Doctoral Thesis

Study on Water-Saving Effects and Economic Optimization of

Hybrid Rainwater-Graywater System in Buildings

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ABSTRACT

Water scarcity, especially urban water scarcity, has seriously restricted the economic development of society and threatened human life. On-site reuse of rainwater and graywater by decentralized water reuse systems in buildings is one of the most effective methods to alleviate urban water scarcity because most water demands of buildings do not require high-quality potable water. A hybrid rainwater-graywater system (HRG) is a decentralized water reuse system that can simultaneously collect, retreat, and distribute rainwater and graywater to provide non-potable water to buildings. Such systems can not only achieve superior water-saving efficiency in buildings but avoid the limitation of separately reusing rainwater and graywater. However, the development of HRGs is still in infancy and the evaluation method and optimization model for HRGs is still a largely underexplored domain. This research is committed to comprehensively evaluating the advantages and limitations of HRGs in buildings and proposing tailored evaluation and optimization models for HRGs to improve the feasibility of such systems in buildings. In addition, the drive factors affecting the feasibility of HRGs in buildings were explored based on the proposed simulation model to the most efficiently implement such systems.

In Chapter 1, RESEARCH BACKGROUND AND PURPOSE, the research background and purpose were introduced. First, the current status of water scarcity around the world and in the urban was introduced. Secondly, the water scarcity in Japan and measures to conserve water were introduced. Thirdly, the advantages and necessity of implementing HRGs were proposed by introducing the origin and development of decentralized water reuse systems. Then, a critical literature review about HRGs was carried out to point out the limitation of implementing HRGs in buildings such as the oversized scale of systems and the high cost of water conservation. Simultaneously, there are still fewer optimization methods to improve these deficiencies of HRGs. In addition, the review also proposed that previous evaluation methods for HRGs are so idealistic that they will misestimate the performance of such systems in buildings. Finally, the research purpose and logical framework of this research were concluded.

In Chapter 2, CONFIGURATIONS AND COMPONENTS OF HRGs, the configurations and components of HRGs were introduced and the optimal configurations and the components of HRGs used in this research were presented. First, the advantages and disadvantages of different HRG configurations including mixed rainwater and graywater in a water tank and separately treated rainwater and graywater were introduced. The configuration of HRGs that separately treated rainwater and graywater has been recommended because of the flexible operation and wider feasibility. Then, the available components of the rainwater subsystems, graywater

subsystems, and disinfection equipment of HRGs were presented. Finally, the components of the HRG used in this research were determined.

In Chapter 3, SIMULATION MODEL OF HRGS BASED ON THE WATER BALANCE MODEL, a simulation model of HRGs to evaluate and optimize the scale of HRGs was proposed. The water balance model, which is widely used to simulate rainwater harvesting systems, was selected as the base model for modeling the simulation model of HRGs. According to the "Yield before spillage" (YBS) and "Yield after spillage" (YAS) algorithms of the water balance model, the water balance of rainwater tanks, wastewater tanks, and graywater tanks of HRGs was proposed to obtain the integrated algorithm for simulating HRGs. Then, the integrated algorithm was coded using MATLAB and used to simulate an HRG on a campus. Finally, the simulating results from the simulation model were used to fit with the actual monitoring data of the HRG from the campus to verify the accuracy of the model. The fitting results show that the simulation model of HRGs can accurately and simply reappear the operation of HRGs to evaluate and optimize the performance and scale of such systems.

In Chapter 4, ENVIRONMENTAL AND ECONOMICAL BENEFITS OF HRGS IN PUBLIC BUILDINGS, a comprehensive evaluation of HRGs was carried out. In this chapter, a campus in Japan was selected to evaluate the feasibility of HRGs in public buildings. The simulation model based on the water balance model with an hourly time step was performed to quantify the performance of the rainwater and graywater subsystems in the HRGs. Second, the electricity consumption of the HRGs was evaluated. Then, a detailed life cycle cost model was designed to calculate the economic benefit of the HRGs under the current and optimization scenarios. Finally, the results obtained are compared with HRGs in residential and commercial buildings to discuss the advantages of HRGs in public buildings. The results indicate that the promotion of HRGs in public buildings can not only achieve higher water-saving efficiency than other building types but also reduce electricity consumption in comparison with the traditional water supply methods. The economical unfeasibility of HRGs is caused by the waste of excess graywater and high maintenance costs. HRGs in public buildings has the potential to be promoted preferentially in regions where the water tariff is higher than 880 JPY/m^3 or the non-potable water tariff is set to at least 200 JPY/m^3.

In Chapter 5, DIMENSIONLESS PARAMETER METHOD FOR GENERAL EVALUATION OF HRGS IN BUILDINGS, a general evaluation model of HRGs was proposed to properly implement HRGs in buildings without the requirement of individual evaluating such systems in each building. This chapter proposes a dimensionless parameter method for the evaluation of three decentralized systems in buildings with stable and seasonal daily non-potable water demands: rainwater harvesting systems (RWHs), graywater recycling systems (GWRs), and hybrid rainwater-graywater systems (HRGs). Japan was selected as a case study to illustrate the feasibility of this method. The results indicate that the favorable precipitation patterns in Japan support the use of RWHs rather than GWRs for conserving water, especially in buildings with seasonal daily non-potable water demands. Upgrading the existing systems to HRGs when RWHs and GWRs cannot meet the demand can increase the maximum water-saving efficiency by 40%.

Thus, the method can effectively determine the optimum scenarios and configurations of RWHs, GWRs, and HRGs and provide policy guidance for the regional implementation of decentralized water reuse systems.

In Chapter 6, ECONOMICAL OPTIMIZATION METHOD FOR IMPROVING THE ECONOMIC BENEFITS OF HRGS, an economic optimization model is proposed to improve the economic feasibility of HRGs. This chapter proposes a comprehensive economic analysis based on the cooperative game theory to explore the economic potential of HRGs. An HRG on campus in Japan was selected as a case study to evaluate its water-saving performance. The economic feasibility of the HRG was then analyzed based on the life cycle cost model. Finally, considering that the implementation of the HRG weakened the profit of the main water plants, the cooperative feasibility and driving factors between the HRG and main water plants were explored in terms of mutual benefits based on the cooperative game theory. The results highlight that the construction costs significantly reduce the economic benefits of HRGs. HRGs have more substantial economic benefits in cooperative games than in non-cooperation. In addition, the subsidy of the government for HRGs makes it easier to drive the success of the cooperation.

In Chapter 7, CONCLUSION AND PROSPECT, a critical summary of each chapter was concluded.

***Keywords*:** water conservation; hybrid rainwater-graywater systems; simulation model; feasibility evaluation

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RESEARCH BACKGROUND AND PURPOSE

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1.1 Research background

1.1.1 Status of the world water resources

(1) Total amount of water resources around the world

Water is the source of life and the vital and indispensable composition in our industrial production and cultural activities. The vocabulary of " Water Resources" is first formally proposed by the USGS Water Resources Division to describe the usable water in the world in 1894 [1]. Subsequently, the United Nations Educational, Scientific and Cultural Organization (UNESCO) and the World Meteorological Organization (WMO) defined "water resources"[2, 3] as the water that has sufficient quantities and suitable quality to be used or may be used to meet the demand in a certain period.

There are about 1.4 billion km^3 of water resources around the world, accounting for almost 70% of surface areas on the earth. The huge amount of water made a great misconception that water is inexhaustible and no need to be saved like oil and carbon. However, freshwater is quite scarce because approximately 97% of the total water resources on the Earth are seawater, which cannot be considered as potable water or domestic water without treating procession. The volume of freshwater on the earth is only approximately 35 million km^3, accounting for 3% of the total water resources, and is used by 8 billion people around the world. In addition, 70% of freshwater resources, about 24 million km^3, exist in the form of ice and permanent snow in the mountains, Antarctic and Arctic regions, and water vapor, which cannot be directly used in reality. Except for the solid and gaseous freshwater, the usable freshwater resources such as rivers, lakes, and groundwater only account for 0.8% of the total water resources on the earth. Furthermore, 30% of the total freshwater resources are stored underground in the form of shallow and deep groundwater, soil moisture, swamp water and permafrost, which are the potential freshwater resources for human beings. The freshwater that can be available to ecosystems and humans is only about 200,000 km^3, accounting for 1% of the total freshwater resources. Considering that these water resources must be shared with other living things, there is not much water left for human beings (Fig 1-1).

Water resources have supported the survival and development of human beings and become a strategic economic resource that reflects the comprehensive national strength of a country. However, water scarcity has suffered in many countries and regions around the world. Currently, the 2.6 billion population distributed in 80 countries around the world is confronted with water scarcity. Among them, approximately 300 million population lives in a state of complete water scarcity and 1.7 billion population distributed in 17 countries live in extremely dehydrated regions where the location that the water-deficient population is more than 80% of the local population (Fig 1-2).

Water scarcity has become a worldwide problem and has transformed into the toughest challenge in the development of the social economy and human civilization. Water scarcity is not only a natural phenomenon but also a disaster caused by human activities. With global climate change, rapid population increase, water pollution, rapid economic development, and unsustainable water consumption patterns of water resources, the global scarcity of water resources, the deterioration of water quality, and the resulting damage to the ecological environment have become increasingly serious. The environment on which human beings depend is in increasing danger.

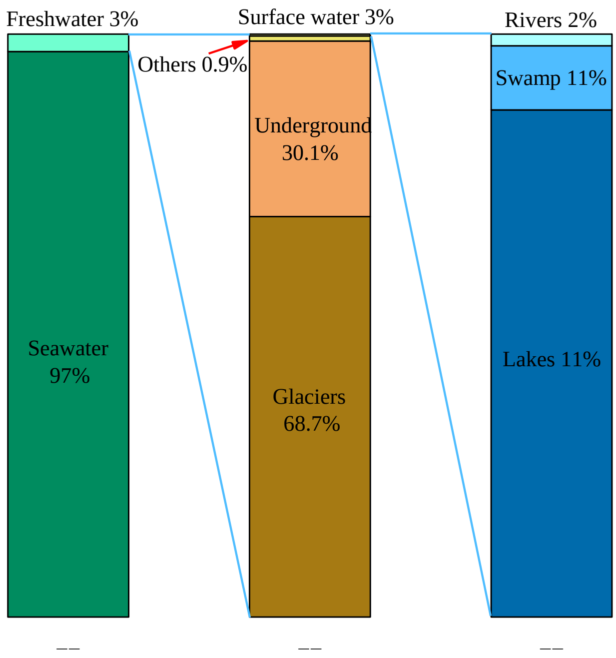

Fig 1-1 Global distribution of water resources [4]

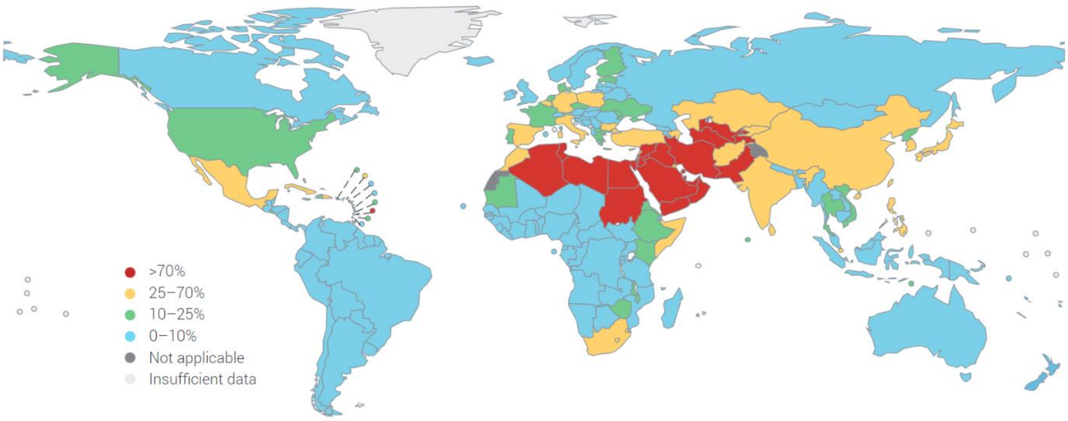

Fig 1-2 Global water stress [5]

(2) Factors affecting water scarcity

Although water scarcity is severe over the world, almost 90% of available water in rivers and lakes is not been utilized because of the unbalanced temporal and spatial distribution of water resources and the geographic and seasonal factors of regions. This also causes water scarcity to be concentrated in some specific countries and regions [6]. Less than 1000 m^3 of water can be used per capita in the Middle East and Africa where have little precipitation, whereas more than 10 thousand m^3 per capita exist in most countries in Southeast Asia with Asian monsoon climate and South America with tropical rainforest climate. Except for local natural conditions, the amount of available water varies with the completeness of the local municipal facilities. Due to the lack of water supply equipment such as dams and reservoirs, many developing countries in Southeast Asia are suffering from water scarcity despite the abundance of water resources exist in the regions. In contrast, the Middle East imports virtual water and develops desalination to ensure the domestic water demand of residents relying on its strong economic strength. A developed country such as Japan and the United States has more opportunities of using water and a higher amount of water consumption, whereas a poor country is more water-scarce. Therefore, improving water consumption patterns and water-use efficiency in developed countries can more directly transform the status quo of world water resources, which not protects nature, but also protects the development of human beings.

Climate change is also exacerbating water scarcity around the world because of the changing of precipitation patterns, the increasing temperature, and evaporation, especially in the arid and semi-arid regions that have already faced water stress. The climate change caused by global warming can lead to abnormal weather such as heavy rains and droughts, which affect the amount of available water. According to the prediction from the sixth assessment report of the Intergovernmental Panel on Climate Change (IPCC) that the available water resources in southern Africa will decrease by 10%-30% in the first half of the 21st century, whereas that in the rainy regions such as Asia and South America will increase by 10%-40% [7]. IPCC also indicated that climate change will bring unpredictable water availability in some regions because precipitation varies with place. Table 1-1 concludes the impacts of climate change on water resources around the world.

Table 1-1 Climate change and its impact on water resources [8]

Climate change	Impact	Consequence
Precipitation decreased	Water scarcity	Insufficient supply to domestic, industrial, and irrigation water consumption
	Runoff decreased	Decrease the potential of hydroelectric power Interfere with the cooling system of thermal power station Affect water organisms because of runoff pollutants increasing
Precipitation increased	Flood	Disrupt public water supply Damage dams Pollute natural water Damage social property
	Increase erosion and sediment transport	Increase the turbidity of reservoir
Temperature increased	Reduce oxygen levels in natural water Glacier snow melt Increase bacterial and fungal in natural water	Decrease water quality Increase the requirement of water treatment Variation in time and magnitude of peak flow

Continued from Table 1-1

Climate change	Impact	Consequence
Rise sea-level	Seawater intrusion into coastal aquifers	Decrease available water resources
	Strom and flood	Damage coastal infrastructure Coastal migration

Furthermore, population growth is exacerbating the stress of water resources around the world because population growth promotes water consumption such as farm irrigation and meat consumption, and the development of human beings exacerbates the pollution of water resources. Consequently, the amount of water demand is increasing, whereas the available water is decreasing. According to the report of Global Environment Outlook from the United Nations, the consumption of water resources is expanding because of population growth, and the freshwater demand around the world will increase by 40% by 2025 [9]. In addition, although the global water withdrawals have grown more than twice to cover the freshwater demand of population growth, the availability of freshwater resources per capita continues to decline. In the past two decades, the availability of freshwater resources per capita in North Africa and West Asia has dropped by 41% and 32%, respectively, and almost less than 1,000 m^3, which is far below the international standard of 1700 m^3. With the global population is expected to be 9.7 billion by 2050, the water scarcity around the world will worsen without the proper management of the limited water resources.

Water quality is a vital part of water resources management. Low-quality water not only threatens human health and ecosystem development, but also makes freshwater unavailable for certain water uses, which reduces the available water resources and poses a huge challenge to supply sufficient high-quality water. Currently, half of the rivers, lakes, and underground water around the world are reduced and severely polluted. In the past two decades, global per capita available freshwater has been decreased by more than 20% because of water pollution. The major reasons for water pollution include the development of urbanization, the increase of agricultural activities, the use of fertilizers and pesticides, land degradation and deforestation, and the proper treatment and disposal methods of wastewater. As a result, approximately 2.4 billion people worldwide, accounting for 30% of the global population, cannot receive a safe water supply. Among them, approximately 844 million people lack the most basic potable water supply. Furthermore, the water source of more than 2 billion people is polluted by excreta. Without more effective management measures of water resources than today, half of the population will live in water-scarce regions, one-third population will not be supplied with safe potable water, and more than one-half population will not implement sanitation facilities by 2025 [10]. Therefore, the general deterioration of water quality worldwide has become the most serious water problem and has threatened the sustainability of water resources. However, the water quality management of wastewater or water sources is seriously inadequate or non-existent in most developing countries because water treatment technologies are often expensive. Furthermore, the new water quality challenges such as emerging pollutants and safe wastewater reuse are emerging with increasing requirements of water quality and need urgent attention.

The water resources around the world require long-term, effective, and sustainable management to ensure a high-quality water supply for the rapidly developing population, society, and ecological environment. For this purpose, the United Nations General Assembly proclaimed March 22 as World Water Day from 1993 in the United Nations Conference on Environment and Development. In addition, at the World Summit on Sustainable Development held in Johannesburg, South Africa in August 2002, all participants unanimously decided to list the water crisis as one of the most serious challenges facing humanity in the next decade. Furthermore, the United Nations announced that 2018 to 2028 will be designated as the International Decade of Action for Water for Sustainable Development and will provide concrete actions on water resources. These activities initiated by the United Nations and some international organizations aim to further affirm that improving water resources is the key to poverty reduction, economic growth, and environmental sustainability.

1.1.2 Status of urban water resources

The 21st century is the era of urban. 55% of the population around the world lives in urban areas and more population live in urban areas than in rural areas [11]. This proportion will rise to 68% by 2050 and the population growth will be concentrated in Africa and Asia. Furthermore, the degree of urbanization will exceed 80% in Latin America and the Caribbean [12]. On the other hand, megacities with a population of more than 10 million are becoming more common as well as megacities are getting bigger and bigger. 27% megacities will exist worldwide by 2050, and 21% of which will be concentrated in the southern hemisphere.

However, not everyone who lives in urban can enjoy the convenience brought by urbanization. Urban is the most vulnerable to water scarcity and is the most vulnerable to result in serious, even catastrophic damage to water resources and ecosystem because urban areas usually have a concentrated population density and a narrow living space, and urban plays an important role in human culture, commerce, and economic development. The future water consumption worldwide will be concentrated in urban areas because the high-density industrial, transportation, and building system in urban areas require a large amount of water resources every year during the development of urbanization. According to the OECD environmental outlook to 2050, the water consumption of the agricultural sector for irrigation is the most part in the global water consumption, accounting for two-thirds of global water consumption, whereas the industrial and domestic water consumption accounts for 20% and 10% of global water consumption, respectively, but the industrial and domestic water demands have grown rapidly in recent years [13]. As of 2014, the industrial water consumption has more than tripled of that in 1961, whereas the domestic water consumption has soared to 6.76 times that in 1961. The global water demand will continue to increase by approximately 55% by 2050 because the water consumption of manufacturing and thermal power generation sectors will continue to soar by 400% and 140%, respectively, and domestic water consumption is projected to increase by 130 % (Fig 1-3). Moreover, with the rapid influx of population, urban areas have gradually expanded and resulted in more and more people living in the peri-urban areas with insufficient public and municipal services. The marginalization of these immigrants leads to outdated urban planning that cannot satisfy the growing water demand of residents, exacerbating the water supply stress on the urban.

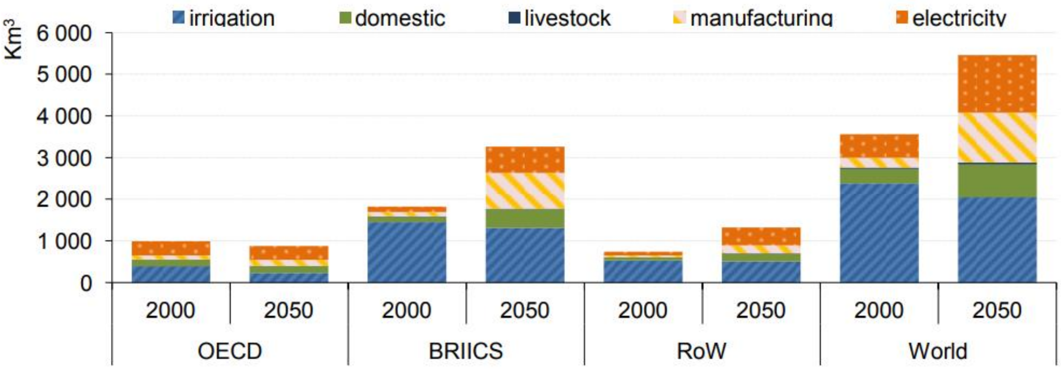

Fig 1-3 Global water demand: Baseline, 2000 and 2050 [13]

Currently, large cities and megacities around the world are generally suffering from water scarcity, especially the coastal cities that account for three-quarters of the large cities [14]. Industrial, commercial, and domestic sectors in urban areas have put forward certain requirements for water resources, including the requirements of water quantity caused by the increase in urban scale and the requirements of water quality brought about by the improvement of living standards. However, the major water demands require the treatment of raw water, whereas the water source is often located far from the urban areas and almost all sectors require water. Therefore, the competition for water resources among various sectors has led to the conflict of water rights, and this conflict will intensify with the development of urban scale and the expansion of political influence. Furthermore, the unreasonable development and utilization of water resources in urban, such as excessive exploitation of groundwater, waste of water sources, and irregular drainage, not only affect the development of the urban and the health of residents, but also affect the long-term development of the economy and ecological environment in the region and surrounding areas. The resulting losses are often disastrous and even irreparable.

