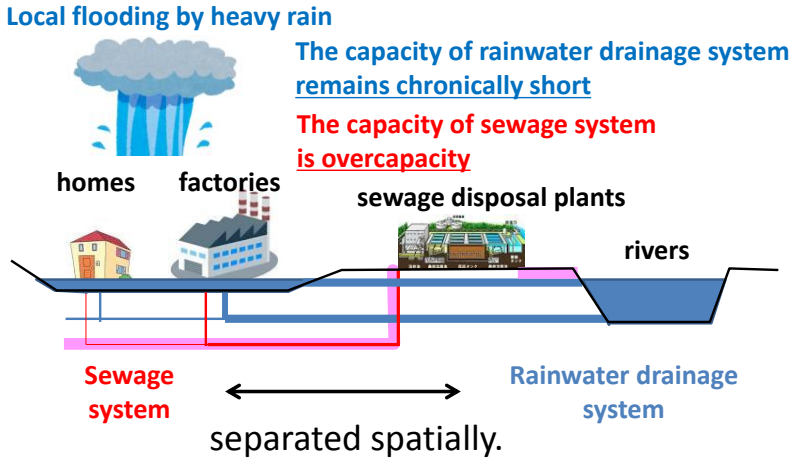

Figure 2: Spatial conditions of the rainwater drainage and sewer systems

3 Hybrid sewer system

3.1 Framework of a hybrid sewer system

Figure 3 depicts the framework for a hybrid sewer system that can accommodate both sewage and rainwater drainage. As a disaster prevention measure, when heavy rain or another critical situation causes the rainwater drainage system to reach capacity, the spare space in the sewage (polluted water) pipes allows rainwater to flow into sewage treatment facilities. Instead of permanently combining the sewer and rainwater drainage systems, a hybrid sewer system has the ability to allow the some rainwater to flow into the sewer system when needed.

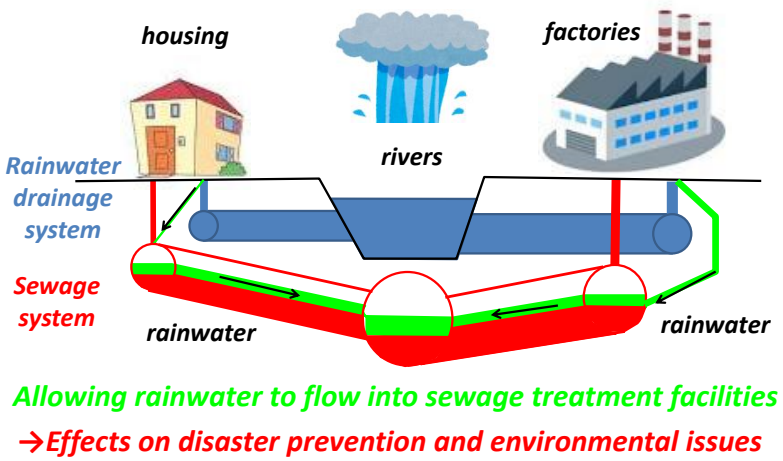

Figure 3: Framework for a hybrid sewer system

3.2 Effects of a hybrid sewer system

3.2.1 Decreased damage from local flooding

Figure 4 shows the impact of increasing the capacity of the rainwater drainage system. Using the currently unused space of the sewer system allows rainwater to flow to sewage treatment facilities,

thereby increasing the capacity of the rainwater drainage system while reducing the frequency of local flooding.

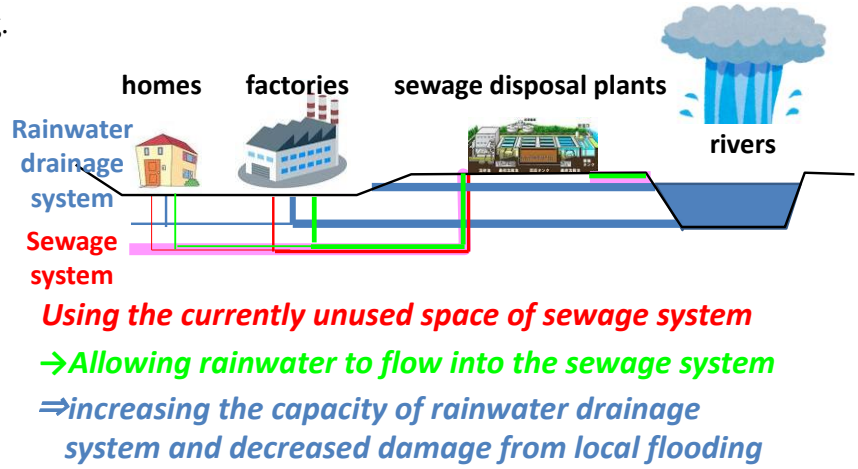

Figure 4: Impact of increasing the capacity of the rainwater drainage system

Figure 5 shows the effect of reducing damage due to local flooding. Prior to implementing a hybrid sewer system, each district has its own rainwater drainage system or systems. However, the hybrid sewer system allows multiple rainwater drainage systems within a district and from different districts to function as one larger unit, which will decrease damage from local flooding.

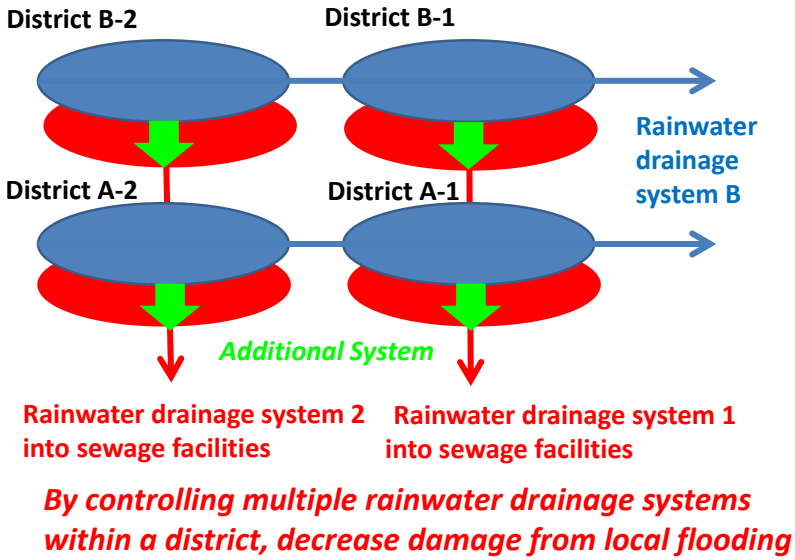

Figure 5: Impact of a hybrid sewer system on damage from local flooding

3.2.2 Impact on environmental issues

Figure 6 shows the effect of a hybrid sewer system on environmental issues. The initial rainwater is polluted water from multiple sources, including dust on the road. By allowing the initial rainwater to flow to sewage treatment facilities, less polluted water will be discharged into the river. Additionally, rainwater will rinse out the sewage (polluted water) pipes, which should have a positive environmental impact, such as deodorizing the sewage pipes.