Improving the water scarcity in urban areas has become the most prominent problem in the global water crisis. In response to water scarcity in urban areas, some urban have implemented large-scale water diversion programs to mobilize water from rural areas, ecological reserves, surrounding aquifers, and large dams. In addition, some urban also transit to relying on engineering solutions to solve urban water scarcity, such as building large-scale water storage and treatment facilities or basin water transfer program. However, these projects are often extremely expensive and cannot stop unsustainable and polluting patterns of water consumption.

In recent years, the focus of countries around the world has transferred from developing new water sources to explore that how to support the rapid development of urbanization with limited urban water resources as well as ensure the clean and safe water demands of the urban population, and simultaneously ensure the sustainable development of the ecological environment. Water recycling paves the way for the efficient utilization of limited water resources in urban areas. The recycling of urban water resources can not only quickly improve the water scarcity of urban areas but also redefine the relationship between urban and water resources and the supervision method of urban water resources. Table 1-2 listed the difference between past water use patterns and future water recycling patterns in urban areas. The focal points of urban water resource recycling are [15]:

1. Coordinate all water sources in the catchment areas of urban, including blue water

(surface water, groundwater, transferred water, and desalinated water), rainwater, black water (high-concentrated wastewater), graywater (low-concentrated wastewater), and virtual water.

2. Match different water sources with various water qualities required for water use.
3. Integrate the storage, treatment, distribution, and recycling of different water sources and implement with corresponding infrastructure planning.
4. Protect, conserve, and develop water resources from the source.
5. Consider users who use the same water source in urban areas and surrounding areas.
6. Coordinate various formal and informal institutions involved in urban water resources management.
7. Balance the economic efficiency, social equity, and environmental sustainability of urban areas.

Table 1-2 Future urban integrated water resources management

Past use patterns of urban water resources	Future recycling patterns of urban water resources
Municipal water systems such as water supply and sewage treatment systems are designed based on historical precipitation records	Municipal water systems integrate from various data such as historical data and predicted data and can adapt to uncertainties caused by climate change and other factors
Water supply is a one-way path from use to treatment to discharge	Water can be re-treated and recycled, and produce a cascading effect with water quality
Rainwater is a burden to cause waterlogging disasters and floods	Rainwater is a cleaner water source and can be retained for reuse and recharge aquifers through infiltration
The collection, treatment, use, and discharge of water resources are independent of each other	Integrate the collection, treatment, use, and discharge of water resources into an integrated system to improve water recycling efficiency
Demand equals quantity. Municipal water systems are determined by end-user demand and wastewater production. Main water plants provide potable water that meets the water quality standards, whereas sewage treatment plants collect all the wastewater for unified treatment	Demand is multifaceted. Municipal water systems match the characteristics of water demand and provide enough quality and quantity of potable water and graywater to meet the reliability of water use
Municipal water systems are centralized and large-scale	Water supply can be decentralized and small-scale
Municipal water systems, graywater systems, and rainwater systems are differentiated	Municipal water systems, graywater systems, and rainwater systems are an integrated and systematic urban water recycling system
Urban infrastructure consists of gray facilities dominated by concrete, metal, and plastic materials	The sustainable urban with a combination of green and gray facilities

Each country has its own polity of water recycling measures, but they have a common goal that provides timely, appropriate, and high-quality water and increases the water supply efficiency without compromising the surrounding water resources. Among them, the reuse of rainwater and graywater is gradually favored by various countries as the most accessible and largest quantity of alternative water source and has laid the foundation for a robust urban water resource recycling system.

Rainwater harvesting is the direct collection, storage, and utilization of natural precipitation. Rainwater harvesting is a simple and inexpensive method to address urban water scarcity, especially conserving water in residential areas. Rainwater can be used as domestic water for toilet flushing, washing machines, and irrigation flowers. Furthermore, rainwater is suitable for industry and agriculture because of the low calcium content. In addition, rainwater harvesting can effectively reduce the pressure of urban floods, drainage, and other disasters caused by imperfect drainage systems. Rainwater harvesting can also reduce the peak flow in the monsoon season, maintain the volume of rivers and lakes, and increase the evaporation of water to improve the urban ecological environment, restrain the deterioration of the environment, and reduce the accumulation of water in roads and courtyards, which can improve the water environment of the community and the living quality of urban residents.

Graywater recycling is also an essential part of alleviating urban water scarcity. The used water can be recollected and retreated to supply to various fields with different water quality requirements, such as agriculture and industry. Urban areas can improve the water structure and ecological water balance through large-scale reuse of domestic and industrial wastewater. graywater recycling is not only easy to obtain and free, but also more reliable than rainwater. In some peri-urban areas, the reuse of treated and untreated wastewater for irrigation has become one of the measures to improve food security. Currently, more than 20 million km^3 of agricultural land is being irrigated with untreated and treated wastewater. Furthermore, the abundance of organics and metal elements in wastewater can reduce the requirement of chemical fertilizers for crops. Graywater can also be used by cooling towers and boilers in industry and toilet flushing that requires lower water quality. Treated graywater can easily meet the large water demand in the industry for alleviating the growing industrial water demand without consuming advanced high-quality potable water. In addition, graywater can be reused for aquaculture and irrigation in parks, green spaces, and urban areas, and can also replenish groundwater, helping to restore water bodies and wetlands.

In summary, relying on a single water source for water supply has been unsuitable for matching the requirements of urban development. In the future, the urban water supply model will become more diversified and sustainable and will be gradually transferred from a centralized system to a decentralized system. Water recycling can ensure that the urban can rely on multiple water sources for coordinated water supply, and through a decentralized system to give this water supply model a higher degree of freedom. For example, a small-scale decentralized system for rainwater harvesting can respond quickly to its own conditions without disturbing the water supply of surrounding areas. As an advanced water supply model, Water recycling is conducive to the optimal allocation of water resources, the improvement of the safety and reliability of the water supply system, the sustainable development of society, and fundamentally solving the urban water scarcity.

1.1.3 Status of water resources in Japan

(1) Total amount of water resources in Japan

Japan is located in eastern Asia and the majority of Japan is located in the Asian monsoon belt. Japan has rich precipitation with annual precipitation of approximately 1697 mm, which is 1.4 times the average annual precipitation of the world (1171 mm). However, the distribution of water resources in Japan is unbalanced with countries (Fig 1-4). Regions such as Hokkaido, Tohoku, and Kanto are lower than the average value of Japan, whereas regions such as Shikoku, Kyushu, and Okinawa are higher than the average value. In addition, the available amount of water resources in Japan fluctuates greatly throughout the year and the low-water periods occur repeatedly because the river flow is concentrated in the thawing season from April to May and the precipitation is concentrated in the rainy season from June to July and typhoon season from September to October [16].

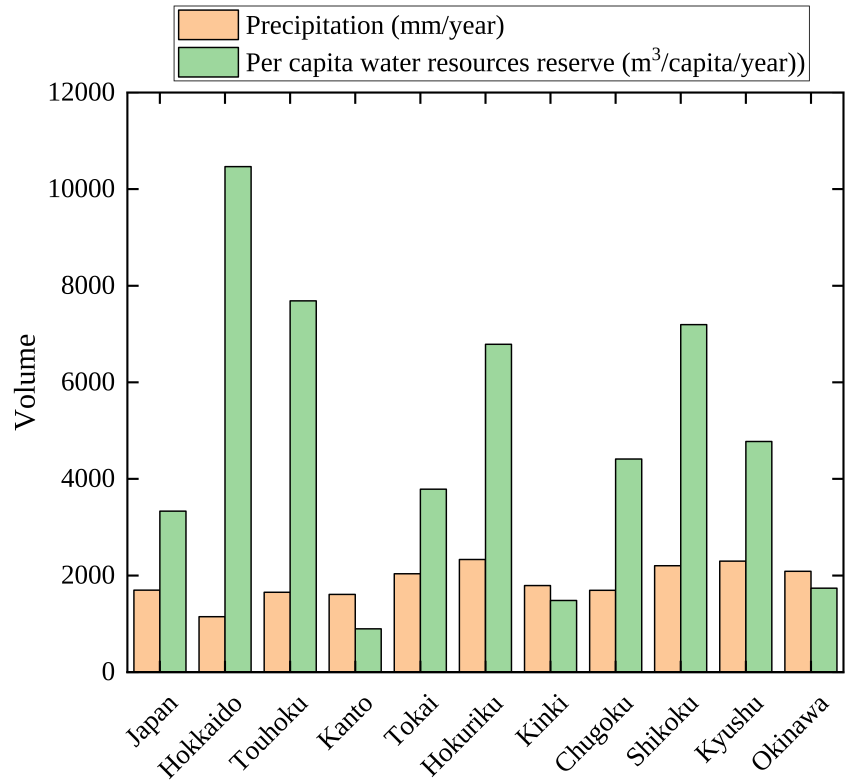

Fig 1-4 The distribution of precipitation in various regions in Japan

Although abundant precipitation exists in Japan, the per capita precipitation in Japan, which is about 5,000 m^3/capita/year, is only about a quarter of the world average. In addition, according to data released of AQUASTAT by the Food and Agriculture Organization of the United Nations (FAO), the per capita water resource storage in Japan is approximately 3400 m^3/year, which is less than half of the world average and only similar to the metropolitan areas of North African and Middle Eastern countries [17]. Natural conditions restrict the effective utilization of water resources in Japan. Japan has a small land surface area and a large population, which leads to a high population density. Moreover, 74% of the land in Japan is covered by mountains and the plain area is small, which causes the fast speed of rainwater runoff. Furthermore, the precipitation in Japan is unevenly distributed with seasons and years and is not conducive to the distribution of water consumption throughout the year. Last but not least, the demand for water resources in Japan has increased with years because Japan has experienced population growth and economic development for decades. Therefore, Japan is a country with relatively short water resources.

(2) Development of water consumption in Japan

The total amount of water resources in Japan in 2018 was approximately 650 billion m^3 including the evaporation of approximately 230 billion m^3 and the storage of approximately 420 billion m^3 [18]. In addition, the total water consumption (according to water withdrawal, the same below) in Japan in 2018 was approximately 79.1 billion m^3/year, which includes 25.6 billion m^3/year of urban domestic and industrial water consumption, accounting for 32% of total water consumption, and 53.5 billion m^3/year of agricultural water consumption, accounting for 68% of total water consumption (Fig 1-5).

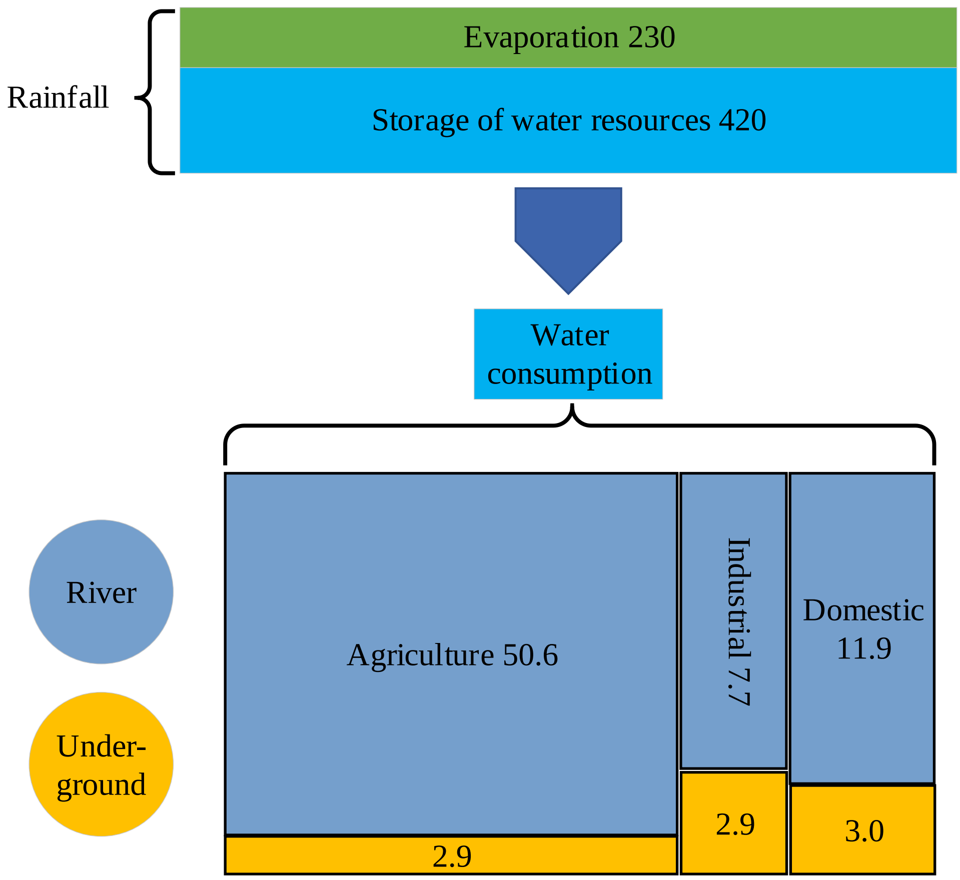

Fig 1-5 Water resources reserve and consumption in Japan in 2018 (billion m^3) [18]

The development of water consumption in Japan has experienced several periods. From the ancient period to the Edo period, the water consumption of agriculture in Japan developed rapidly. With the continuous expansion of the rice planting scale, the increasing demand for irrigation has driven the development of small and medium-sized rives utilizing and promoted the water conservancy management of large rivers such as the Tone River.

From the Meiji period to the prewar period, the foundations of modernization and socio-economic development of Japan had been gradually formed and the water consumption began to transfer from agriculture to heavy industry and aquaculture. The water demand for industrial in Japan increased sharply in this period. In addition, the government of Japan has developed modern main water plants in regions such as Yokohama to respond the population growth and urban expansion and ensure a safe water supply for residents. On the other hand, the electricity demand in Japan has increased with the advancement of urbanization and industrialization, resulting in the rapid increase of the hydropower industry in this period.

From the post-war period to the modern period, human settlements have played an essential role in social and economic development, and domestic water demand, as well as industrial and agricultural water demands, have increased. In addition, a higher requirement for the safety and reliability of water has been proposed with the quality improvement of life. Therefore, the government of Japan carried out a comprehensive development of national water resources, such as the construction of multi-purpose dams and weirs, and constructed a large number of water storage facilities during this period to guarantee a steady water supply throughout the year regardless of the fluctuations in rivers and precipitation. At present, the newly developed water resources in Japan accounted for 55% of the domestic and industrial water consumption, which are approximately 16.6 billion m^3/year. Taking the urban area of Tokyo as an example, the total amount of water resources stored in the Tokyo Reservoir in 1996 doubled from 1964, from 185 million m^3 to 371 million m^3.

However, Japan has faced severe water scarcity on several occasions over the past few decades, such as the Lake Biwa drought in 1939, the Tokyo Olympics drought in 1964, the Nagasaki drought in 1967, the Takamatsu drought in 1973, and the Fukuoka drought in 1978, because the demand for water continued to rise and was accompanied by the large fluctuations of the rainy period. In response to droughts, the government of Japan has to put forward a series of water restriction policies to many cities (Table 1-3). For example, Fukuoka experienced a severe drought in 1978 because the precipitation in that year was only approximately 70% of that in a normal year and there was not enough water in the reservoirs. Therefore, the government of Fukuoka was forced to implement a water restriction policy for nearly 10 months, as long as 287 days, of which 5 months could only provide water for 5 to 10 hours a day. During the summer vacation, the residents in Fukuoka had to be evacuated to relieve the water supply pressure. Such a long-term severe water scarcity is the first time ever in Japan. This large-scale water scarcity will have a huge impact on domestic life and social activities, such as being unable to cook, use toilets, and even cause factory shutdowns and crop withers because the comfortable life and high-quality service in modern society are guaranteed on the premise of a stable water supply. Therefore, water scarcity will directly threaten the economic development of society. For example, during drought in Japan in 1994, 16 million people were affected by the cut-off of potable water and depressurized water supply, and approximately 140 billion JPY of the national crops were lost, which were three times the normal situation.

In order to improve the water scarcity, the government of Japan has adopted various measures to control the utilization of rivers and groundwater and rationally use potable water, such as conserving water, reusing water, and adjusting the structure of water utilization, one of which is the reuse of rainwater and graywater.

Table 1-3 Water restriction policies in Japan from 1964 to 1981

Year	City	Water restriction days	Maximum water restriction rate
1964	Tokyo	84	50%
1967	Nagasaki	72	88%
	Kitakyushu	130	
1973	Matsue	135	40%
	Takamatsu	58	60%
	Fukuyama	49	
	Hiroshima	52	40% (industrial)
1977	Okinawa	167	Water supply every other day
	Koigawa	115	50% (industrial)
1978	Fukuoka	287	48%
	Kitakyushu	171	20%
	Koigawa	62	50% (industrial)
1981	Okinawa	326	

(3) Development of rainwater and graywater reuse in Japan

Japan has been focusing on the reuse of rainwater and graywater since 1955. Since being affected by the adjustment of energy-saving policy in 1977 and the water scarcity in Fukuoka in 1978, the national and local governments of Japan have gradually begun to formulate guidelines and mandatory policies for the reuse of rainwater and graywater. Therefore, the development of rainwater and graywater reuse systems has accelerated since 1980. In general, the government of Japan has begun to vigorously implement the reuse of rainwater and graywater following the basic principles:

1. The reuse of rainwater and graywater is an inevitable trend of comprehensive management from the perspective of alternative water resources, environmental resources, and energy resources.
2. Rainwater and graywater can be preferentially utilized in social activities to reduce the dependence on surface water and groundwater of urban regions. In addition, rainwater and graywater can be regarded as two of the most convenient water resources to use in the emergency situations such as earthquakes and tsunamis.
3. Rainwater can be reused as a low-carbon renewable resource and is conducive to the formation of a healthy water cycle, reducing the heat island effect, reducing the environmental load, reducing the flood damage, and helping to recharge groundwater resources.
4. Graywater is not only an alternative water resource to conserving potable water, but the heat energy in the reclaimed water can also be used as low-carbon energy.

Subsequently, Japan began to implement the Rainwater Utilization Promotion Law on May 1, 2014, requiring the national government to promote rainwater utilization nationwide. Then, on March 10, 2015, the Cabinet of Japan decided that the national government and independent administrative agencies should use their own rainwater systems when maintaining buildings. The national government and independent administrative agencies have decided that, in principle, the implementation rate of rainwater systems in new buildings should be 100%. In addition, the Basic Policy for Promoting Rainwater Utilization was decided by the Japanese Cabinet, and the basic and important matters for the promotion of rainwater utilization were stipulated, and actively promotes rainwater utilization by implementing measures such as subsidy measures, grant systems, and taxation systems.

With the implementation of a series of policies, the number of rainwater reuse systems built in Japan has grown rapidly since 1994, from 344 to 2979 in 20 years (Fig 1-6). As of 2020, approximately 3797 rainwater reuse systems have been implemented in Japan, and the annual rainwater reuse is approximately 12.31 million m^3 (Fig 1-7). In terms of water uses, rainwater is mostly used for toilet flushing, domestic irrigation, and municipal irrigation, accounting for approximately 70% of all rainwater utilization methods, following is building cleaning, firefighting, municipal landscape water, and cooling (Fig 1-8).