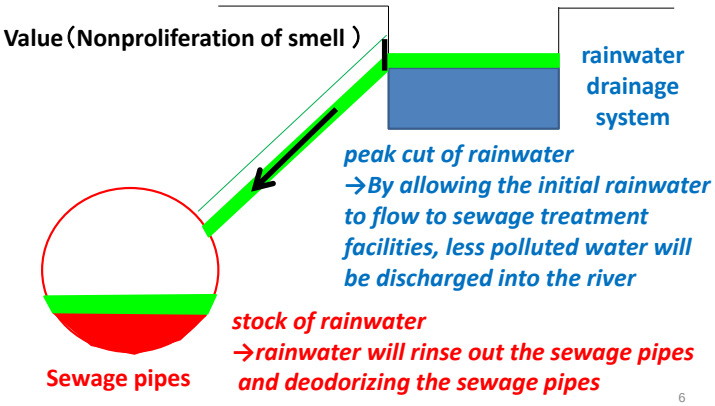

Figure 6: Effects on environmental issues

4 Circumstances to reduce inland flooding damage in Nagaokakyo City

4.1 Overview of the rainwater drainage pipes, sewage pipes, and inland flooding areas

Figure 7 shows the location of the rainwater drainage pipes, sewage pipes, and inland flooding areas. Rainwater in Furo River's drainage zone flows into the Obata River through Imazato rainwater's pump station and inflow entrance 4. Rainwater in Inu River's drainage zone flows into the Inu River through inflow entrance 1. Sewage water flows into sewage pipes (city) as well as sewage pipes (prefecture), and eventually is treated at the Rakusai sewage disposal plants.

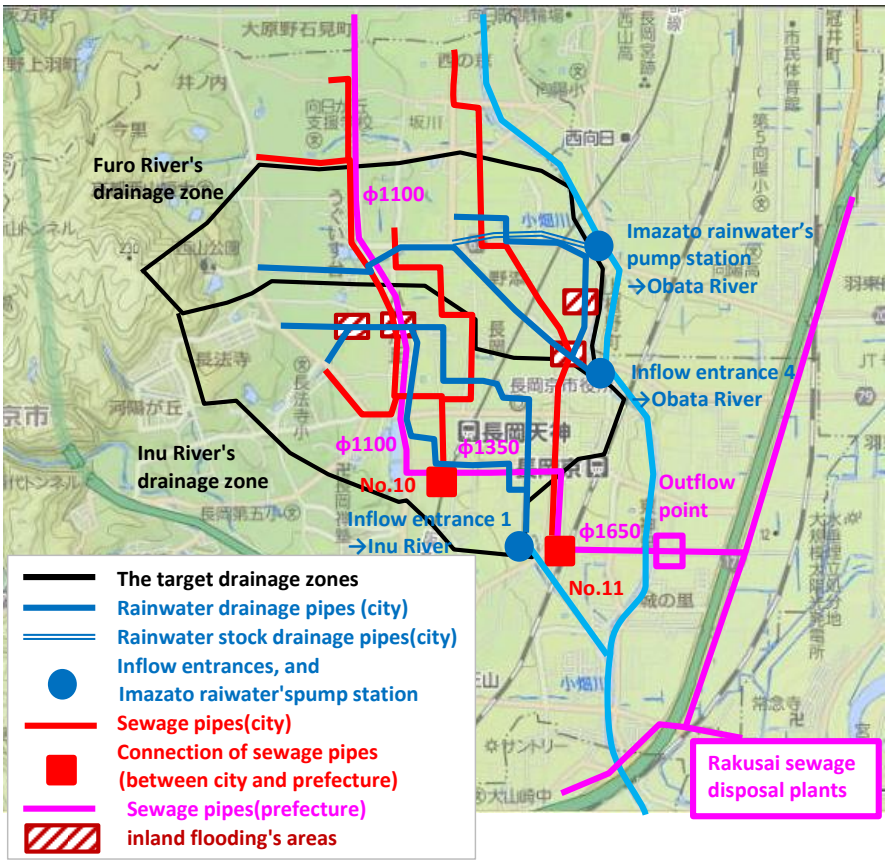

Figure 7: Locations of the rainwater drainage pipes, sewage pipes, inland flooding areas

4.2 Factors leading to inland flooding damage

Figure 7 shows four inland flooding's areas: two within the lower side of the Furo River's drainage zone and two on the upper side of the Inu River's drainage zone. In the Furo River's drainage zone, which often sustains inland flooding damage, river reforming work was planned with an outflow of 53.1 mm/hr rainwater (return period: 5 years). In 2005, Nagaokakyo City constructed both rainwater stock drainage pipes and Imazato rainwater's pump station, which control an outflow of 61.6 mm/hr. rainwater (return period: 10 years). In the Inu River's drainage zone, river reforming work was planned under an outflow of 61.6 mm/hr. rainwater (return period: 10 years). However, a narrow space where the Inu River crosses the lower side of inflow entrance 1 and the JR Tokaido Line, which is a vital railroad route between Osaka and Tokyo, remains. In rainy weather, rainwater flowing into the Inu River is stocked and flows backward from this crossing place. Consequently, inland flooding damage occurs in this area.

4.3 Current situation and future prospects to reduce inland flooding damage

The first part of the policy is to reduce inland flooding by reforming the river. Although this policy has shown positive results, progress is unsteady because both the Furo River's and the Inu River's drainage zones are densely populated residential areas.

The second part of the policy is to construct rainwater drainage pipes as part of sewerage projects. In the Inu River's drainage zone, an outflow capacity of 61.6 mm/hr. rainwater (return period: 10 years) is satisfactory, but the Furo River's drainage zone requires an outflow capacity of 53.1 mm/hr. rainwater (return period: 5 years) due to the limited underground space. Rainwater stock drainage pipes have been constructed in the Furo River's drainage zone. However, rainwater flowing into stock drainage pipes must be pumped out because the level of the rainwater stock drainage pipes is lower than those for the Obata River. As a result, Nagaokakyo City has spent 3.8 billion yen to construct Imazato rainwater's pump station.

The future policy must include projects to reform the Inu River where it crosses the JR Tokaido Line. The estimate cost is over 10 billion yen because the JR Tokaido Line has quadruple track. Hence, future prospects to reduce inland flooding damage by conventional schemes remain deadlocked due to monetary constraints.

5 Increased capacity of the rainwater drainage system by a hybrid sewer system

5.1 Hybrid sewer system

Figure 8 depicts a hybrid sewer system where the connection pipes are constructed with stick-traps between rainwater drainage pipes and sewage pipes. In dry weather, the stick-traps prevent the foul-smelling gas in the sewage pipes from escaping. However in rainy weather, the

overflow-rainwater should flow from the rainwater drainage pipes to the sewage pipes, but not flow backward from the sewage pipes.

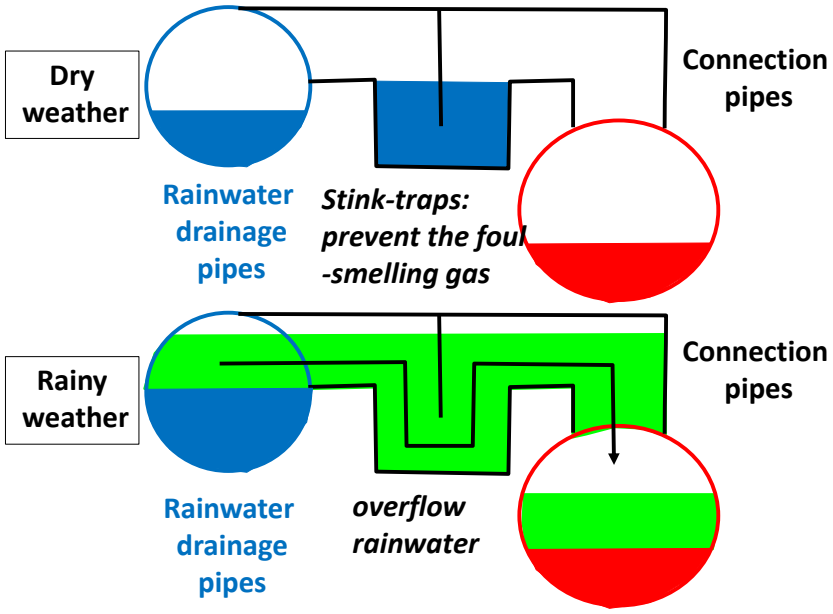

Figure 8: Connection pipes in a hybrid sewer system

5.2 Selection of connection points (CPs)

First places where the connection pipes between rainwater drainage pipes and sewage pipes are lined up at appropriate positions are identified as candidates (Fig. 9). Of the four connection points (CPs), two connection points in the drainage zone are feasible and efficient locations for connection points.