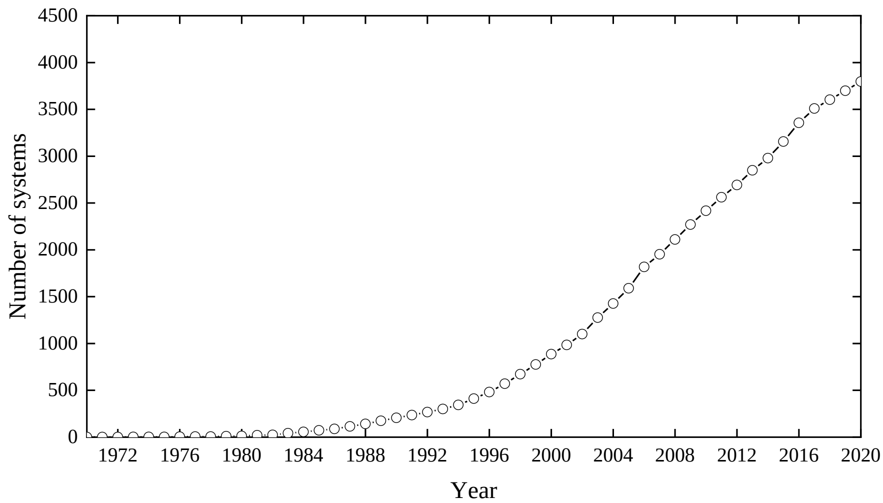

Fig 1-6 Number of rainwater reuse systems in Japan from 1970 to 2020 [18]

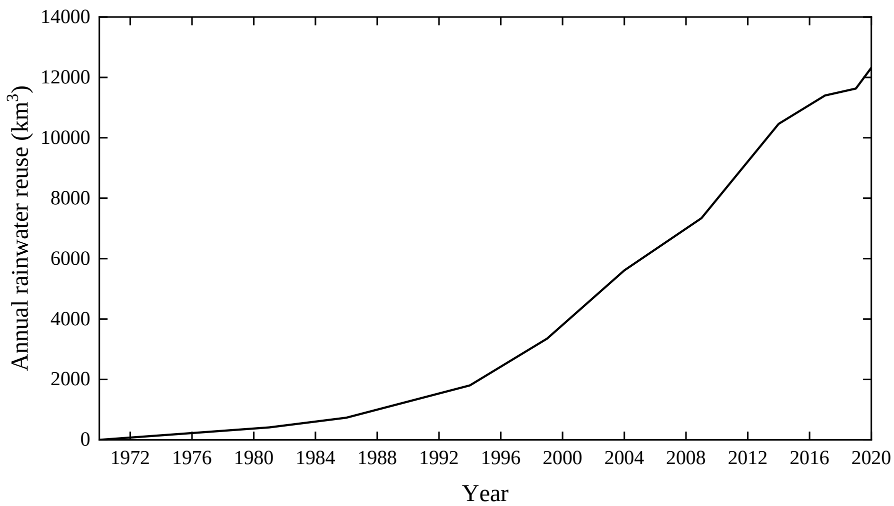

Fig 1-7 Annual rainwater reuse in Japan from 1970 to 2020 [18]

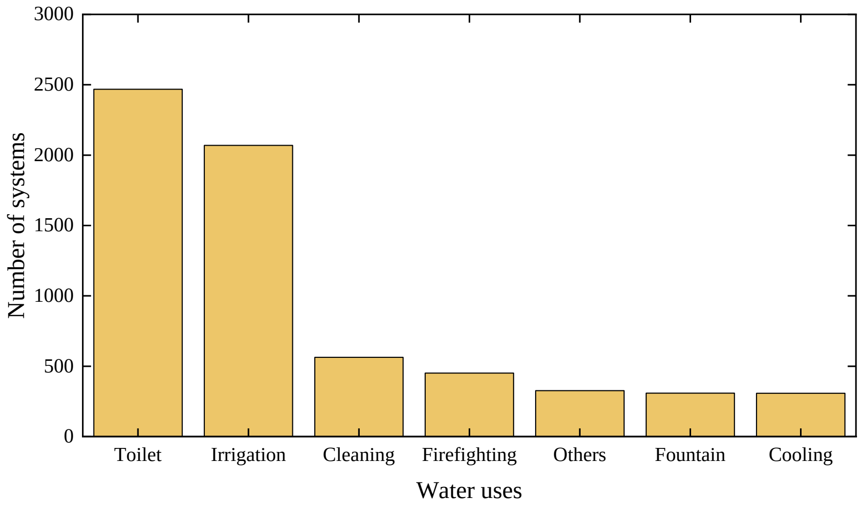

Fig 1-8 Water end uses of rainwater in 2020 [18]

Japan has vigorously developed sewage treatment plants to supply graywater by treating domestic wastewater and industrial wastewater for river conservation, melting snow, toilet flushing, agricultural irrigation, and industrial water uses after the water scarcity in Fukuoka in 1987. The graywater reused far exceeds that of rainwater because the sources of domestic and industrial wastewater are stable and abundant. As of 2018, approximately 2,200 sewage treatment plants nationwide have discharged approximately 14.6 billion m^3 of treated wastewater every year, of which 296 sewage treatment plants send out the treated wastewater as graywater, with an annual graywater supply of approximately 200 million m^3 (Fig 1-9). Such graywater is mainly used in water end-uses that do not require high quality but consume large amounts of water, such as river conservation (34.75%), municipal irrigation and landscape (26.06%), melting snow (19.64%), and industry and agriculture (15.97%). Although the utilization rate of graywater in Japan is extremely low, which is only 1.4% of the discharge, from the perspective of water conservation in urban regions, the reuse of graywater can not only replace high-quality potable water to meet some water demands, and can be used for new applications such as road sprinkler to reduce heat islands. Therefore, the importance of reusing graywater will further increase in the future.

The pressure on the water supply in Japan has been greatly eased in recent years because of the advancement of rainwater and graywater reusing. Domestic water refers to the water used in households such as drinking, cooking, laundry, cleaning, toilet flushing, and watering flowers. According to the statistics of the Tokyo Metropolitan Water Bureau in 2015, domestic water is concentrated on bathing, accounting for 40%, and toilet flushing, accounting for 21%, followed by cooking (18%), laundry (15%), and others such as washbasins (6%), and the domestic water consumption shows a trend of the peak in summer and less in winter [19]. Furthermore, urban activities include commercial water such as the consumption of restaurants, shopping malls, and hotels, and public water such as the consumption of fountains and public toilets are also domestic water.

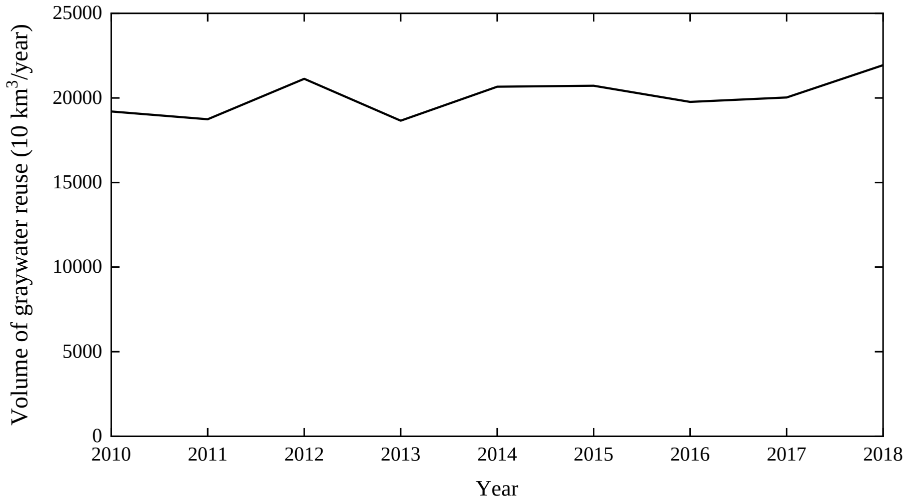

Fig 1-9 Annual graywater reuse in Japan from 2010 to 2018 [18]

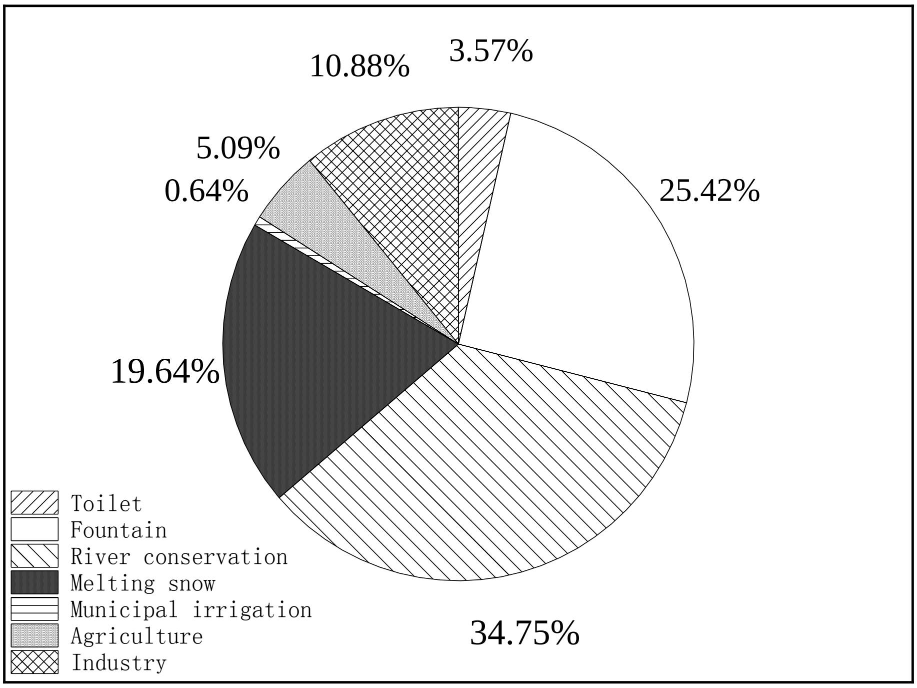

Fig 1-10 Water end uses of rainwater in 2018 [18]

Domestic water demand in Japan tripled between 1965 and 2000 and peaked in 1998 because of the increased population of water supply, the popularity of flush toilets, and the change of lifestyles. Subsequently, since the rainwater and reclaimed water became popular in 1998, some water demand of domestic water has been transferred from potable to rainwater and graywater, such as toilet flushing and fountains, which has shown a gradual downward trend in recent two decades (Fig 1-11).

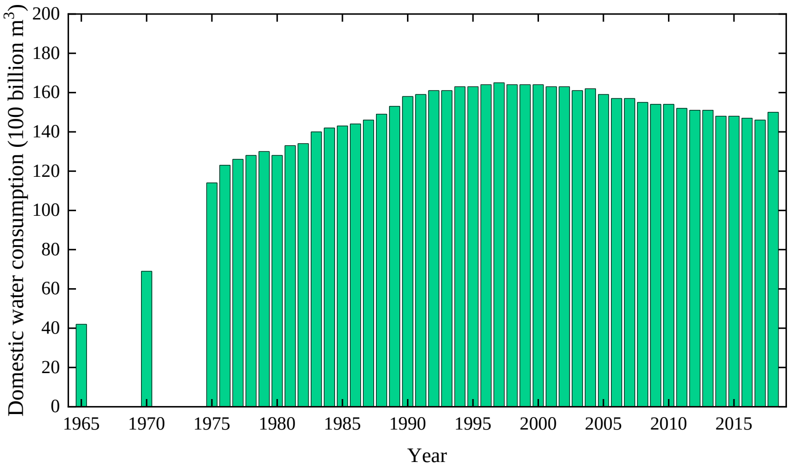

Fig 1-11 Domestic water consumption from 1965 to 2018 in Japan [18]

Industrial water refers to the water consumption of industrial activities, such as boilers, raw material manufacturing, product treatment, equipment cleaning, equipment cooling, and temperature regulation, but excludes the water consumption for public utilities such as electricity, gas, and heating. The chemical, steel, and paper manufacturing industries account for about 73% of total industrial water consumption and have the greatest impact on it [18]. Industrial water demand in Japan increased steadily from 1965 to 2000 and had changed to increase slowly since 1980. Then, industrial water demand peaked in 2000 in Japan. However, from the perspective of water conservation and environmental production, the industrial sector in Japan began to recycle industrial wastewater, which reduces the potable water demand of industrial water. Therefore, the potable water supply for industrial water in Japan has gradually decreased since 1973. As of 2015, the annual wastewater utilization rate of various industries in Japan has reached 77.9% (Fig 1-12).

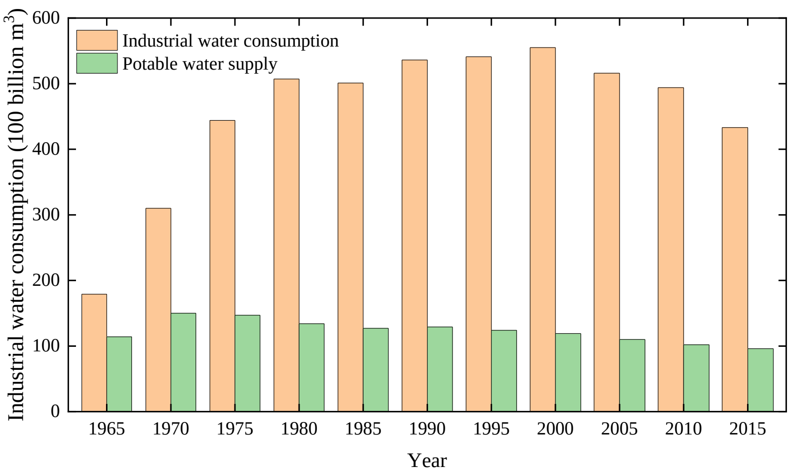

Fig 1-12 Industrial water consumption from 1965 to 2015 in Japan [18]

Agricultural water includes irrigation for the growth of crops and vegetables and breeding for livestock. Agricultural water demand in Japan has barely changed. However, after reusing rainwater and graywater to improve the demand for domestic and industrial water, Japan has begun to promote rainwater and reclaimed water for maintenance of rives and agricultural irrigation. Therefore, the agricultural water demand in Japan has shown a downward trend since a series of policies for rainwater and reclaimed water were promulgated in 1998 (Fig 1-13).

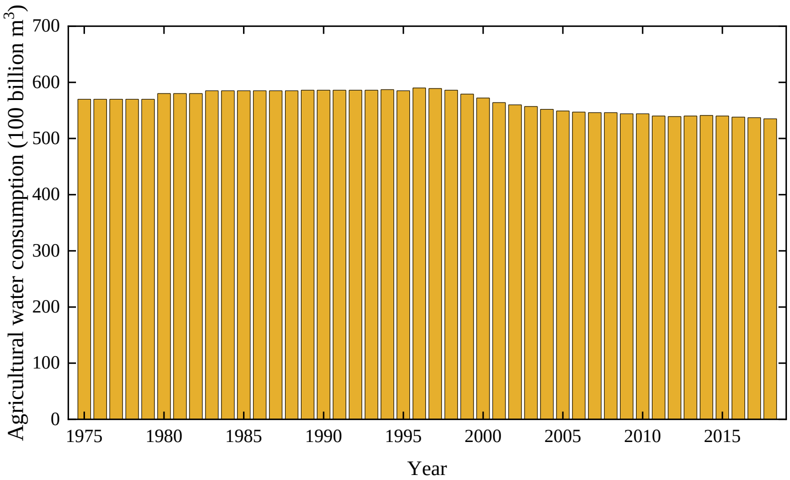

Fig 1-13 Agricultural water consumption from 1975 to 2018 in Japan [18]

The reuse of rainwater and graywater has greatly improved the water scarcity in Japan. Taking Fukuoka as an example, the Fukuoka government formulated the “Outline of Measures for Water-Saving Water Utilization in Fukuoka City” based on the experience of severe water scarcity in 1978, which committed to building a water conserved city, and formulated the “Water-Saving Promotion Regulations” in 2003. The regulations apply to new large buildings with an area of more than 5000 m^3 (3000 m^3 for the urban center) are obliged to implement systems that can utilize rainwater or graywater. The regulation is also the first regulation on conserving water in Japan. As a result of a series of policy advancements, although the precipitation in Fukuoka in 1994 was lower than that in 1978, the total water restriction time was reduced by approximately 40%. Furthermore, despite the 3rd lowest precipitation on record in 2005, water restriction has not been required in this period.

Table 1-4 Water scarcity and water restriction in Fukuoka from 1978 to 1994

Year	1978	1994	2005
Precipitation (mm/year)	1,130 (5th lowest in the observational record)	891 (1st lowest in the observational record)	1,020 (3rd lowest in the observational record)
population	1,028,000	1,250,000	1,388,000
Total water restriction time (h)	4,054	2,452	0
Average daily water restriction time (h)	14	8	0

1.2 Decentralized Hybrid rainwater-graywater systems

The building sector is recognized as one of the largest users of urban water resources worldwide [20]. The massive construction and operation phases of buildings will deplete existing water resources with population growth and social development, which include construction water of housing for the new urban population, domestic water for maintaining the living conditions of existing residents, industrial water for improving social productivity, and commercial water for improving the quality of resident life. As more and more countries gradually realize the importance of conserving urban water resources, the reuse of alternative water such as rainwater and graywater to improve the water supply model of the building sector has become one of the main measures because some water demands of buildings do not require high-quality potable water from main water plants [21]. Therefore, water reuse systems in buildings have been widely developed and implemented in recent decades, among which rainwater harvesting systems (RWHs) and graywater recycling systems (GWRs) are the most widely used. RWH refers that the harvested rainwater by buildings or water storage facilities is directly supplied to buildings for non-potable water demands, such as toilet flushing and air conditioning cooling, after preliminary physical filtration. GWR refers that the wastewater in buildings, such as industrial cooling water, light wastewater produced by washbasins, and even dark wastewater produced by toilets, is supplied to buildings as graywater for non-potable water demands after physical, chemical, and biological treatments according to the water quality requirements of water uses. The treated rainwater and graywater can even be reused as potable water in some regions with extreme water scarcity in Australia [22].

Furthermore, water reuse systems in buildings can be divided into centralized and decentralized based on their reuse scale. The centralized water reuse system is similar to the main water plant, which refers that rainwater and wastewater in buildings within a specific range of the urban are centralized collected and sent to a rainwater treatment plant and a graywater treatment plant for treatment, and then re-supplied to the buildings for non-potable water demands (Fig 1-14). The decentralized water reuse system refers that rainwater and wastewater collected by an individual building or multiple in a small region, such as residential areas or a campus, can be treated on-site by a treatment system implemented in the building and reused as non-potable water [23] (Fig 1-15).

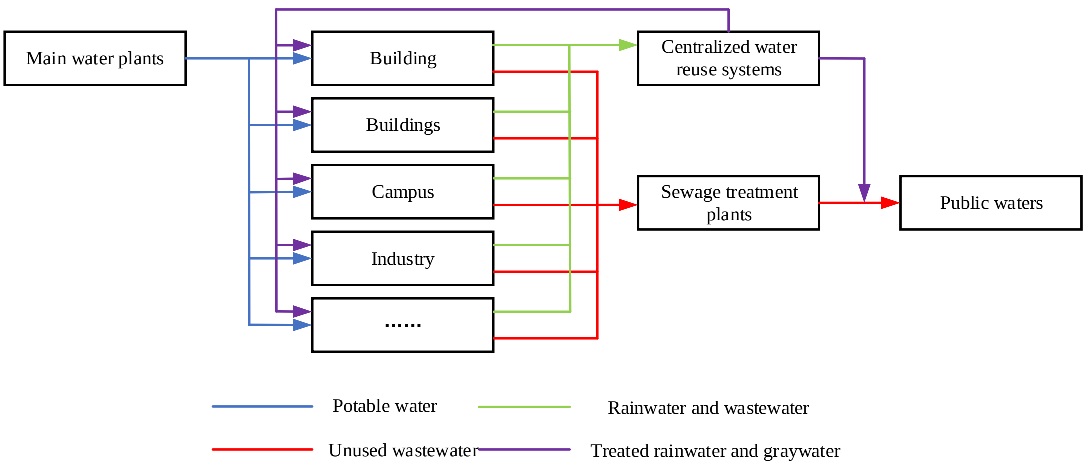

Fig 1-14 Lay out of centralized water reuse systems

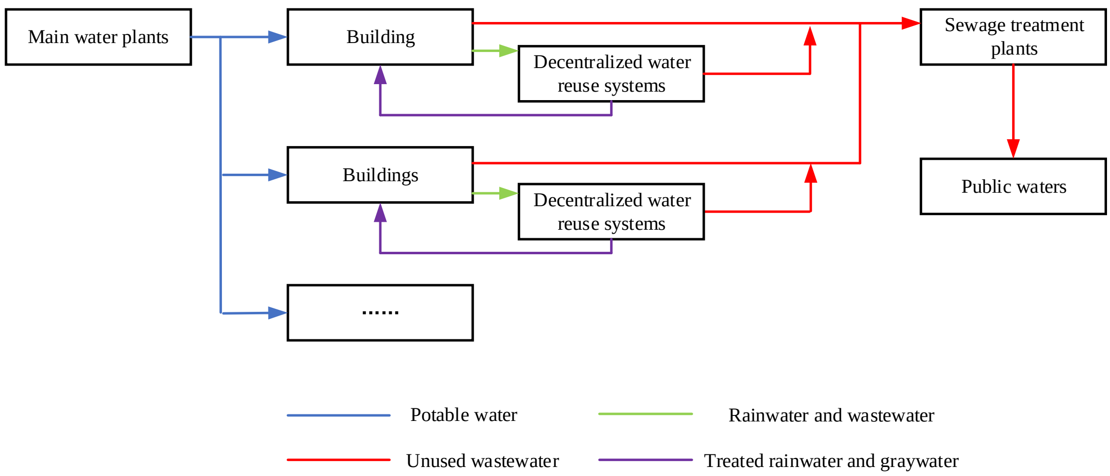

Fig 1-15 Lay out of decentralized water reuse systems

However, pumping the treated rainwater and graywater from a centralized water reuse system to buildings is energy-intensive because the distance between buildings and centralized water reuse systems is usually long [24]. On the other hand, a water distribution network that is independent of the municipal water supply network is required by centralized water reuse systems to return the treated rainwater and graywater to buildings, known as a dual-pipe network, which requires a new urban planning strategy. Therefore, centralized water reuse systems are also known as dual-pipe systems. Decentralized water reuse systems are more flexible than centralized water reuse systems and can be tailored for the location-specific situation, which can meet the specific water quality requirements of buildings to avoid producing the same quality of water for all water uses [25]. Decentralized water reuse systems also have lower sewage coverage, which is easier to control the quality of raw water. Furthermore, decentralized water reuse systems can reduce pumping water over long distances to reduce direct and embody energy [26]. From an economic perspective, decentralized water reuse systems can avoid expensive expansion of centralized systems because of the expansion of service scope, and also avoid the inherent financial risks of large centralized systems [27]. Therefore, between large-scale centralized systems and batches of small-scale decentralized systems, mass implementation of decentralized water reuse systems has recently received much attention. Developing countries have pioneered the implementation of decentralized water reuse systems to conserve water. Some developed countries, especially Australia, the United States, and Japan, have also widely implemented decentralized water reuse systems to meet urban water demand and protect the environment. In addition, Australia has developed a clustered decentralized water reuse system to coordinate with the municipal system, which connects or can be connected to the existing sewage network to integrate manage the decentralized water reuse systems and urban sewage [28].

RWHs are often used as decentralized water reuse systems because of the simple treatment process and low cost. However, RWHs can be affected by low precipitation in arid climates and small catchment areas and small tanks due to building areas, which result in an insufficient water supply. In contrast, the water supply of GWRs is more stable because the production of wastewater in buildings is stable but additional treatment is often required by wastewater before it can be reused, which results in the unit treatment cost of wastewater may be higher than that of potable water and the cost of graywater may be higher than water tariffs because decentralized GWRs in buildings are often small scale [29]. In addition, GWRs are sensitive to changes in per capita water demand, which may result in insufficient because of factors such as building occupancy. Therefore, GWRs are often implemented as centralized systems.