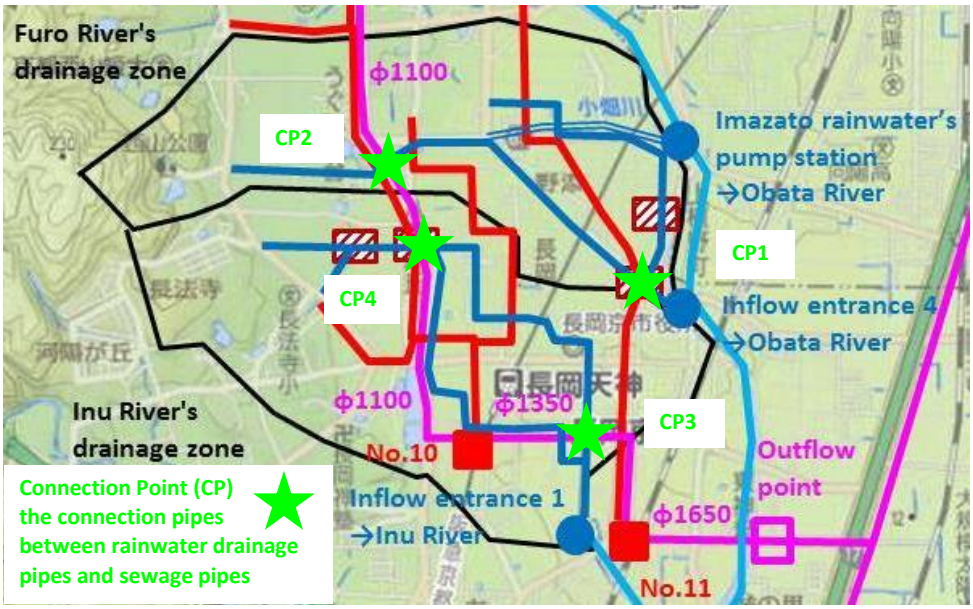

Figure 9: Location of the connection points (CPs)

In the Furo River's drainage zone, CP1, which is upstream of the junction of two rivers, is a candidate because constructing connections pipes from the Furo River's first drainage pipes to the sewage pipes (city) should reduce inflow into the Obata River. Similarly, CP2, which is the crossing area of the Furo River's first rainwater drainage pipes and sewage pipes (prefecture), is a candidate because connection pipes at this location will reduce inflow to the Furo River.

In the Inu river's drainage zone, CP3, which is the crossing area of rainwater drainage pipes and sewage pipes (prefecture) No.10–No.11, is a candidate because connection pipes at this location will restrain inflow backward from the Inu River. CP4, which is the crossing area of the rainwater drainage pipes and sewage pipes (prefecture), is a candidate because inflow to the Inu River's first rainwater drainage pipes will be reduced by constructing the connection pipes at this location.

In order to reduce construction costs and time, all the proposed connection points are where rainwater drainage pipes and sewage pipes intersect. Additionally, each location has extra space for the connections; CP1 is located at the intersection of two-lane roads, while CP2, CP3, and CP4 are located on four-lane roads. Moreover, the connections points of the rainwater stock drainage pipes can be secured underground at these locations.

5.3 Definition and calculation of the rate of allowance space

We define the rate of allowance space as the percentage of spare space to the total capacity of the sewage pipes. The allowance space's rate (Ra) can be expressed as

$$\mathrm{Ra} = 1 - \mathrm{Rs} - \mathrm{Rw} \quad (1)$$

Ra: Percentage of spare space to the capacity of sewage pipes

Rs: Percentage of sewage inflow to the capacity of sewage pipes

Rw: Percentage of rainwater flowing into sewage pipes naturally to the capacity of sewage pipes

Rs of equation (1) can be expressed as

$$\mathrm{Rs} = \mathrm{Vs}/\mathrm{Cs} \quad (2)$$

Vs: Sewage inflow of the sewage pipes (m3/s)

Cs: Capacity of sewage pipes (m3/s)

Rs is set to 47.8%, which is the percentage of the average daily wastewater flow in dry weather (143,736 m3/day) relative to the maximum hourly wastewater flow (300,500 m3/day) in the Rakusai sewage disposal plants [4].

Rw of equation (1) can be expressed as equations (3) and (4).

$$\mathrm{Rw} = \mathrm{Vw}/\mathrm{Cs} \quad (3)$$

$$\mathrm{Vw} = \delta \times \mathrm{A} \times \mathrm{r}(\mathrm{T}, \mathrm{t}) \times \mathrm{t}/\mathrm{Tf} \quad (4)$$

δ: Volume of rainwater flowing into sewage pipes naturally when 1-mm rainwater falls into a 1 ha. zone (m3/ha/mm)

A: Target zone size (ha)

$r(T, t)$: Rainfall intensity (mm/hr.)

T: Return period (year/times)

t: Continuous time of rainfall (hr.)

Tf: Time when rain subsides and rainfall is outflowing from the target area minus the time when rainfall begins (s)

δ is set to 0.2862 m3/ha/mm as a percentage of increasing sewage inflow to the plants for 1-mm rainfall (1,181 m3) to the size of the sewage treatment area in the Rakusai sewage disposal plants (4,127 ha).

To evaluate the increased capacity of the rainwater drainage system by the hybrid sewer system, we assume that 61.6 mm/hr. rainwater (return period: 10 years) falls into the two zones (Furo River's drainage zone and Inu River's drainage zone, 288 ha) continuously over 1 hr.

When we assume$Tf = 7{,}200$ s, the values of some indexes of the sewage pipes at the outflow point are$Vw = 0.705\ \mathrm{m3/s},\ Cs = 5.648\ \mathrm{m3/s},\ Rw = 12.5\%,\ Ra = 39.7\%.$

5.4 Increased capacity of the hybrid rainwater drainage system

We evaluate the increased capacity of the rainwater drainage system quantitatively by constructing the four connection pipes (CP1–CP4) between the rainwater drainage pipes and the sewage pipes and operating the hybrid sewer system. The preconditions are as follows:

- 61.6mm/hr. rainwater (return period: 10 years) falls into the two zones (Furo River's drainage zone and Inu River's drainage zone) continuously for 1hr.
- The designed discharge in the Furo River's drainage zone is 14.755 m3/s (return period: 10 years). The designed discharge in the Inu River's drainage zone is 23.841 m3/s (return period: 10 years) [5].
- Each rainwater inflow volume into the sewage pipes in CP1–CP4 is allocated as the increasing rate of discharge in the Furo River's drainage zone, which is similar to the one in Inu River's drainage zone.
- The rainwater inflow volume to the sewage pipes in each CP cannot exceed Ra × the capacity of each sewage pipe.
- The sum of the rainwater inflow volume to the sewage pipes in CP1–CP4 cannot exceed Ra × the capacity of sewage pipes (prefecture) (⌀ 1650).
- The sum of the rainwater inflow volume to the sewage pipes in CP2, CP3, and CP4 cannot exceed Ra × the capacity of sewage pipes (prefecture) (⌀ 1350).
- The sum of the rainwater inflow volume to the sewage pipes in CP2 and CP4 cannot exceed Ra × sewage pipes (prefecture) (⌀ 1100).

When the hybrid sewer system is operating, the rainwater drainage systems in the two zones are effective, even if 65.0 mm/hr. rainwater falls for an hour. .The percentage of spare space to the capacity of sewage pipes is 39.0%. The sum of rainwater inflow volume to sewage pipes in CP1–

CP4 is 2.132 m3/s. The increasing rate of discharge in the two zones is 5.52%. Table 1 shows the details of the calculated increased capacity.

Table 1: Increased capacity of the rainwater drainage system

	CP1	CP2	CP3	CP4	Outflow Point
Name of rainwater drainage pipes	Furo river 1st	Furo river 1st	Inu river 1st	Inu river 1st	two zones
Name of sewage pipes	(city)	(prefecture)	(prefecture)	(prefecture)	(prefecture)
Inside diameter of sewage pipes ø(mm)	800	1100	1350	1100	1650
Slope of sewage pipes I	1/500	1/200	1/170	1/200	1/500
Designed discharge of river's drainage zone(m3/s)	14.755	14.755	23.841	23.841	38.596
The capacity of sewage pipes (m3/s)	0.506	2.312	4.962	2.312	5.648
Percentage of spare space to the capacity of sewage pipes	39.0%	39.0%	39.0%	39.0%	39.0%
Maximun of rainwater inflow volume to sewage pipes(m3/s)	0.197	0.901	1.935	0.901	2.202
Rainwater inflow volume to sewage pipes(m3/s)	0.197	0.618	1.033	0.283	2.132
The increasing rate of discharge	1.34%	4.19%	4.33%	1.19%	5.52%
The increasing rate of discharge (river's drainage zone)		5.52%		5.52%	5.52%