The Japan Water Facilities Environmental Hygiene Association has conducted a survey on the operation and maintenance management of 318 decentralized RWHs and GWRs [30]. The results show that 104 of them still require to be supplemented with potable water because of insufficient water supply, 75 of them have the heavy burden of operation and maintenance costs, and 63 of them have unstable raw water sources. It can be seen that the main obstacles of implementing decentralized water reuse systems are insufficient water quantity and cost. Therefore, the development of decentralized water reuse systems should actively develop the systems with large water quantity and low cost to conserve water in buildings.

Hybrid rainwater-graywater systems (HRGs) are a new type of decentralized water reuse system, which can simultaneously collect, treat, and reuse rainwater and graywater in buildings to conserve potable water. HRG can combine the advantages of RWHs and GWRs to offset the disadvantages of implementing a single system alone. For example, the reuse of graywater can reduce the dependence of RWHs on seasonal precipitation because graywater production is not affected by climatic conditions, which allows HRGs to supple graywater in the dry season and supple rainwater in the rainy season [31]. In addition, adding rainwater to GWRs can reduce the sensitivity of GWRs to graywater generation and demand because simultaneously reusing rainwater and graywater can conserve more water than separately reusing rainwater and graywater [32]. This also resulted in that such systems can prioritize rainwater, a cleaner alternative water source, for reuse, reducing the necessity of GWRs to collect dark graywater from buildings because of insufficient water volumes, which reduces the system costs. On the other hand, HRGs can simultaneously capture contaminated rainwater and wastewater at the source to reduce surface runoff, flood risk, and the load of sewage treatment plants [33].

However, HRGs also have some disadvantages. For example, simultaneously reusing rainwater and graywater increases the complexity of systems, which may cause additional environmental impacts. In addition, the implementation of HRGs in some buildings may be oversized to exceed the non-potable water demands of the buildings, which may cause secondary waste of resources. Moreover, the operation and maintenance costs of HRGs because such systems must simultaneously implement the treatment units of rainwater and graywater, which may result in insufficient economic benefits of HRGs in some buildings. Disadvantages such as these have led to the fact that HRGs only stay in "Green Buildings" that have high requirements for conserving water and some pilot projects, which hinders the further development of HRGs. Optimizing the various problems that implementing HRGs in buildings is one of the prerequisites for the widespread implementation of such systems from “Green Buildings” and pilot projects. However, only a few studies have explored the feasibility of HRGs in specific scenarios, whereas the optimization methods of the limitation that implementing HRGs in buildings are still a large underexplored domain. Therefore, modeling for HRGs to evaluate and improve the technical, environmental, and economic feasibility of HRGs in various scenarios is essential for promoting the implementation of such systems.

1.3 Literature review

1.3.1 Rainwater harvesting and graywater collecting

(1) The feasibility of rainwater harvesting

In urban regions, rainwater harvesting is the potentially useful precipitation harvested from the impervious surface areas of buildings such as capture areas and patios to directly supply for non-potable water demand of buildings [34]. The quality of those harvested rainwater is one of the factors affecting the willingness of people to reuse rainwater because it determines the health risks of reusing rainwater [35]. The quality of untreated rainwater is listed in Table 1-5.

The quality of untreated rainwater depends on the material of the relevant components of RWHs including the materials of capture areas, gutters, and plumbing systems [36]. Capture areas, usually the roof of a building, are a major source of pollutants in rainwater, where the material and slope of the roof significantly affect the concentration of pollutants in rainwater [37-39]. Dry deposition and wet deposition deposit atmosphere pollutants in the capture area and these pollutants will be washed by runoff into RWHs after physicochemical reactions with the materials of the capture area, which results in high concentrations of total suspended solids (TSS), total nitrogen (TN), total phosphorus (TP), anions, cations, and heavy metal elements in rainwater. These pollutants will be increased with the number of day days before a precipitation event and the duration of the precipitation [40, 41]. In addition, concrete capture areas significantly increase the pH of rainwater because of the dissolution of calcium carbonate, whereas galvanized capture areas can lead to elevated metal elements in rainwater [42-44]. The harvested rainwater from rough capture areas, such as wooden and shingled roofs, have the highest concentrations of heavy metals and the worst quality [45]. On the other hand, a more sloping capture area can reduce the retention time of rainwater because the runoff coefficient is increased, which can improve the quality of harvested rainwater [46]. Escherichia coli (E. coli) had a high positive detection rate in untreated rainwater and the concentration varied greatly (Table 1-5), which caused by the reason that capture areas are often contaminated with bird and small mammal droppings, and such contamination varies with wind speed and direction and wildlife type [38]. However, the concentrations of total coliform and fecal coliform were significantly lower in rainwater from metal roofs than other materials because a higher surface temperature can inactive coliforms [41]. Therefore, smoother and more angled capture areas can significantly improve rainwater quality [47].

Gutters and plumbing systems mainly provide more heavy metal elements for the harvested rainwater, especially copper pipes will exudate more copper into rainwater [48-50]. A protective layer inside the components and plumbing systems is essential for protecting the rainwater quality. Finally, rainwater flowing into the rainwater tank will further deposit pollutants to the bottom of the tank to form sludge [51, 52]. Therefore, the withdrawal of rainwater from rainwater tanks should follow the principles: 1) Avoid withdrawing the sludge at the bottom of the tank; 2) The rainwater at the bottom of the tank should be used first to avoid the accumulation of stagnant water [53]; and 3) The rainwater tank should be cleaned regularly to improve the quality of rainwater.

Table 1-5 Quality of untreated rainwater, light wastewater, and dark wastewater [43, 48, 54-67]

	Rainwater		Light wastewater [a]		Dark wastewater [b]	
	Min	Max	Min	Max	Min	Max
pH	3.10	11.40	5.80	8.10	6.20	10.00
Chroma (Platinum Cobalt Chromaticity Units)	0.40	310.50	7.50	547.5	3.00	205.00
E. coli (CFU/100 mL)	0.0	4.2	0.0	6.4	0	6.7
Fecal coliforms (CFU/100 mL)	0.0	3.2			3.5	6.9
Total coliforms (CFU/100 mL)	0.0	6.4	3.4	8.5	0	8.3
Biological oxygen demand BOD_5 (mg/L)	0.00	3.00	12.00	424.00	1.10	890.00
Total organic carbon TOC (mg/L)	0.00	0.00	40.00	120.00	110.00	582.00
Turbidity (NTU)	0.20	303.50	10.80	240.00	20.80	239.70
TSS (mg/L)	1.00	153.00	40.00	303.00	68.00	625.00
Total dissolved solids TDS (mg/L)	1.00	750.00	520.00	787.00	590.00	1396.00
DO (% sat.)	4.41	6.79	0.00	0.00	0.00	0.00
Ammonia nitrogen (mg/L)	0.00	0.00	0.00	15.00	0.10	10.70
Pb (μg/L)	2.00	271.00	0.00	10.20	0.00	33.00
Fe (μg/L)	0.00	1390.00	36.00	1100.00	1.00	1000.00
Mn (μg/L)	0.50	533.00	0.00	54.00	0.00	320.00
Mg (μg/L)	0.00	9350.00	1400.00	2300.00	1100.00	2900.00
Zn (μg/L)	0.50	3200.00	16.00	6300.00	5.00	320.00

Note: [a]: generated from washbasins;
[b]: generated from laundry, washbasins, and showers

Previous studies have demonstrated that the harvested rainwater contains high pollutants at the beginning of the rainfall event and the quality of untreated rainwater will be improved with the duration of precipitation [42, 68]. In other words, most of the matters on capture areas can be washed away during the initial period of the precipitation event, which is known as "first flushing" [69]. Therefore, discarding the 1-2 mm runoff in the initial period of the precipitation event by installing a first flushing device in RWHs can simply and efficiently improve the quality of rainwater without compromising water-saving efficiency and avoiding other complex chemical and biological treatment processes [40]. The amount of discarded rainwater varies with the intensity and frequency of precipitation and is recommended to from 0.11 mm (11 L per 100 m^2 of capture areas) to 2 mm (200 L per 100 m^2 of capture areas) [70-72]. In addition, flocculation, filtration, and disinfection of the harvested rainwater after being stored in rainwater tanks can further ensure the safe reuse of rainwater.

In summary, despite the untreated rainwater having lower quality, RWHs can significantly improve the quality of rainwater by selecting specific material and concise devices, which will decrease the maintenance difficulty and investment cost of such systems. Therefore, the focus that hinders the implementation of RWHs has transferred to the available amount of rainwater, which is called as the reliability of RWHs. The reliability of RWHs is affected by several factors, such as capture roof areas [73], precipitation [74], rainwater tank size [75], and non-potable water demand

[76], and is more susceptible to climate changes [77, 78]. This results in the differences in the feasibility of rainwater harvesting with regions, thus requiring a feasibility evaluation of buildings in each country to ensure the efficient implementation of such systems [79].

Currently, a series of mature evaluation methods and simulation models have been proposed to analyze the feasibility of harvesting rainwater in buildings to conserve water, such as linear programming approach [80], stochastic approach [81-83], water balance model [84-86], and life cycle assessment [87]. Previous studies summarized that rainwater harvesting is more suitable for humid subtropical, warm semi-arid, and Mediterranean continental climate regions, whereas it is unfeasible in cold semi-arid and warm desert regions [88, 89]. Furthermore, in terms of the urban fabric, rainwater harvesting has higher environmental benefits in high-density cities than in sprawled cities [90]. On the other hand, in terms of the building characteristics, the reuse of rainwater in buildings with non-potable water demands from 0.1 L to 1 L per unit roof area per day to conserve water can meet more than 80% of the total non-potable water consumption and the optimal rainwater tank size required per unit roof area of the buildings varies from 0.15 m^3 to 0.9 m^3 depending on the local precipitation [91-93]. Among such ranging of rainwater tank sizes, climate changes will have less impact on a larger rainwater tank [94, 95]. This makes the rainwater harvesting in residential buildings to conserve water less reliable under the climate changes because residential buildings generally have smaller catchment areas and less space to install rainwater tanks [96]. However, Devkota, J.P., et al, found that small-scale rainwater harvesting has lower greenhouse gas emissions [97]. Therefore, further research of RWHs should focus on combining rainwater with other alternative water sources for building water conservation in regions with less precipitation and develop reasonable optimization methods to improve the impact of climate changes on the RWHs.

(2) The feasibility of graywater recycling

Graywater recycling refers to retreating the wastewater of buildings, which includes light wastewater generated from showers and washbasins and dark wastewater generated from kitchen sinks, washing machines, and toilets, as graywater for non-potable water reuse [72, 98, 99]. Such wastewater accounts for over 44% of the total water consumption of buildings [100]. Therefore, the impact factors of graywater recycling mainly include the difference in water consumption caused by the number of residents inside the building and their living habits [101]. For example, the water consumption of washbasins accounts for the highest proportion of the total potable water consumption of residential buildings in the UK at 32%, whereas the water consumption of showers is the highest proportion of that in Japan, which accounts for 40%, and the water consumption of washbasins in residential buildings in Japan only accounts for 15% of the total potable water consumption (Fig 1-16 and Fig 1-17). This results in differences in the quantity and quality of wastewater in different regions, but this will not affect the water-saving potential of graywater recycling because the non-potable water demand is always lower than the total water consumption in a building. Therefore, the reuse of graywater in buildings to conserve water has a sufficient available amount in comparison to rainwater harvesting.

As shown in Table 1-5, the concentration of pollutants in wastewater, such as TSS, TDS, organic matters, and microorganisms, is higher than that in rainwater, whereas the heavy metal elements in wastewater, such as Mn, Mg, and Ni, are lower than that in rainwater because the quality of wastewater is depended on the lifestyle of the residents rather than system materials [72]. For example, the concentration of heavy metal elements in the wastewater generated from the laundry is higher than that in the wastewater generated from showers, especially Pb [56]. The difference of source characteristics also results in the turbidity of wastewater being lower than that of rainwater (Table 1-5). However, microorganisms and viruses in wastewater are more attention in comparison to the physicochemical characteristics such as heavy metal elements because such bacteria and pathogens can directly contact with and be ingested by the human body when reusing graywater, ultimately causing human health risks [102]. Fountoulakis. et al, found that organic matters account for 30% of total wastewater and nutrients account for 9% to 20% of total wastewater, which is beneficial for facilitating the growth of microorganisms and bacteria [103]. Therefore, the most representative fecal index in wastewater has been accepted to be used as a proxy for the quality of wastewater to indicate the possibility of pathogens in wastewater because detection of all pathogens in graywater requires huge detection and monitoring costs. The concentration of fecal coliforms in graywater is significantly higher than that in rainwater (Table 1-5) and these pollutants are major concentrated on the wastewater generated from showers and toilets, which also varies with the health of people [104]. Therefore, the wastewater generated from the buildings, such as hospitals and laboratories, is prohibited to reuse as graywater.

In order to ensure the safe reuse of rainwater and graywater, despite there is no clear international guideline to regulate the quality of rainwater and graywater, various countries have successively issued specific water reuse standards [105]. These standards have different requirements of pollutant type for treated rainwater and graywater, but they all have clear requirements for the number of pathogenic microorganisms (fecal and total coliforms) and nutrients (BOD_5), which require a low level of pathogenic microorganisms and nutrients in treated rainwater and graywater (Table 1-6). Therefore, the raw graywater must be vigorously disinfected to reduce the concentration of pathogenic microorganisms and nutrients after a series of physical and chemical treatment processing to meet non-potable water demands in buildings.

The wastewater with a more complex composition should be properly treated before reuse because graywater does not have the first flushing phenomenon like rainwater, especially for irrigation, groundwater recharge, and non-potable water use that can indirectly contact with human body, to avoid secondary pollution to soil and groundwater and harm to people’s health because of accidental touching and eating [106, 107]. Leong, J.Y.C., et al. have reviewed the impact of different treatment processes on the quality of graywater and Oh, K.S., et al. have summarized the impact of different disinfection processes on the quality of graywater [72, 107]. Generally, wastewater needs to be filtered to remove coarse particles and suspended solids and then needs to be purified by further physical, chemical, and biological treatment processes and disinfection to meet the quality requirements of non-potable water. However, these processes are more expensive and complex than the first flushing device of RWHs [108]. Therefore, the investment cost and the environmental benefits during the operation of GWRs significantly affect the implementation of such systems because the financial cost determines the willingness of residents to implement water reuse systems [109, 110].

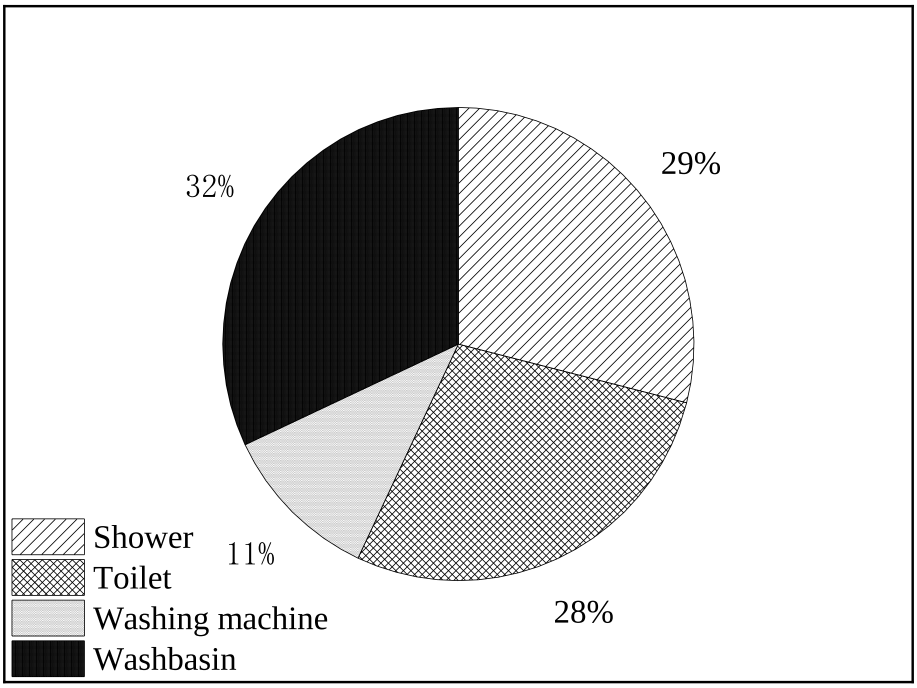

Fig 1-16 Distribution of domestic water consumption in the UK [111]

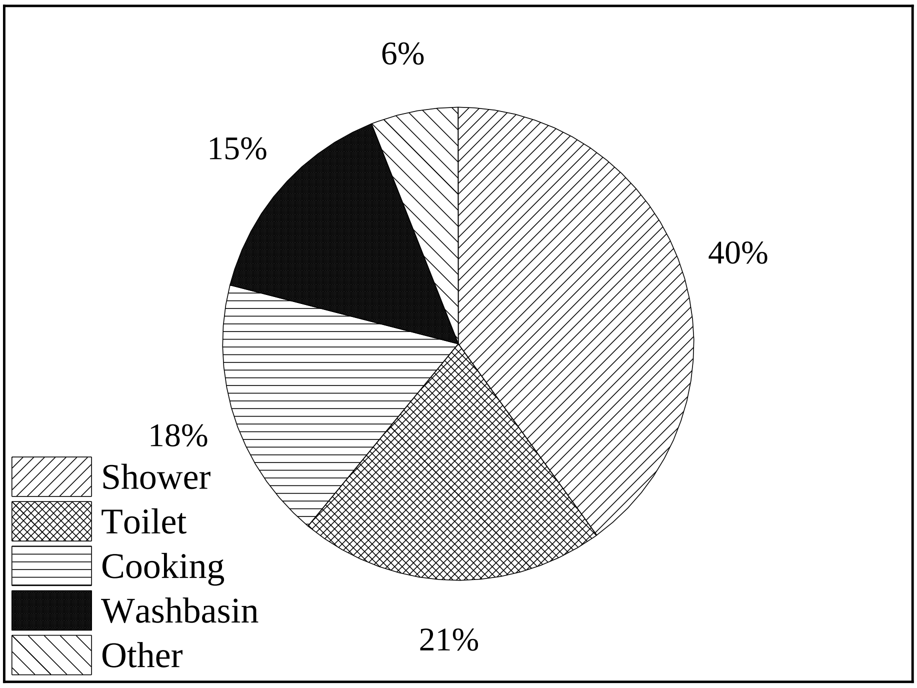

Fig 1-17 Distribution of domestic water consumption in Japan [18]

Table 1-6 International water reuse standards [100, 112, 113]

	pH	Fecal coliforms (max CFU/100 mL)	Total coliforms (max CFU/100 mL)	Helminth egg (#/L)	BOD_5 (max mg/L)	Turbidity (max NTU)	TSS (max mg/L)	TDS (mg/L)	DO (min % sat.)	Cl_2 residual (min mg/L)	Ammonia nitrogen (mg/L)	Fe (mg/L)	Mn (mg/L)
Italy	6-9.5	--	<10	--	<20	--	<10	--	--	--	TN<15	--	--
China	6-9	--	≤3	--	≤10	≤5	--	≤1000	≥1	End of pipe ≥0.2	≤5	≤0.3	≤0.1
Canada	--	≤200	≥0.5	--	≤20	≤5	≤20	--	--	≥0.5	--	--	--
Australia	--	<2/50	--	--	>20	<2	--	--	--	--	--	--	--
Arizona	4.5-9	<1	--	--	--	1	--	--	--	--	--	--	--
California	--	2.2	--	--	2	--	--	--	--	--	--	--	--
Cyprus	--	50	--	--	10	--	10	--	--	--	--	--	--
France	--	<1000	--	<1	--	--	--	--	--	--	--	--	--
Germany (g)	6-9	100 (g)	500 (g)	--	20 (g)	1-2 (m)	30	--	80-120	--	--	--	--
Japan (m)	6-9	10	10	--	10	5	--	--	--	--	--	--	--
South Africa	--	0 (g)	--	--	--	--	--	--	--	--	--	--	--
Spain (Canary Islands)	6.5-8.4	--	2.2	--	10	2	3	--	--	1	--	--	--
Israel	--	--	12 (80%)	--	15	--	15	--	0.5	0.5	--	--	--

*m: mandatory; g: guideline; --: not required.

Continued from Table 1-6

	pH	Fecal coliforms (max CFU/100 mL)	Total coliforms (max CFU/100 mL)	Helminth egg (#/L)	BOD_5 (max mg/L)	Turbidity (max NTU)	TSS (max mg/L)	TDS (mg/L)	DO (min % sat.)	Cl_2 residual (min mg/L)	Ammonia nitrogen (mg/L)	Fe (mg/L)	Mn (mg/L)
Florida (m)	----	25 (75%)	--	--	20	--	5	--	--	1	--	--	--
Texas (m)		75 (m)	--	--	5	3	--	--	--	--	--	--	--
Tunisia	6.5-8.5	--	--	<1	30	--	30	--	7	--	--	--	--
UAE	--	--	<100	--	<10	--	<10	--	--	--	--	--	--
The UK	6-9	100 (g)	500 (g)	--	--	2 (g)	--	--	80-120	--	--	--	--
Singapore	6-9	--	<10	--	<5	<2	--	--	--	0.5-2	--	--	--
America (EPA)	6-9	≤800	--	--	≤30	--	≤30	Irrigation (≤2000)	--	≥1	--	--	--
Jordan	6-9	--	--	--	≤30	≤10	≤50	--	≥2	--	TN≤45 NO_3-N≤30	--	--
WHO (lawn irrigation)	--	200 (g)	--	--	--	--	--	--	--	--	--	--	--

*m: mandatory; g: guideline; --: not required.