5.5 Reduced likelihood of inland flooding damage

We estimated the likelihood of inland flooding damage in the target zones with a hybrid sewer system using an analysis program for rain, AMEDAS (Automatic Meteorological Data Acquisition System) [6]. The Fair-formula used this program can be expressed as equation (5).

$$r(T,t) = \frac{bT^m}{(t+a)^n} \tag{5}$$

$r(T,t)$: Rainfall intensity (mm/hr.)

T: return period (year/times)

t: continuous time of rainwater (hr.) t=1

a, b, m, n: parameters designed by the target district (Nagaokakyo City 1976-2000)

(a=0.13, b=38.35196, m=0.232421, n=0.6687551)

The likelihood of inland flooding damage is estimated before and after implementing a hybrid sewer system. Prior to a hybrid sewer system, inland flooding damage occurs when rainfall exceeds 61.6 mm/hr. with a frequency of 0.0916 times/year. After implementing a hybrid sewer system, inland flooding damage does not occur until rainfall exceeds 65.0 mm/hr., reducing the frequency to 0.0727 times/ year. Consequently, implementing a hybrid sewer system would reduce the likelihood of inland flooding damage in two zones by 20.7%.

Table 2: Reduced likelihood of inland flooding damage

	Before	After
continuous time of rainwater (hr)	1	1
rainfall intensity(mm/hr)	61.6	65.0
return period(year/times)	10.918	13.760
The likelihood of inland flooding damage(times/year)	0.0916	0.0727
Reduced likelihood		20.7%

6 Conclusion

This study commented on the conditions and problems with Japan's infrastructure, mainly the sewer and rainwater drainage systems. Space allocation is required to improve the spatial conditions and functions. We propose a strategy involving a hybrid sewer system as an economically feasible long-term solution, and demonstrate its impact on environmental issues and disaster prevention using a target district in Japan. In addition to fully utilizing the sewer system, which is currently not operating near full capacity, we estimated that the capacity of the rainwater drainage system would improve from 61.6 mm/hr. to 65.0 mm/hr. without degrading the current quality of the sewer system. This increased capacity will reduce the likelihood of inland flooding damage in two zones by 20.7%.

In addition, the estimated increase in wastewater inflow in the Rakusai sewage disposal plants is about 16,000 m3 by operating a hybrid sewer system under our evaluation's conditions. Compared to the wastewater inflow in the Rakusai sewage disposal plants from Nagaokakyo City, which is 11,276,816 m3/year, this increase is negligible. We estimate that construction costs of the connection pipes will be about several hundreds of million yen. Because the policy to reduce inland flooding damage must be more efficient and effective, the hybrid system based on our new scheme is a viable approach, and should be considered along with river reforming works and rainwater stock drainage pipe works based on conventional schemes.

Although adopting the strategy of a hybrid sewer system will resolve many issues, there are some institutional and technical hurdles. Because the sewer system is operated as a business based on city planning decisions, it is important to readjust the various relevant authorities. Another technical problem is how to control the inflow and outflow of rainfall into sewage treatment facilities. That is, the inflow load for sewage must remain at the current reduced levels. To address these problems, we suggest the following two measures. First, the rainwater drainage and sewer systems should be considered as one single entity that is managed by city (and not individual districts). Second, the Intelligent Rainwater and Sewage Systems (IRSS) should be adopted in consideration of environmental issues and disaster prevention. However, the proper management and policies will provide a long-term strategy for disaster prevention and environmental protection [7], while meeting the needs of the citizens.

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