Previous studies have widely evaluated the feasibility of GWRs in different regions by life cycle assessment and life cycle cost assessment. GWRs should be priority considered by multi-story and super high-rise residential buildings and the groups of buildings because the increase of non-potable water demand can amortize the treatment costs of graywater to make GWRs being economically feasible [114, 115]. In buildings with sufficient space, a relatively concise constructed wetland is recommended to be used by GWRs to treat graywater because it can not only ensure the quality of the reclaimed water, but also recover the investment cost of the systems in a short payback period [116]. In addition, Shanableh, A., et al. determined that implementing GWRs in buildings with air conditioning cooling towers will not be investment attractive [117].

The energy consumption of GWRs is still one of the bottlenecks in the implementation of such systems. The majority of studies acknowledge that small-scale decentralized GWRs will consume more energy than centralized systems when the building is close to the main water plants and the total energy consumption will decrease as the life cycle of the buildings increase [118-120]. Therefore, GWRs have better environmental benefits at regions where far away from centralized main water plants and buildings at high altitudes regions because long-distance water distribution pipe systems have high investment and maintenance costs and pumping water into a long-distance and a high altitude is energy-intensive [121]. Risch, Boutin, et al. concluded that the environmental benefits exhibited by GWRs in remote regions increased significantly as the distance between the systems and the sewer network decreased [122]. Currently, membrane reaction (MBR) is considered to be the most energy-efficient treatment equipment among the mature treatment processes, whereas the investment and maintenance costs of GWRs with MBR are always higher than that of GWRs with other treatment equipment [123, 124]. Kobayashi, Y., et al. proposed that the feasibility of GWRs with constructed wetlands is better than that of GWRs with MBR even in community-scale graywater reuse scenarios [125]. Therefore, MBR-based GWRs must depend on a higher local water tariff and a larger non-potable water demand to support the investment attractiveness of such systems [126]. In addition, sharing graywater collected on a small scale to surrounding regions can also increase the economic feasibility of GWRs [127].

On the other hand, the selection principle of the graywater tank is different from that of the rainwater tank because the material of the water tank does not affect the performance of GWRs. The graywater water tank should be sized according to the graywater collected to avoid storing the graywater for more than 24 h because long-term storage of graywater will cause the growth of bacteria and increase the health risks of reusing graywater [111].

In summary, further research of GWRs should focus on developing the new technology of treatment equipment to reduce the energy consumption of GWRs and improving the investment and operation costs of GWRs to increase the economic feasibility of such systems. For example, the treatment process of GWRs can be simplified to control the investment cost by choosing to recycle light wastewater or dark wastewater. In addition, de Koning et al. recommended different levels of graywater treatment depending on the "fit-for-purpose" of the reclaimed water to avoid uniform treatment of all graywater [128].

1.3.2 The feasibility of hybrid rainwater-graywater systems

RWHs cannot provide sufficient non-potable water in some scenarios because of specific building characteristics and natural conditions, whereas GWRs are too expensive to be unfeasible in some scenarios because of lower non-potable water demands. In addition, a single alternative water source may not be enough in scenarios with considerable irrigation space, large buildings and, densely populated buildings, such as shopping malls and residential areas. The above scenarios may become an exceptional case in previous studies, but they are common across regions. Developing a suitable water reuse system for these buildings is essential for improving water scarcity in urban regions. Hybrid rainwater-graywater systems (HRGs) offer new opportunities for water conservation in these buildings. HRGs allow RWHs and GWRs to complement the limitations of each other by simultaneously collecting and reusing rainwater and graywater in a building. In addition, the alternative water sources of HRGs are more flexible and sufficient, which can significantly reduce the scale of RWHs and GWRs [32]. For example, HRGs are beneficial to reduce the rainwater tank size because the finite building spaces limit the installation of large water tanks with high performance [129-131]. Finally, HRGs allow providing "fit-for-purpose" of alternative water for different water uses, which will reduce the treatment cost of rainwater and graywater [72].

Currently, the development of HRGs is still infant, which is not only reflected in the lack of clear conclusions to guide the advantages and limitations of HRGs in different scenarios, but also that there are no evaluation and optimization tools specifically for HRGs. Therefore, the feasibility evaluation of HRGs still stays in case studies based on hypothetical systems with simplified models, especially drawing support from simulation models for RWHs coupled with simple estimates of graywater input and output, which will overestimate or underestimate the performance of HRGs.

Brazil and Malaysia have made great contributions to the feasibility evaluation of HRGs. Ghisi, E. and S. Mengotti de Oliveira evaluated the water-saving efficiency and economic feasibility of HRGs in single-family buildings in Brazil [129]. The method they used to evaluate the virtual HRG combined the simulation software for RWHs, the Neptune, to determine the optimal rainwater tank for the rainwater subsystem of the HRG with a simple estimate that allows the amount of graywater generated from showers, toilets, and washbasins to equal to the non-potable water demand to simulate the graywater subsystem. The authors also assumed that the non-potable water efficiency of graywater subsystems equals the demands if the graywater volume excesses the demands, otherwise the non-potable water efficiency of graywater subsystems equals the amount of graywater generation. The evaluation method for HRGs has been recognized and applied by other authors [32, 132, 133]. The authors concluded that rainwater harvesting can almost meet the non-potable water demands in single-family buildings with 33.8% to 36.6% of water-saving efficiency, and HRGs are unfeasible in single-family buildings because such systems cannot significantly improve the water-saving efficiency, which from 33.8% to 36.4%, to be economically unfeasible. Similarly, Leong, J.Y.C., et al. also found that HRGs are unfeasible in single-family buildings in Malaysia because it is uneconomic to use a large amount of renovation cost to upgrade RWHs to HRGs only to improve the slight trace water-saving efficiency [134]. In addition, Leong, J.Y.C., et al. recommended that HRGs in residential buildings should use rainwater first and followed by graywater [135]. Ghisi, E. and D.F. Ferreira used the same method to evaluate the feasibility of HRGs in multi-story buildings in Brazil and obtained an opposite conclusion [32]. The authors determined HRGs can significantly improve the water-saving efficiency in comparison to RWHs and GWRs because the capture areas of multi-story buildings are too small to meet the great non-potable water demands, thus HRGs in multi-story buildings have economic benefits. However, these studies have simplified the configuration of HRGs, which assume cheaper treatment equipment such as artificial wetland to treat wastewater and ignore the investment costs of necessary facilities such as septic tanks, grilles, and disinfection equipment because of the collection of dark wastewater from buildings, thus seriously underestimated the economic benefits of HRGs.

Therefore, HRGs may be more feasible in multi-story buildings because single-family buildings do not have substantial non-potable water demands and are unnecessary to reuse multiple alternative water sources for water conservation. In addition, considering that the actual HRGs are more complex than the virtual systems, HRGs in multi-story buildings are recommended to cooperate with surrounding buildings to improve the installation willingness and economic feasibility of HRGs by increasing non-potable water demands to reduce the water supply costs.

On the other hand, HRGs are also the most expensive water reuse systems in other large-scale buildings. Leong, J.Y.C., et al. proposed that upgrading GWRs to HRGs in commercial can significantly improve the water-saving efficiency from 21.1% to 57.1% because the wastewater source in commercial is only from washbasins and cannot meet the non-potable water demand of toilet flushing [135]. However, although HRGs can provide superior water-saving effects in commercial buildings, such systems are still uneconomically feasible over a 50-year life cycle [134]. Furthermore, Naserisafavi, N., et al. found that HRGs have the most investment and operation costs in mixed-use buildings in comparison to RWHs and GWRs, and Zang, J., et al. concluded the payback period of HRGs in a student and staff accommodation in India is over 250 years even if such systems have the most water-saving efficiency [136, 137]. Therefore, according to the above review, HRGs can provide higher water-saving efficiency than the separate use of rainwater of graywater in large-scale and mixed-use buildings because of the large non-potable water demand, but the economic unfeasibility is still a limitation that affects the acceptance of such systems. Users may prefer higher quality and cheaper potable water from main water plants without any subsidies from the government, which will cause stakeholders to lose investor confidence in HRGs. In addition, improving the economic feasibility of HRGs cannot rely on the increasing of future water tariff because the changes in water tariffs are unpredictable in the future [138].

In summary, economic feasibility has severely hindered the implementation of HRGs. Nevertheless, HRGs have a more flexible scale and better adaptability to natural changes than RWHs and GWRs, which makes such systems have the potential for further generalization. Therefore, further research is recommended to commit to modeling for improving the economic benefit of HRGs to optimize the feasibility of such systems. Otherwise, previous studies about the feasibility evaluation of HRGs are limited in specific regions and virtual systems. For example, the current evaluation of HRGs in residential buildings has focused on tropical and rainy regions, whereas similar evaluation of HRGs in boreal and arid regions have yet to be found. This not only fails to understand the feasibility of HRGs in different scenarios, but also ignores the high complexity of HRGs and thus overestimates the performance of HRGs. Therefore, a wide evaluation of HRGs in different regions must be conducted, especially based on the actual data, to understand the water conservation and economic benefit various of HRGs with the different characteristics of precipitation and water consumption. On the other hand, developing tailored models to simulate and optimized the optimal scale of HRGs are highlighted for the development of such systems.

1.3.3 Potential environmental benefits of hybrid rainwater-graywater systems

(1) Environmental impacts of hybrid rainwater-graywater systems

The implementation of HRGs can bring other environmental impacts except for the direct benefit of water conservation. For example, HRGs allow using treated wastewater as graywater for irrigation to avoid nutrients in wastewater entering soil and groundwater, which will reduce the concentration of nitrogen and phosphorus in the natural water to alleviate the deterioration of water eutrophication [132, 139]. In addition, Marinoski, A.K. and E. Ghisi pointed out that a residential HRG in Brazil can reduce 36.1% of total energy consumption, whereas it has the highest impact on human toxicity (kg de 1.4-DB eq.), Freshwater ecotoxicity (kg 1.4 – DB eq. for fresh water), Marine ecotoxicity (kg 1.4 – DB eq. to the oceans), and metal depletion (kg de Fe eq.) [132]. Conversely, Leong, J.Y.C., et al. found that a commercial HRG in Malaysia has the lowest impacts on acidification potential (kg SO^{2-} eq.), eutrophication potential (kg phosphate eq.), freshwater ecotoxicity, global warming (kg CO^{2-} eq), human toxicity, photochemical ozone creation (kg ethene eq.), and water stress index in 50-year life cycle [134]. These environmental impacts of HRGs will change with locations and use characteristics. For example, there is still debate about the impact of HRGs on global warming. Rygaard, M., et al. indicated that an HRG in industrial harbor areas has the most severe impacts on global warming because it consumes more energy than the conventional water supply method. Marinoski, A.K., et al. also concluded the water conservation strategy with the worst total energy indexes in residential buildings in Brazil is HRGs in comparison to RWHs and GWRs [133]. The conclusion is also confirmed by Leong, J.Y.C., et al [134]. Furthermore, Zang, J., et al. emphasized that the water boosting in buildings is usually ignored when calculating the energy consumption of HRGs, and the related electricity consumption for pumping water to water end-uses are usually borne by consumers, which will significantly underestimate the energy consumption of HRGs [137].

The energy consumption of HRGs becomes one of the potential factors that hinder the implementation of such systems. Throughout the whole life cycle of HRGs, plumbing systems and rainwater tanks account for the major embodied energy consumption of rainwater subsystems, whereas concrete accounts for the major embodied energy consumption of graywater subsystems [133, 140]. These embodied energy consumptions of HRGs decrease with the increase of life cycle. In terms of direct energy consumption, the rainwater subsystems of HRGs consume almost no energy during the operating phase, whereas the treatment process of graywater subsystems consumes a lot of energy during the operation phase of HRGs [136]. Therefore, an effective measure to reduce the total energy consumption of HRGs is recommended as another important factor for the implementation of such systems, such as developing low-energy-consumption materials and designing the optimal scale to reduce embodied energy consumption, especially improving the treatment process and treating wastewater following "fit-for-purpose" to reduce the operating energy consumption of HRGs. In addition, Rygaard, M., et al. recommended that combining HRGs with renewable power generation technology will be the more preferable solution to implement such systems in the future [141]. Secondly, current conclusions about the environmental impacts of HRGs have only considered the specific configuration of HRGs, which uses treated graywater for toilet flushing and uses rainwater to meet other non-potable water demands. Leong, J.Y.C., et al. proposed that mixing rainwater and wastewater can neutralize the rainwater pH and dilute the wastewater quality to extending the life cycle of treatment equipment, whereas the mixing water may increase the pathogen concentration to require more intensive disinfection processes, which will increase the life cycle impacts of HRGs [72]. Therefore, the other challenge of implementing HRGs is conducting multi-regional and multi-configuration life cycle assessments to fully understand the environmental impact of HRGs.

(2) Impacts of hybrid rainwater-graywater systems on runoff and wastewater flows

Consensus from previous studies that decentralized RWHs can reduce flood damage during small and medium-sized flood events. Therefore, widely implementing RWHs in a region can reduce urban flood disasters through cumulative benefits, including the risk of costs resulting from damage to buildings and municipal facilities. Palla, A., et al. believed that the wide implementation of RWHs in a region can reduce the runoff in the region by approximately 25%-35% in precipitation events below 25mm/h and can effectively reduce the cost damage of flooding, which makes the implementation of RWHs economically feasible [142]. Jamali, B., also found that the large-scale implementation of RWHs can reduce the cost damage by about 30% in small and medium flood events with a return period of 2-20 years without considering potential cost damage such as the psychological impact, pollution, and health risk caused by floods [143]. Furthermore, the rainwater spilled from rainwater tanks is rich in iron elements [144]. These iron elements inhibit the formation of hydrogen sulfide in sewers to improve the environment of the sewers, which increases the feasibility of RWHs.

Similarly, GWRs can reduce the pressure on sewage treatment plants by reducing wastewater discharge to improve the potential economic benefits of GWRs. In addition, the implementation of GWRs can also reduce the proportional depth in sewers, which allows more users to be connected to the same sewers to avoid investment costs in expanding the sewer network [145]. However, the reduction of drainage is a double-edged sword because the sewer system is a complex ecosystem and the irregular changes in wastewater flow and wastewater quality can exacerbate the odor, corrosion, and blockage of the sewer. For example, Marleni, N., et al. found that GWRs can significantly reduce the wastewater flow and the contaminant load in wastewater, but this will increase the concentrations of COD, sulfates, and sulfides in wastewater [144]. These are the main contaminants in sewers that promote the formation of hydrogen sulfide, which contributes to the odor of sewers.

Compared to RWHs and GWRs, which can have a single impact on the sewers, HRGs can simultaneously reduce both runoff and wastewater flows. However, only a limited number of studies have quantified the difference in the impact of HRGs on runoff and wastewater flows in comparison to RWHs and GWRs, which can influence stakeholders' selection of the optimal decentralized water reuse systems for buildings. Sapkota, M., et al. conducted a comparison between the impact of RWHs, GWRs, and HRGs on the sewers and pointed out that both HRGs and RWHs can effectively reduce the runoff flow and the concentrations of TN, TP, TSS, and BOD in the runoff flow, and the reduction of runoff flow by HRGs is less than that of RWHs and both have the same effect on contaminant concentrations in runoff flow [146]. Interestingly, the authors found that HRGs have almost the same effect on wastewater quality and quantity, which is blamed on the assumptions made in the study of the scenarios of water consumption. The authors assumed that the reclaimed water generated from HRGs was supplied for irrigation and toilet flushing which accounted for most of the non-potable water demands in the building. Therefore, it is necessary to further explore the throttling effect brought by HRGs and its potential economic benefits, which is not only conducive to improving the economic feasibility of HRGs, but also provides support for the selection of optimal systems for building water conservation.

1.4 Research purpose and logical framework

1.4.1 Research purpose and core content

Under the background of alleviating the urban water scarcity, the development of multiple alternative water sources is imperative. The implementation and popularity of decentralized water reuse systems is also a general trend. Therefore, this study is committed to further promoting HRGs, and the advantages and limitations of such systems in different scenarios were analyzed and compared to understand the factors that affect the implementation of HRGs. Then, dedicated models for evaluating and optimizing HRGs were developed from a theoretical perspective. Finally, HRGs are optimized from the two aspects of environmental and economic benefits to improve the feasibility of such systems.

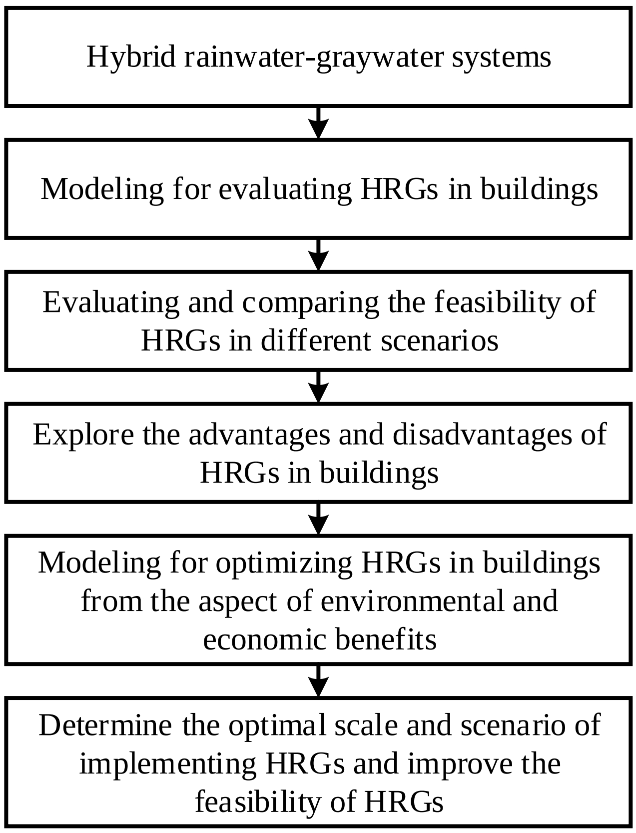

Fig 1-18 Research logic of the study

1.4.2 Chapter content overview and related instructions

The chapter names and basic structure of this study are shown in Fig 1-19 and the brief chapters are shown in Fig 1-20

Research background & Purpose	**Chapter One** Research background and purpose	
Study object & System description	**Chapter Two** Configurations and components of HRGs	
Methodology	**Chapter Three** Simulation model of HRGs based on the water balance model	
Feasibility analysis	**Chapter Four** Environmental and economic benefits of HRGs in public buildings	
Modeling development	**Chapter Five** Dimensionless parameter method for general evaluation of HRGs in buildings	**Chapter Six** Cooperative game method for improving the economic benefits of HRGs in buildings
Conclusions	**Chapter Seven** Conclusion and prospect	

Fig 1-19 Chapter names and basic structure

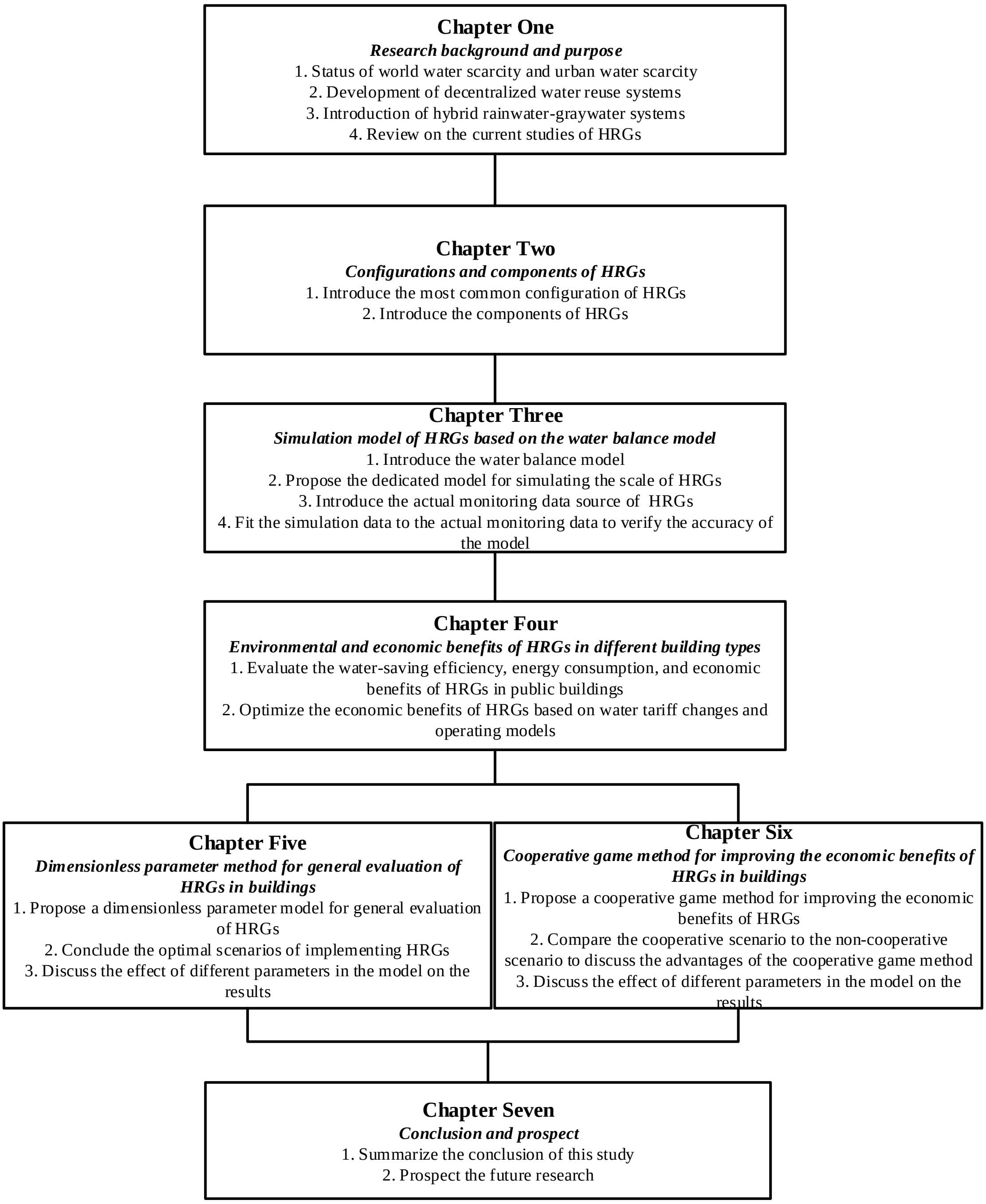

Fig 1-20 Brief chapter introduction

In Chapter 1, Research background and purpose:

Decentralized water reuse systems are one of the important measures to alleviate urban water scarcity. HRGs have a more flexible scale and better adaptability to natural changes than RWHs and GWRs, which makes such systems have the potential for further promoting. However, there is still a huge underexplored domain about the technical, environmental, and economic feasibility of HRGs in various scenarios. This chapter first introduced the status of world water scarcity and urban water scarcity. Then, the development of decentralized water reuse systems and hybrid rainwater systems was expounded with the help of the development of water conservation in Japan. Next, the current research progress of HRGs and the challenges of implementing HRGs in buildings were reviewed. Finally, the research purpose was proposed in this chapter.

In Chapter 2, Configurations and components of HRGs:

HRGs can simultaneously collect, treat, and supply rainwater and graywater in buildings. Therefore, various configurations can be selected by HRGs, such as mixing rainwater and wastewater and separately treating rainwater and wastewater. Furthermore, different degrees of treatment and disinfection processes can be selected by HRGs to treat rainwater and wastewater according to the requirement of non-potable water. This chapter introduced the advantages and disadvantages of various HRG configurations and determined the most common configuration for this study. In addition, the common components of HRGs were introduced in this chapter.

In Chapter 3, Simulation model of HRGs based on the water balance model:

Previous evaluation method for HRGs independently simulated the rainwater subsystem and graywater subsystem and made simple water balance assumptions for the graywater flows, which ignored the integrity of HRGs and resulted in insufficient precision in subsequent calculations. There is still no dedicated model to effectively simulate the operation state of HRGs. This chapter first introduced the water balance model and proposed the dedicated simulation model for HRGs based on the water balance model to evaluate and optimize the scale of such systems. Then, the actual monitoring data of an HRG on campus was obtained by field research and was introduced in this chapter. Finally, the actual monitoring data were fitted to the simulation data to verify the feasibility of this model.

In Chapter 4, Environmental and economic benefits of HRGs in different building types:

Currently, the feasibility evaluation of HRGs is still staying in a few regions and mainly focuses on residential buildings and commercial buildings. The HRGs in public buildings have rarely been explored, especially lacking a comprehensive evaluation based on the actual monitoring data, which had limited the popularity of hybrid systems. In chapter 4, a campus in Japan was selected to evaluate the feasibility of HRGs in public buildings based on the actual monitoring data. Second, the electricity consumption of the HRGs was evaluated. Then, a detailed life cycle cost model was designed to calculate the economic benefit of the HRGs under the current and optimization scenarios. Finally, the results obtained are compared with HRGs in residential and commercial buildings to discuss the advantages of HRGs in public buildings. This chapter concluded the advantages and disadvantages of HRGs in different building types. In addition, the results obtained can be used as a comparison tool for other studies and provide data support for stakeholders to popularize HRG.

In Chapter 5, Dimensionless parameter method for general evaluation of HRGs in buildings:

The performance of the decentralized water reuse systems that are widely implemented for the conservation of building water is affected by various characteristics, such as the location and type of building. Generalized methods to evaluate and compare different system configurations under various scenarios are currently lacking. Previously devised methods have focused on specific parameters describing buildings and are therefore not suitable for regionalized application.

This chapter proposes a dimensionless parameter method with four dimensionless parameters to determine the optimal scenarios for using RWHs, GWRs, and HRGs in buildings: the rainwater demand fraction, graywater demand fraction, storage fraction, and treatment fraction. Furthermore, the feasibility of using RWHs, GWRs, and HRGs in buildings with seasonal daily non-potable water demand was discussed to ensure that the method is not limited to specific scenarios in which the daily non-potable water demand of a building remains stable throughout the year. Finally, the dimensionless parameter method was used to obtain design curves for RWHs, GWRs, and HRGs in the buildings studied in Japan. The proposed method in this chapter can comprehensively and easily evaluate different decentralized water reuse systems for use in buildings and provide new ideas for a generalized design method that can produce decentralized systems at a regional level.

In Chapter 6, Cooperative game method for improving the economic benefits of HRGs

HRGs as efficient decentralized water reuse systems have a profound potential for conserving water in buildings. However, the economic unfeasibility has been hindered the implementation of HRGs. The method that improving the economic benefit of HRGs has rarely been explored. This chapter proposed a comprehensive economic analysis based on the cooperative game theory to explore the economic potential of HRGs. An HRG on campus in Japan was selected as a case study to evaluate the water-saving performance. Then, the economic feasibility of the HRG was analyzed based on the life cycle cost model. Finally, considering the implementation of HRGs has been weakened the profit of main water plants, the cooperative feasibility and drive factors between the HRG and main water plants for mutual benefits were explored based on the cooperative game theory. This chapter can provide new orientation for stakeholders to improve the economic benefit of HRGs and make such systems more economically attractive for conserving water in buildings.

In Chapter 7, Conclusion and prospect

This chapter summarized the conclusions obtained from previous chapters and prospected the further research of HRGs.

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Chapter 2

CONFIGURATIONS AND COMPONENTS OF HRGS

Contents

2.1 Configurations of HRGs

Because most countries prohibit the reuse of potable water in buildings by implementing decentralized water reuse systems, this section only introduced the configurations of HRGs for non-potable water reuse to conserve water.

Configuration 1 of HRGs mixed untreated rainwater and wastewater into a storage tank before treatment processes (Fig 2-1). The potable water demands of buildings are supplied by main water plants. Untreated rainwater and wastewater are stored in a storage tank after filtering and then are treated by chemical or biological treatment processes. Finally, the treated mixed water is supplied to the non-potable water end-use of buildings after disinfecting. In addition, potable water from main water plants can be directly supplemented into treated water tanks to avoid the insufficient non-potable water supply of HRGs. The excess rainwater is spilled into the storm drains and the excess graywater is spilled into the sewers. The uncollected wastewater discharges into the sewers.

The advantages of such HRGs can allow the cleaner rainwater to dilute the more polluted wastewater to minimized health risks and the acidity of rainwater is offset by neutral wastewater to reduce corrosion rates [1]. In addition, this configuration of HRGs can make the mixed rainwater and graywater supply non-potable water uses more stable because the untreated wastewater can provide a stable source of non-potable during dry monsoon in comparison to seasonal rainwater. However, this configuration of HRGs will require oversized treatment equipment and higher doses of disinfectant to reduce the economic benefits of such systems because the mixed rainwater and wastewater may increase pathogen concentrations [2].

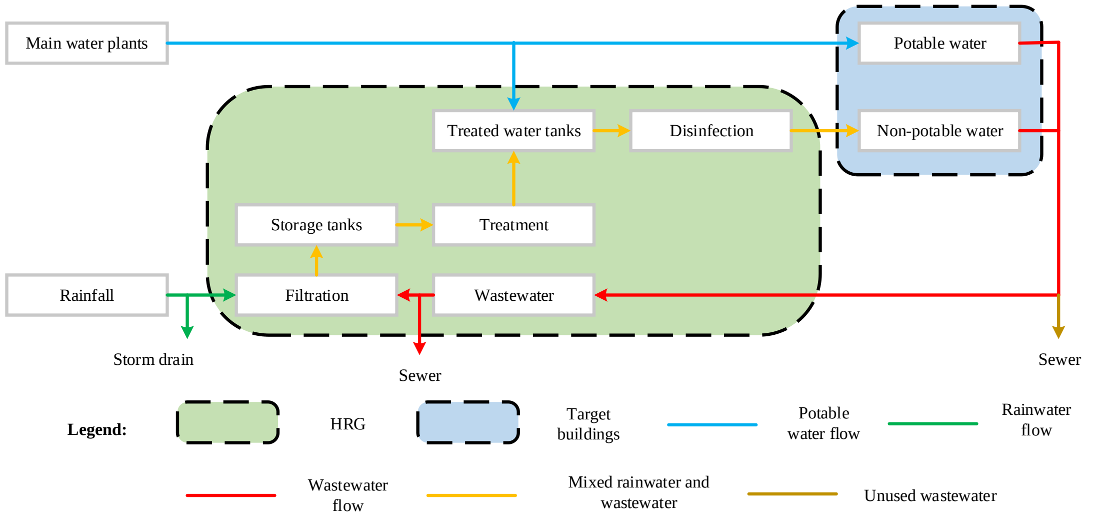

Fig 2-1 Configuration 1 of HRGs: combine rainwater and wastewater for treatment

Therefore, configuration 1 of HRGs is more suitable for large-scale non-potable water reuse to reduce water supply costs. However, configuration 1 of HRGs does not allow the systems to provide adapted quality of non-potable water according to the quality requirements of water uses because the rainwater and wastewater will be treated simultaneously. In addition, the stable water supply of this configuration cannot accommodate the buildings with daily non-potable water demands, such as the water demand of air-conditioning cooling, which will result in low water-saving efficiency of HRGs during peak non-potable water demand periods.

An alternative to configuration 1 of HRGs is to treat rainwater and wastewater separately (Fig 2-2). The potable water demands of buildings are supplied by main water plants. Untreated rainwater is stored in rainwater tanks after filtering and then supplied to some non-potable water demands of buildings after disinfection. Untreated wastewater is stored in wastewater tanks to adjust the quantity and quality after filtering and then it is stored in graywater tanks after chemical or biological treatment to be reused. Finally, the graywater is supplied to other non-potable water demands of buildings after disinfecting. In addition, potable water from main water plants can be directly supplemented into rainwater tanks to avoid the insufficient non-potable water supply of rainwater because of less precipitation. A one-way plumbing system for transporting water into the graywater tanks is installed on the rainwater tanks to cope with insufficient water supply due to the substandard effluent quality of treated graywater and avoid emptying of the graywater tanks because of cleaning. The excess rainwater is spilled into the storm drains and the excess graywater is spilled into the sewers. The uncollected wastewater is discharged into the sewers and transfers to the sewage treatment plant.

The advantages of configuration 2 include that the rainwater and graywater can flexibly meet the non-potable water demands according to the quality required to avoid the economic loss of HRGs caused by the excessive treatment of rainwater and graywater. For example, rainwater can be reused for irrigation and graywater can be reused for toilet flushing because using graywater for irrigation may have negative long-term impacts on the soil [3]. In addition, configuration 2 of HRGs is suitable for seasonal daily non-potable demand scenarios because rainwater can be stored in rainwater tanks during wet monsoon to reuse during the peak of non-potable water demand, whereas graywater is not recommended to be stored over 24 hours [4]. However, the disadvantage of such configuration is that the HRGs can be affected by the climate because the plumbing systems from rainwater tanks to graywater tanks are one-way systems to avoid the secondary pollution of rainwater, which will cause the graywater can not supplement to rainwater tanks when there is insufficient rainwater in HRGs.

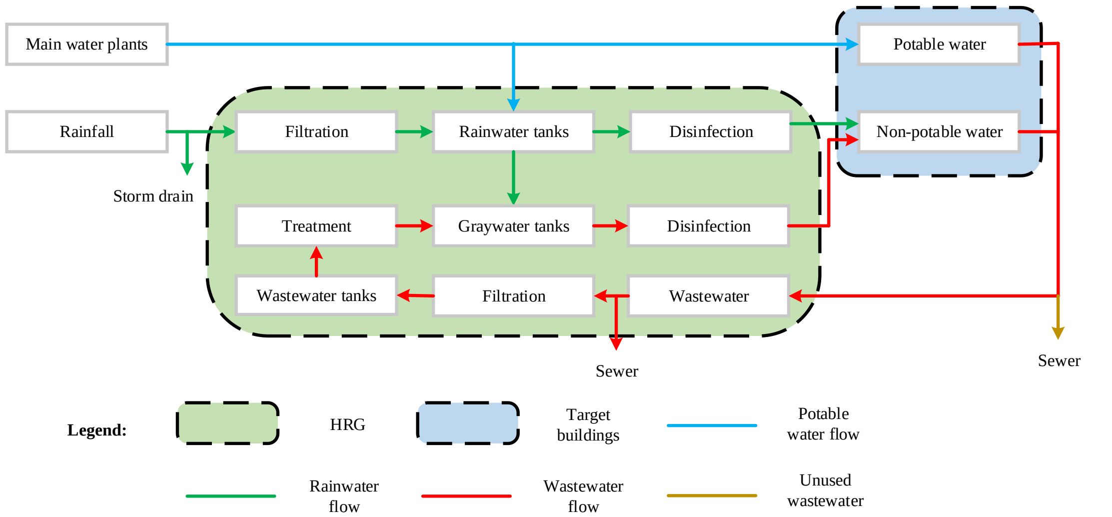

Fig 2-2 Configuration 2 of HRGs: separate rainwater and wastewater for treatment

Configuration 2 of HRGs has been used in many countries as the basic model to evaluate the environmental benefits and economic feasibility [5-7]. Therefore, this configuration was selected as the recommended configuration of HRGs in this study because of the flexible operation and wider feasibility. The components of the HRGs for configuration 2 will be introduced in detail in the next section.

2.2 Components of HRGs

An HRG includes a rainwater subsystem and a graywater subsystem. The rainwater subsystem is installed to harvest, treat, and pump rainwater to buildings, and the graywater subsystem is installed to collect and retreat wastewater and pump graywater to buildings. Therefore, the components of rainwater subsystems and graywater subsystems are required to design in HRGs.

2.2.1 Components of rainwater subsystems

The main components of rainwater subsystems are (1) the capture area, (2) the filter equipment, (3) the rainwater tank, and (4) the treatment equipment (Fig 2-3). In addition, the rainwater subsystems of HRGs also include the gutter, valves, pumps, and relative plumbing systems.

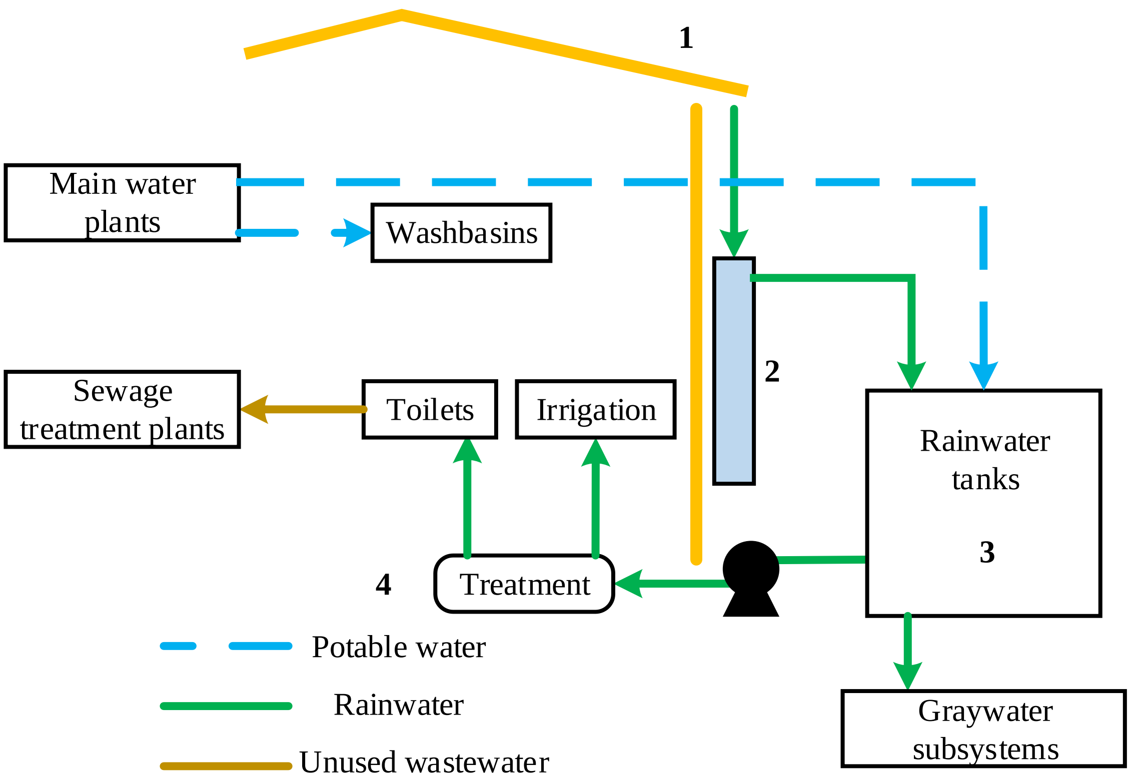

Fig 2-3 Rainwater subsystems of HRGs

(1) Capture area

The number of 1 in Fig 2-3 shows the location of the capture area in rainwater subsystems. Rainwater is harvested by the capture area of buildings, usually referring to the roofs and impervious areas of buildings, during precipitation events. However, the harvested rainwater will evaporate on the capture area and the long retention time of rainwater staying at the capture area will increase the concentration of contaminants in rainwater [8]. Therefore, the capture area of buildings is usually designed more sloping and smoother to obtain a higher runoff coefficient (RC) for rapidly harvesting rainwater. The RC is recommended over 0.8 to implement rainwater subsystems [9-11]. In addition, the material of capture areas will affect the concentration of contaminants in rainwater. Generally, rainwater harvested by wooden and tile capture areas has lower water quality than that of concrete and metal capture areas because the surface of wooden and tile capture areas is coarser and it will accumulate more contaminants from the atmosphere [12-14].

A new development trend of capture areas is the green roof. Fig 2-4 shows the diagram of the green roof. A green roof consists of roof vegetation, a growing medium, and a waterproofing layer, and can include additional layers of drainage and irrigation systems. As a technical measure for low-impact development (LID) and sponge cities, the green roof can significantly improve the heat island effect, reduce roof temperature, improve atmosphere quality, and harvest rainwater. In addition, the quality of harvested rainwater by green roofs is better than the conventional roofing materials [15].

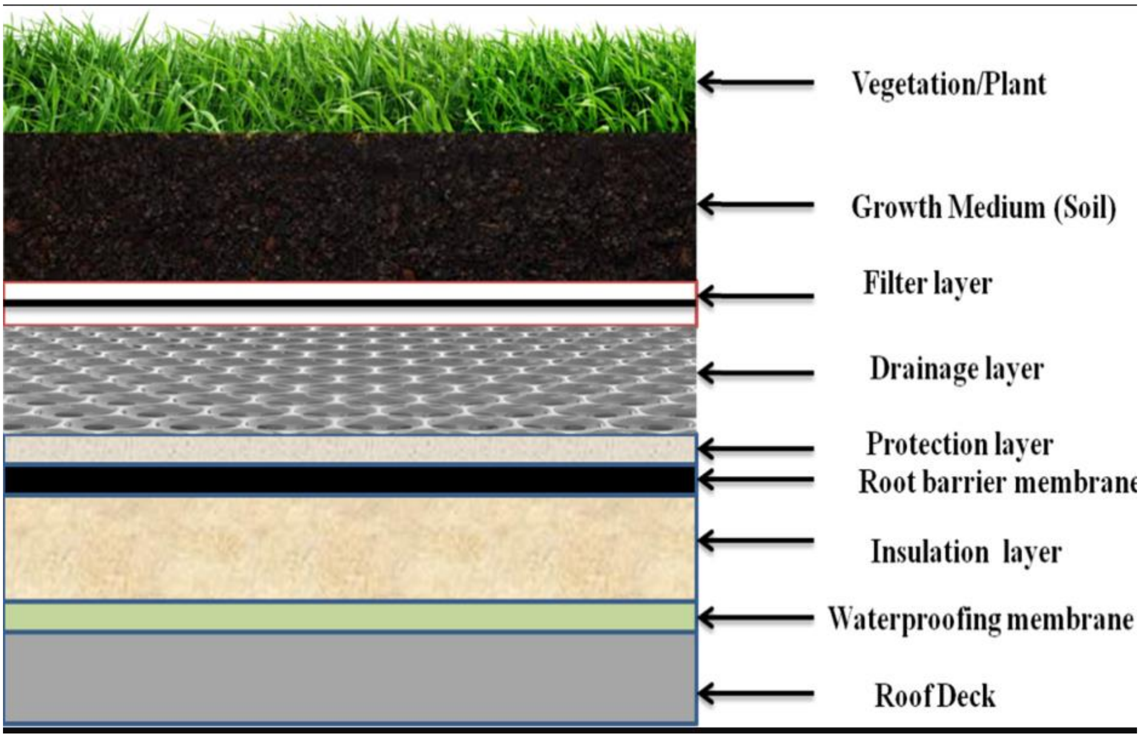

Fig 2-4 the diagram of green roof [16]

However, the limitation of green roofs is the economic benefit. The investment cost of green roofs is twice that of conventional roofs, which reduces the economic feasibility of HRGs. In addition, the complex construction of green roofs and the preservation of rainwater add large stress to building roofs, which can overload buildings and cause collapse. Therefore, an additional support structure is required by green roofs to ensure safe use, which hinders the widespread implementation of green roofs.

(2) Pre-treatment

The harvested rainwater requires to be filtered to remove the large suspended solids such as twigs, leaves, and bird droppings before reuse. The filtration process prevents the accumulation of organic matter in rainwater tanks, reduces the rate of corrosion in plumbing systems, and reduces the potential for damage to pumps [17]. First flushing devices are the most effective measure to remove the TSS of rainwater by discarding the 1-2 mm runoff at the initial rainfall [18]. The initial 1-2 mm of rainfall contains not only the large solids accumulated on the capture area during the dry period, but also high concentrations of E. coli and dissolved ions [19]. The amount of first flushing varies with rainfall intensity, frequency, and duration, but the minimum recommended value is 0.11 mm [2]. Harvested rainwater generally does not require additional treatment to meet non-potable water reuse standards after the first flush. Therefore, first flushing devices are usually used as the most common device for the pre-treatment process of rainwater subsystem. First flushing devices are usually installed before rainwater tanks and the size of the devices is determined according to the capture area and precipitation. The number of 2 in Fig 2-3 shows the location of first flushing devices.

(3) Rainwater tank

The harvested rainwater will be stored in rainwater tanks after first flushing for further use. Rainwater tanks are the core component of rainwater subsystems. The number of 3 in Fig 2-3 shows rainwater tanks of rainwater subsystems. Rainwater tanks determined the water-saving efficiency [20-23], environmental impacts [24], economic benefits [25-27], and sensitivity to climate changes [28-30] of rainwater subsystems. In general, rainwater subsystems with large rainwater tanks have superior water-saving efficiency and reliability, whereas large rainwater tanks will cause the high investment cost of rainwater subsystems. In addition, the limited space of buildings may hinder the installation of large rainwater tanks [31]. However, small rainwater tanks can limit the performance of rainwater subsystems. Therefore, the feasibility of rainwater subsystems focuses on the design of the rainwater tank size.

Rainwater tanks are generally made on-site or purchased in a local market with a specified size and are connected to capture areas and water uses through a separate plumbing system. Small plastic or metal rainwater tank can meet the demand for small HRGs, such as for residential buildings, whereas the large non-potable water demand for large-scale buildings requires a larger size of concrete rainwater tanks. In addition, rainwater tanks are recommended to be closed to promote the reduction of microorganisms in the rainwater and the breeding of mosquitoes [32, 33]. On the other hand, floats or electronic monitoring equipment are required to be installed in rainwater tanks to avoid insufficient rainwater.

The inlet should be located on the side of rainwater tanks rather than in the center to reduce suspended solids in rainwater tanks [34]. In addition, the withdrawal tap should be set at the bottom of rainwater tanks and at least 0.5 m away from the bottom to prevent the formation of stagnant water and avoid the extraction of sludge in rainwater tanks because the water quality in rainwater tanks decreases from the top to the bottom [35].

(4) Additional treatment

Additional treatment can be installed in rainwater subsystems of HRGs after rainwater tanks as shown by number 4 in Fig 2-3 to further reduce the health risks brought by reusing rainwater. In the rainwater subsystems, the additional treatment equipment can be installed with the first flushing device to further pure rainwater and also can be used alone to remove the contaminants in rainwater.

The common additional treatment processes of rainwater subsystems include rapid sand filters, slow sand filters, and directly adding chemical flocculants to rainwater tanks to flocculate contaminants in rainwater.

Rapid sand filters use relatively coarse sand and other granular media to remove particles and impurities trapped in the filter. Subsequently, these captured impurities are converted into floes by adding flocculants. Finally, the flocs in the rainwater are trapped in the sand matrix by gravity or pumping pressure. In addition, adding chemical reagents to rapid sand filters can significantly reduce the turbidity, total E. coli concentration, and metal ion concentration of rainwater [36]. Rapid sand filters have a compact structure and the fast treatment makes such filters are suitable for installation in buildings with limited space. However, Rapid sand filters are complex and expensive to operate and maintain, as well as require frequent cleaning, which increases the economic risk of implementing such filters.

A low-cost and low-flux alternative is slow sand filters, and such filters are more effective than rapid sand filters in removing E. coli from rainwater [37]. Contaminants in rainwater are absorbed by the microorganisms on the sand layer of slow sand filters, thus such filters do not rely on electric pumps and chemical reagents. The inexpensive and effective filters will have many advantages in low-income regions. However, slow sand filters work slowly, and rainwater may tank longer to pass through the filters, which is unreliable in buildings with high non-potable water demands.

Recently, a low-cost and high-flux suspension filter has been raised in Japan. The filter medium with high antibacterial properties is used by suspension filters. The rainwater is first pumped from the bottom of the suspension filter to the filter material during the treatment process, and the contaminants in the rainwater can be removed after a short adsorption process and discharged directly from the top of the suspension filter without adding chemical reagents. When the suspension filter is cleaned, the filter material and the cleaning water are fully stirred by the mixer inside the suspension filter, and then the cleaning water is discharged from the bottom of the suspension filter by gravity. The unique cleaning mode of this suspension filter reduces the volume of wash water by approximately 75% compared to conventional sand filters. Simultaneously, the suspension filter is low-cost and space-saving because the large-diameter cleaning, cleaning pipes, and cleaning water tanks are not required by the filter and solves the limitations when implementing conventional sand filters. The rainwater subsystems can install the suspension filter without the need to install the first flushing device, which can reuse the rainwater at the beginning of the precipitation event for non-potable water to harvest rainwater to the greatest extent. The operating principle and cleaning process of the suspension filter are shown in Fig 2-5.

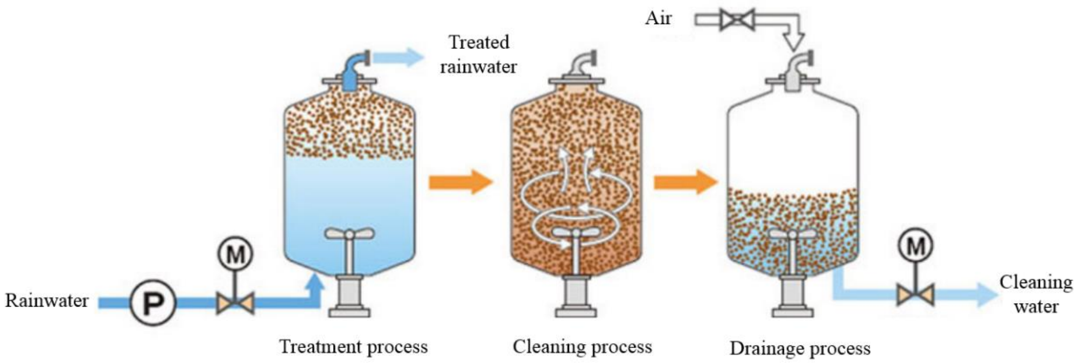

Fig 2-5 The operating principle and cleaning process of the suspension filter

2.2.2 Components of graywater subsystems

The main components of graywater subsystems are (1) the physical treatment equipment including coarse filter; (2) the wastewater tank and the graywater tank, (3) the mandatory treatment chain. In addition, the graywater subsystems of HRGs also include the gutter, valves, pumps, and relative plumbing systems. Fig 2-6 shows a generic graywater subsystem of HRGs. It is worth noting that the graywater subsystems of HRGs can select to collect light wastewater or dark wastewater according to non-potable water demands. The remaining wastewater in buildings can be discharged directly into the sewer as unused wastewater without inflowing to the graywater subsystems.

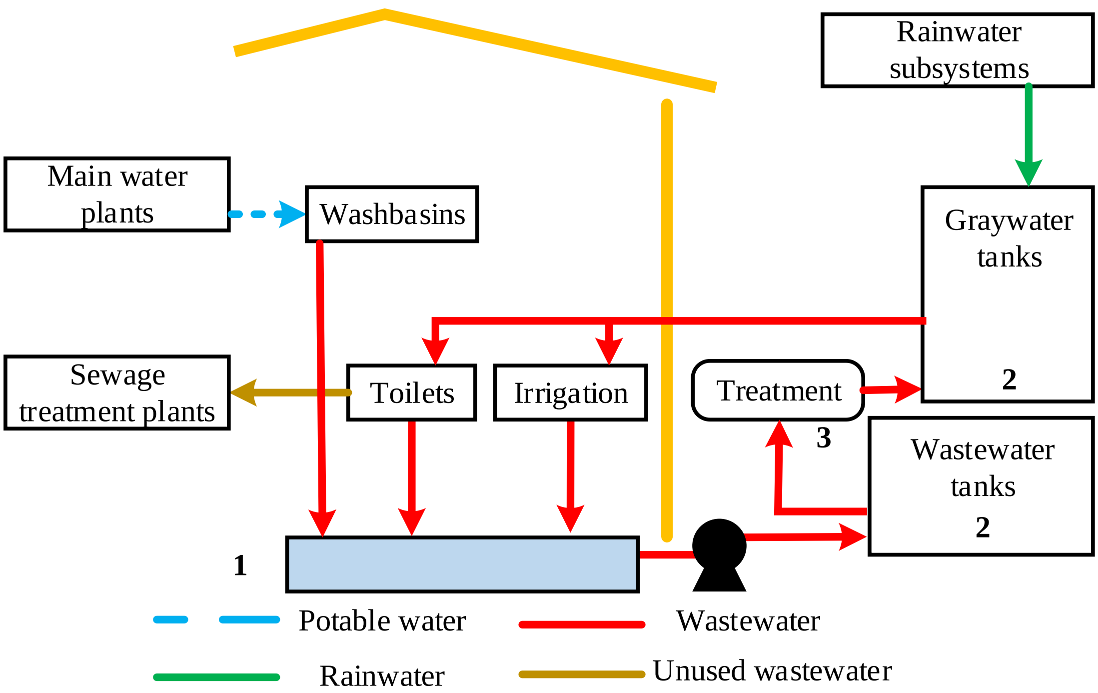

Fig 2-6 graywater subsystems of HRGs

(1) Physical treatment

The physical filter is required by graywater subsystems before the wastewater inflows into the wastewater tank to remove the total suspended solids (TSS) in the wastewater, which can improve the efficiency of the subsequent treatment and disinfection process [38]. The number of 1 in Fig 2-6 shows the location of physical treatment in graywater subsystems. In addition to the rapid sand filter and slow sand filter already mentioned, the commonly used physical filtration methods also include the simplest grids and more complex membrane filters, which include ultrafiltration, nanofiltration, reverse osmosis, and microfiltration.

Grills are the simplest physical treatment devices. Grills are composed of several groups of parallel grid bars, which are placed obliquely in front of the wastewater tank to remove TSS and part colloids in wastewater to prevent clogging of pumps and plumbing systems. Grids can be divided into fine grills, medium grills, and coarse grills according to the space of gird bars. The graywater subsystems can select the appropriate grills according to the type of collected wastewater from buildings for physical treatment.

Membrane filters have the highest effluent quality, but membrane filters are the most expensive filters. Membrane filters are sophisticated separation technology that utilizes the selective permeability of membrane voids for two-phase separation to achieve molecular-level filtration. Membrane filters use the pressure difference on both sides of the membrane as the driving force to pass small molecular substances through the membrane with clean water, whereas retaining particles and macromolecules. Membrane filters are divided into ultrafiltration, nanofiltration, reverse osmosis, and microfiltration according to the different membrane voids and operating principles. Smaller membrane voids of membrane filters result in better effluent quality, whereas smaller voids require higher transmembrane pressures, cleaning frequency, and energy costs [39, 40].

The filtration particle size of ultrafiltration is between 5 nm to 10 nm and the operating pressure of ultrafiltration is between 0.1 MPa to 0.25 MPa. The reclaimed water recovery rate of ultrafiltration is over 95%, and such membrane can be easily washed, which is not easy to block. In addition, ultrafiltration is inexpensive to operate because ultrafiltration does not need to rely on electric pumps to apply pressure, which can be met by water pressure to perform filtration. Ultrafiltration can remove 83% of total organic carbon (TOC) and 56% of BOD in raw wastewater [41]. However, previous studies indicated that wastewater filtered by ultrafiltration alone cannot meet the non-potable water reuse standard [2].

The interception particle size of nanofiltration is generally between 0.1 nm to 1 nm, and the operating pressure of nanofiltration is between 0.5 MPa to 1 MPa. The precision of nanofiltration is between ultrafiltration and reverse osmosis, and nanofiltration requires electricity to provide pressure. In addition, the graywater recovery rate of nanofiltration is lower than that of ultrafiltration, which wasted 30% of wastewater in the nanofiltration process. However, nanofiltration has higher effluent quality, which can remove organic matter and suspended solids in wastewater by 93% and 100%, respectively [42].

Reverse osmosis is a reverse process of osmosis. Reverse osmosis obtains graywater by adding a pressure higher than the osmotic pressure to wastewater to compress solvent to the other side of the semipermeable membrane. The filtration particle size of the reverse osmosis membrane is between 0.2 nm and 1.0 nm, and the operating pressure is between 1 MPa and 10 MPa. Reverse osmosis filters almost all impurities in graywater, including beneficial and harmful matters, allowing only water molecules to pass through [43]. However, reverse osmosis generally wastes nearly 50% of wastewater, resulting in higher filtration costs.

Microfiltration is one of the membrane technologies that use the static pressure difference as the driving force and uses the sieving effect of the membrane to filter and separate. Microfiltration membrane relies on the neat and uniform porous structure with the action static pressure difference to pass the smaller particles through the filter membrane to achieve the interception effect. The interception particle size of microfiltration is generally between 0.025 μm to 10 μm, and the operating pressure of microfiltration is between 0.01 MPa to 0.2 MPa. Microfiltration can filter large particles of impurities such as sediment and rust in wastewater but cannot remove harmful substances such as bacteria in wastewater. Moreover, the filter element of microfiltration cannot be cleaned and usually need to be required to be replaced frequently because the filter element is usually a one-time material. Table 2-1 compares the characteristics of different membrane filters.

Table 2-1 Characteristics of different membrane filters

	Ultrafiltration	Nanofiltration	Reverse osmosis	Microfiltration
Interception particle	5 nm - 10 nm	0.1 nm - 1 nm	0.2 nm - 1.0 nm	0.025 μm - 10 μm
Membrane material	Polypropylene	Hollow fiber, ceramic membrane	Polyamide	Polyacrylamide
Membrane type	Symmetric membrane	Asymmetric membrane	Asymmetric membrane	Asymmetric membrane
Operating pressure	0.1 MPa - 0.25 MPa	0.5 MPa - 1 MPa	1 MPa - 10 MPa	0.01 MPa - 0.2 MPa

(2) Wastewater tank and graywater tank

Wastewater tanks and graywater tanks of graywater subsystems are used to store untreated wastewater and treated graywater, respectively. The quantity and quality of wastewater generated in buildings will be varied with holidays, peak water consumption periods, and water consumption characteristics, whereas the subsequent chemical or biological treatment processes of graywater subsystems require stable quantity and quality of wastewater to ensure the treatment efficiency. Therefore, the collected wastewater needs to be accumulated in wastewater tanks to adjust in quantity and quality in wastewater tanks to ensure that the wastewater can enter the subsequent treatment equipment stably.

Different from the rainwater tanks of rainwater subsystems, where the material of tanks can affect the quality of rainwater, the material of wastewater tanks and graywater tanks in graywater subsystems is usually not focused because a series of strict treatments are required before the graywater can be reused. Therefore, the selection of wastewater tanks and graywater tanks in graywater subsystems only needs to ensure that adequate non-potable water is available for buildings while avoiding the deposition of stagnant water. In addition, wastewater tanks and graywater tanks should be equipped with a vent line and cleaned regularly to reduce the health risk of graywater reuse.

(3) Mandatory treatment chain

Graywater cannot meet the non-potable water reuse standard only relying on the coarse filter. In addition, the use of membrane reactors to treat wastewater cannot effectively remove some indicators such as odor and chromaticity in wastewater, and membrane reactors are usually required to combine biological treatment to pure wastewater and are set after the wastewater tanks, which will be introduced in the next section. Therefore, graywater subsystems must install the mandatory treatment chain including chemical treatment, biological treatment, and disinfection to treat wastewater to meet the non-potable water reuse standard. The selection of treatment process is determined by the type of collected wastewater from water uses in buildings and the requirements of graywater quality. Number 3 in Fig 2-6 shows the location of the mandatory treatment chain in graywater subsystems.

Chemical treatment refers to adding specific chemical reagents to wastewater to adsorb or chemically react with contaminants in the wastewater to achieve the purpose of purifying wastewater. Chemical treatment can effectively remove TSS, organics, and surfactants from wastewater [44]. Common chemical treatments of graywater subsystems include coagulation, ion exchange, and photocatalytic oxidation.

Coagulation treatment refers to adding coagulants to wastewater to destroy the stability of the colloid in the wastewater for aggregating the TSS and colloid in the wastewater into flocs for separation. Commonly used coagulants mainly include aluminum sulfate, ferric chloride, ferrous sulfate, and magnesium sulfate. The coagulation treatment is divided into two stages: coagulation and flocculation. Coagulation refers to the process by which contaminants in wastewater destabilize and form tiny flocs, whereas flocculation is the process by which these tiny flocs form larger flocs. The flocculated wastewater can be filtered to obtain cleaner graywater. Coagulation treatment can reduce sensory indicators such as turbidity and chromaticity in wastewater and can also remove a variety of harmful contaminants in wastewater. Previous studies have proposed that combining coagulation treatment with other treatments such as sand filters can further improve the effluent quality of graywater [45-47]. In addition, the temperature, pH, concentration of contaminants, and hydraulic of wastewater will affect the effect of coagulation treatment, which causes the wastewater tanks must be used to adjust the quantity and quality of wastewater. However, the disadvantage of coagulation treatment is the frequent disposal of waste sludge, which increases the complexity of the operation [40].

Ion exchange treatment refers to the exchange process of exchange ions in the ion exchanger with the ions in the wastewater to remove harmful ions in the wastewater. Ion exchangers can be classified into organic matters such as zeolites and inorganic matters such as resins. These exchangers are attached to inert and electrically neutral precursors that do not participate in the exchange process and use their own active groups to exchange reactions with anions and cations in the wastewater. Among them, the exchanger that can exchange cations (acidic active groups) are called cation exchange resins, whereas that can exchange anions (basic active groups) are called anion exchange resins. During the ion exchange treatment to treat wastewater, the wastewater first flows into the ion exchanger and undergoes ion exchange. Then the exchanged ions enter the treated wastewater in the opposite way to obtain cleaner graywater. The ion exchange treatment follows the principle of equal exchange, which cause the size of the ion exchanger requires to be determined according to the concentration of contaminants in the wastewater. However, ion exchange resins must be periodically regenerated because ion exchange is a reversible reaction [48].

Photocatalytic oxidation treatment refers that the oxygen and hydrogen peroxide molecules in wastewater being excited to transform into excited states under the action of a specific wavelength light to chemically react with the contaminants in wastewater to generate new substances or intermediate produces that initiate other reactions. The main light source of photocatalytic oxidation treatment is ultraviolet light, thus the utilization of solar energy for photocatalytic oxidation for wastewater treatment has always been the focus. Photocatalytic oxidation treatment can effectively remove contaminants from light wastewater including refractory substances such as polychlorinated biphenyls, whereas such treatment cannot cope with dark wastewater with high organic matter and TSS concentrations because these concentrations will hinder the penetration of ultraviolet light into wastewater and limit the efficiency of photocatalytic oxidation treatment [49-51].

In summary, the chemical treatment of graywater subsystems is only suitable for light wastewater with low organic matter, whereas it has a limited effect on wastewater with high organic concentration. Therefore, biological treatment is essential for HRGs to purify such high concentration wastewater.

Biological treatment can be divided into aerobic treatment and anaerobic treatment. Common biological treatment processes include rotating biological contactor (RBC), sequencing batch reactor (SBR), artificial wetland (AW), membrane bioreactor (MBR), and up-flow anaerobic sludge bed (UASB).

The RBC is an aerobic treatment for wastewater and has been widely used to treat wastewater by graywater recycling systems in buildings for non-potable water reuse [52]. Fig 2-7 shows the diagram of RBCs.

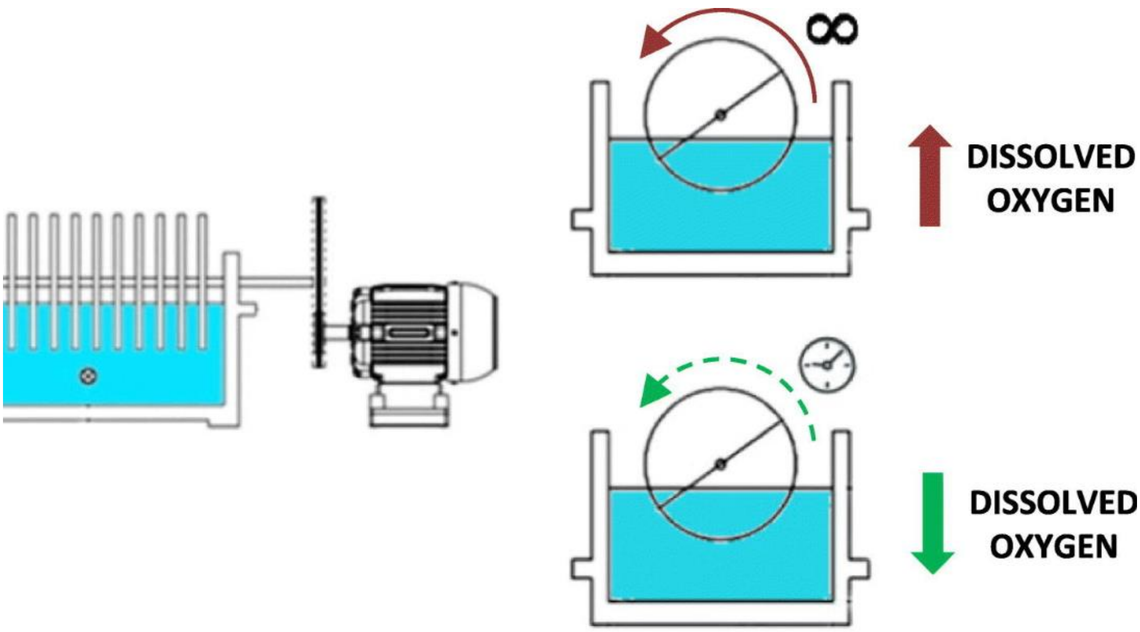

Fig 2-7 The diagram of RBCs [53]

The RBC is composed of several groups of parallel disks with biological glue fixed on the horizontal axis with small intervals, and approximately 50% of the disks are immersed in untreated wastewater. When the RBC starts to process the wastewater, the motor drives the disc to rotate, and the biological glue on the disks is fully contacted with the wastewater to oxidize and decompose the organic matter in the wastewater. Then, the disks exposed to the air are fully contacted with oxygen to supplement the biological glue with oxygen. In addition, adjusting the rotation speed of the RBC disks can change the dissolved oxygen concentration in the wastewater, which allows the RBC to perform nitrification and denitrification to remove nitrogen from the wastewater.

The RBC can effectively remove inorganic matter and organic matter from wastewater. Friedler, et al., found that the use of RBC to treat wastewater that had been screened can remove 94% of turbidity, 69% of COD, and 96% of BOD in wastewater [54]. Similarly, Nolde found that RBC can remove BOD_7 in wastewater from 15 mg/L to 5 mg/L [55]. On the other hand, Eriksson, E., et al., found that the RBC in pilot graywater recycling plants can remove 84% of COD, 97% BOD, and 94% TOC in graywater [56].

The full name of SRB is Sequencing Batch Reactor Activated Sludge Process, which was invented by British scholars Ardern and Locket in 1914. The SBR is a treatment method based on the method of intermittent aeration, which is based on the degradation of contaminants in wastewater by suspended microorganisms under aerobic conditions [57]. The treatment sequence of SBR is divided into five basic processes: wastewater inflow, aeration, sedimentation, drainage, and standby. Fig 2-8 shows the treatment sequence of SBRs.

The core component of SBR is the SBR reaction tank, which integrates the functions of homogenization, sedimentation, and treatment in one tank without the need for a sludge return system. In addition, the SBR does not require setting up adjustment tanks for adjusting wastewater and sedimentation tank, which is convenient for operation and maintenance management. On the other hand, the sludge in SBR is easy to settle and has strong impact resistance. Therefore, the SBR is suitable for buildings with limited space, intermittent discharge of wastewater with large flow changes. However, SBR relies heavily on modern automated control technology because all reactions of SBR are carried out in one reaction tank. If manual operation is used, problems such as cumbersome operation and easy blockage of the aeration device will occur during the treatment process of SBR.

SBR can significantly reduce COD, total nitrogen, total phosphorus, and surfactants in high concentration wastewater by 90%, 24%, 33%, and 97%, respectively [58]. In addition, SBR have similar life cycle costs as RBC and low operating energy consumption, which has favorable economic advantages [40].

Aws are artificially designed swamp surfaces to treat wastewater through adsorption, retention, filtration, redox, precipitation, microbial decomposition, transformation, plant shading, residue accumulation, transpiration of water and nutrient absorption, and the action of various animals [59]. Fig 2-9 shows the diagram of AWs.

AWs allow wastewater to flow into the wetland in a controlled manner and flow in the same direction, using the physical, chemical, and biological triple synergy between soil, artificial media, plants, and microorganisms in the wetland to complete the purification of wastewater to obtain graywater.

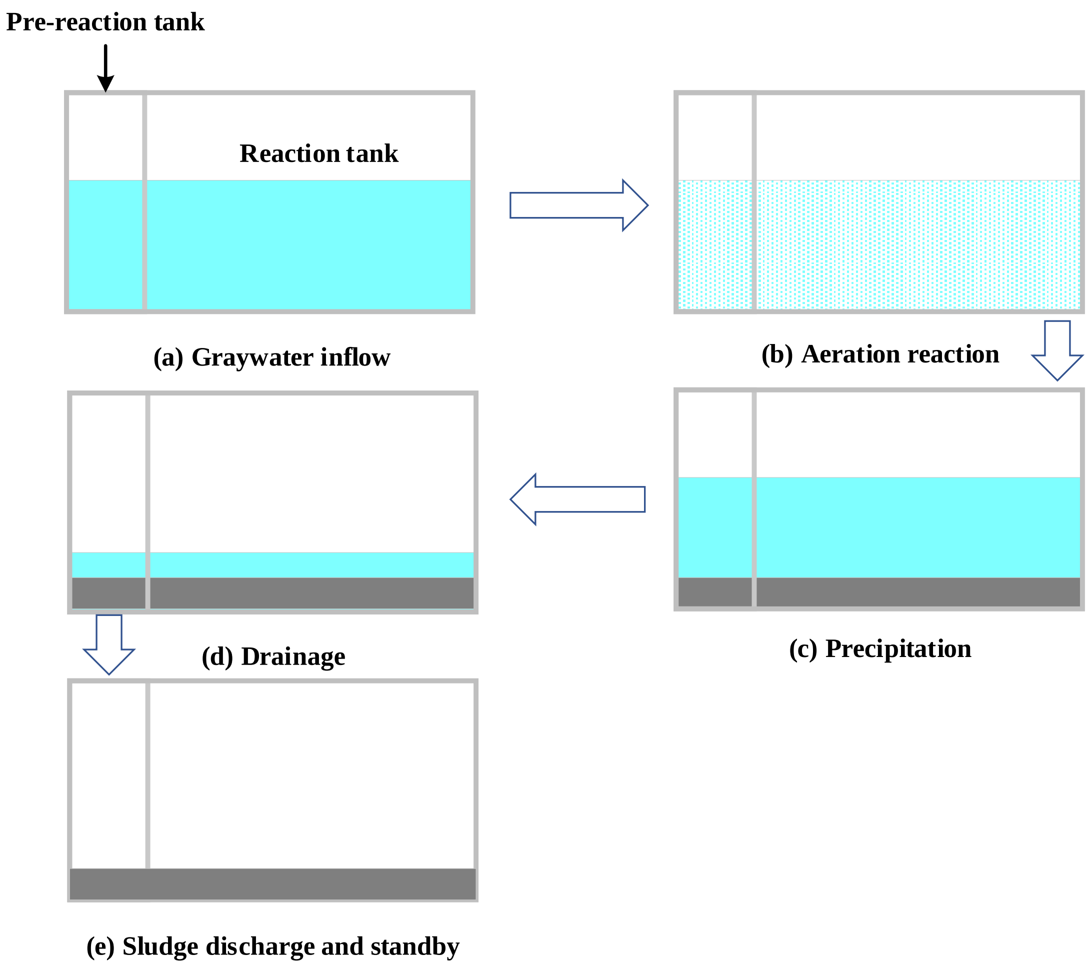

Fig 2-8 The treatment sequence of SBRs

AWs are also an integrated ecosystem. AWs use the principles of species symbiosis and material recycling in the ecosystem while treating wastewater and give full play to the virtuous cycle of resources to prevent secondary pollution of the environment. In addition, AWs can also provide oxygen for natural water bodies because of the planting of plants, which controls the pollution of natural water bodies.

The core of AWs is the microorganisms in the wetlands. Aerobic microorganisms can decompose organic contaminants in wastewater into carbon dioxide through respiration. In addition, anaerobic bacteria can decompose organic contaminants in wastewater into carbon dioxide and methane and reduce ammonium salts in wastewater to nitrogen. AWs can return these harmless products will be returned to nature, while producing graywater that meets non-potable water reuse standards.

Installing AWs in graywater subsystems to treat wastewater has many advantages and has been widely used in HRGs to on-site treat wastewater generated from buildings for non-potable water reuse [6, 60, 61]. For example:

1. AWs have lower investment and operation costs;
2. AWs are easy to maintain because AWs mainly rely on plants and microorganisms to decompose harmful contaminants in wastewater;

3. AWs allow changes in the quality and quantity of inflowed wastewater, in other words, AWs are resistant to shocks from hydraulic and pollution loads;
4. AWs can provide graywater that meets non-potable water reuse standards;
5. AWs can provide potential benefits such as increasing greenery, reducing pollution of natural water bodies, and providing habitat for wildlife.

However, AWs also have some disadvantages:

1. AWs require a large area of building space;
2. AWs are vulnerable to pest disasters;
3. AWs take a long period to build because the plants in the wetlands need two to three life cycles to achieve optimal treatment efficiency, which requires a few years after the AWs are built to operate stably.

Because of the limited space of buildings, it may be impossible to support the installation of surface flow artificial wetlands on the surface of the capture areas in buildings. Therefore, in recent years, subsurface artificial wetlands have gradually been favored by the graywater subsystems of HRGs. Subsurface artificial wetlands can be divided into horizontal subsurface artificial wetlands and vertical subsurface artificial wetlands. The horizontal subsurface artificial wetlands are horizontally distributed with sand, medium, and plant roots. The graywater flows into the water inlet of the horizontal subsurface artificial wetlands and passes through the wetland in the horizontal direction to the water outlet to obtain graywater that meets the non-potable water reuse standard.

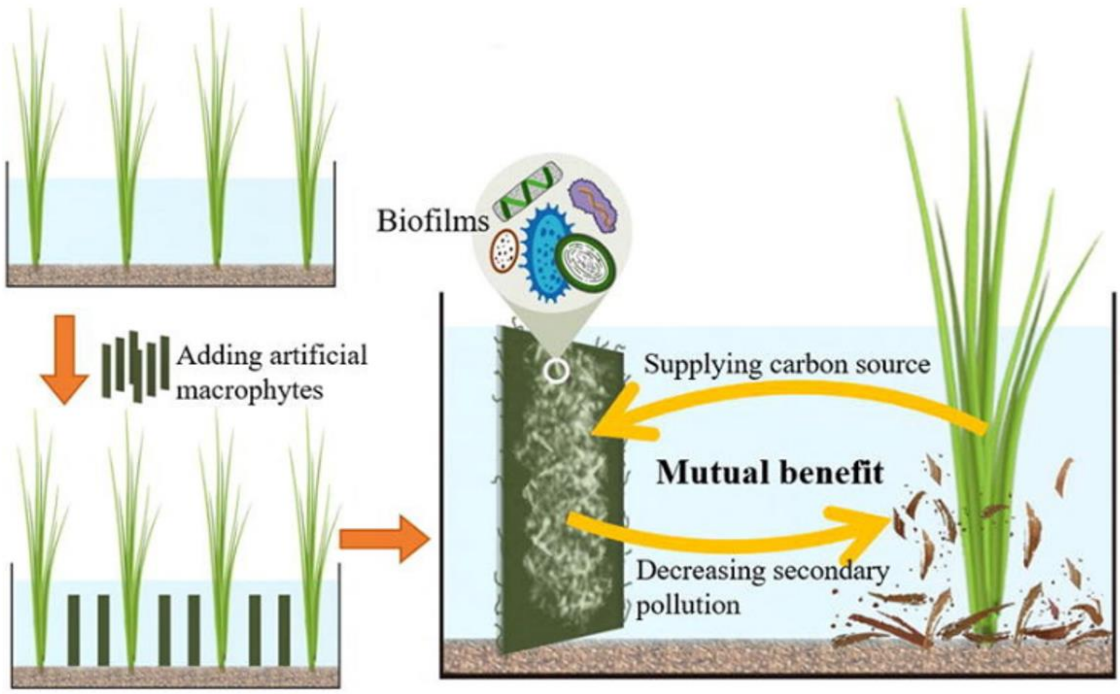

Fig 2-9 The diagram of AWs (modified from [62])

Vertical subsurface artificial wetlands are another form of subsurface artificial wetlands, which allow wastewater to flow longitudinally from the wetland surface to the bottom of the bed. During the process of longitudinal flow, the wastewater passes through different media layers in turn to achieve the purpose of purification. The vertical subsurface artificial wetlands have a complete water distribution system and water collection system. The vertical subsurface artificial wetlands can be completely built underground, thus such systems occupy smaller building spaces than other forms of wetlands. In addition, the treatment efficiency of vertical subsurface artificial wetlands is also superior to that of other wetlands because of the flow rate of wastewater accelerated by gravity.

Green wall is a new graywater treatment process based on AWs. Green walls use media such as vermiculite, river sand, expanded clay, perlite, and plants to filter graywater [63]. These media act as adsorbents for contaminants in wastewater, whereas the nutrients in wastewater nourish the growth of plants in the green walls [64]. Green walls have lower operational consumption and space requirements than conventional AWs [65]. However, green walls are not suitable for drought regions because the plants in the green walls highly depend on water. On the other hand, green walls are not suitable for the treatment of high concentration wastewater because the retention time of green walls for treating wastewater is short, which will affect the treatment efficiency of treating high concentration wastewater.

MBR is a new graywater treatment technology that organically combines membrane reactors and biodegradation and has a higher removal efficiency of contaminants in wastewater than RBC and SBR and produces high-quality graywater that meets non-potable water reuse standards [45, 66]. The core component of MBRs is the MBR reaction tank, which includes microbial colonies, membrane modules, wastewater collection systems, water yield systems, and aeration systems. MBRs utilize the membrane module to remove TSS and macromolecular organic matter in wastewater and then the wastewater undergoes the separation of mud and water and the degradation of organic matter in the MBR reaction tank. In addition, the MBR membrane module can be directly immersed in the biological reaction tank and can replace the secondary sedimentation tank of the conventional biological treatment process, which can reduce the installation area of MBRs in buildings. The membrane modules of MBR can maintain high activated sludge concentration and low sludge load in the biological reaction tank to reduce the amount of excess sludge while improving the treatment efficiency of graywater, which makes the MBR-based HRGs in buildings easy to operate and maintain. Fig 2-10 shows the diagram of MBRs.

MBR-based HRGs in buildings have many advantages:

1. MBRs have high activated sludge concentrations, which can effectively separate the solid and liquid of wastewater to improve the effluent quality of graywater, especially the effluent suspended solids and turbidity of the graywater are approximately 0;
2. The high activated sludge concentration of MBRs enables the system to have a high resistance to the impact of contaminant loads;
3. The membrane module of MBRs has an efficient interception effect, which can retain microorganisms with longer life cycles. This can not only deeply purify the wastewater but also improve the high denitrification and phosphorus removal efficiency because the nitrifying bacteria can fully multiply in the biological reaction tank. Therefore, MBRs have a superior purification effect on high-concentration and refractory organic wastewater;
4. The hydraulic retention time and sludge age of MBRs can be controlled independently, which makes the operation of MBRs flexible and stable;

5. MBRs integrate aeration tanks, reaction tanks, and secondary sedimentation tanks in one reaction tank, which can greatly reduce the volume of systems and save the installation of space;
6. MBRs have a higher sludge age, which improves the removal effect of refractory organic matter in wastewater;
7. The characteristics of the high volumetric load, low sludge load, and long sludge age make MBRs extremely low in excess sludge yield to reduce sludge disposal costs;
8. The MBR reaction tank can realize modular design to make the system more flexible and easier to expand.

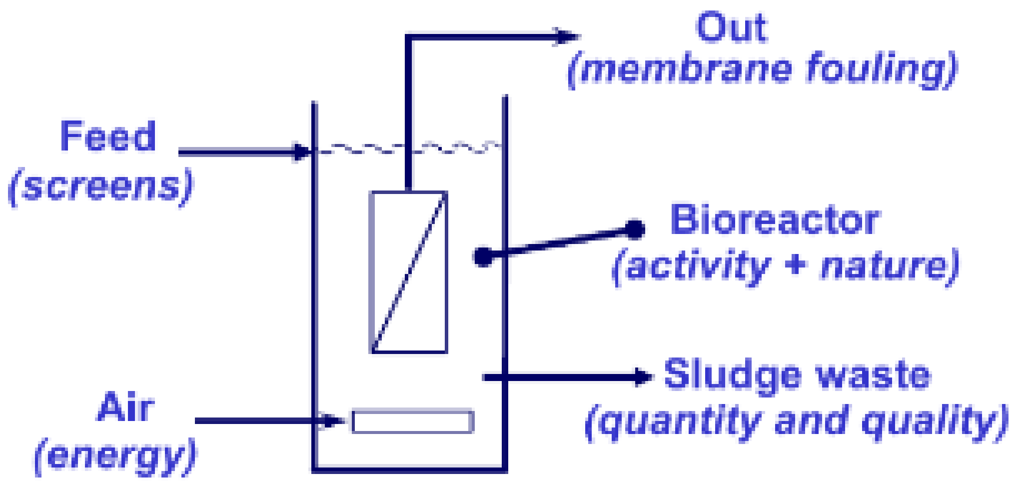

Fig 2-10 The diagram of MBRs [67]

MBRs can be divided into separate and integrated membrane bioreactors according to the placement of membrane modules and bioreactors.

Separation membrane bioreactors (SMBRs) are also known as external membrane bioreactors. SMBRs separate the membrane module from the bioreactor. Wastewater is first fully contacted with microorganisms through the bioreactor and is subsequently pressurized into the membrane module of SMBRs. Then the wastewater passes through the membrane module under pressure to obtain graywater. The activated sludge in the treated graywater is retained and returned to the bioreactors.

Integrated membrane bioreactors (IMBRs) are also known as submerged membrane bioreactors, which place the membrane modules directly in the bioreactor. The treatment process of wastewater in IMBR is all carried out in a reactor and the graywater is obtained by pumping. In addition, aeration devices are installed directly under the membrane modules of IMBR, which can make the wastewater flow upward with the airflow and generate shear force on the surface of membrane modules to reduce the pollution of membrane. IMBRs have been widely used in graywater recycling systems to treat wastewater and have superior performance to remove turbidity, fecal coliforms, anionic surfactants, organics, TSS, and pathogens in wastewater [45, 68, 69].

Simultaneously, MBRs can be divided into aerobic and anaerobic membrane bioreactors according to the requirement of supplying oxygen to the reactor. Aerobic membrane bioreactors can effectively remove special contaminants such as grease contaminants from wastewater, whereas anaerobic membrane bioreactors can effectively treat the wastewater with high organic concentration.

Therefore, MBR-based HRGs can effectively replace RBCs, SBRs, and AWs for safer graywater. However, MBRs have higher investment and operation costs [70]. With the advancement of MBR technology, the application of new membrane materials such as polyethylene hollow fiber membrane and ceramic membrane can greatly reduce the investment costs of MBRs. In addition, membranes prepared from waste food and biodegradable materials have been shown to be effective in removing contaminants from graywater, which further increases the economic potential of MBRs [71].

UASBs utilize anaerobic biological treatment to remove contaminants from wastewater [72]. Anaerobic biological processes produce less sludge than aerobic biological process and do not require addition energy for aeration. In addition, the methane produced by the anaerobic biological processes can be reused as a clean energy source [40]. Fig 2-11 shows the treatment process of UASBs.

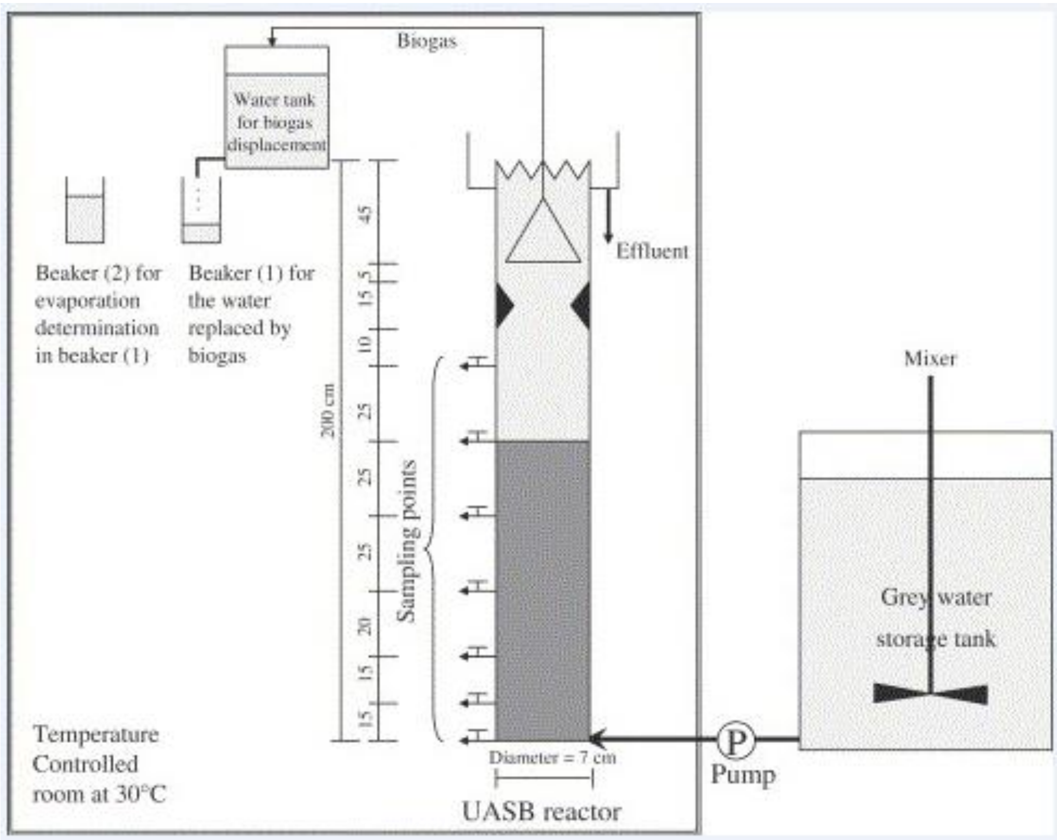

Fig 2-11 The treatment process of UASBs [72]

The reactor of UASB can carry out biological reaction and precipitation processes at the same time. The reactor consists of the water inlet system, the reactor, the three-phase separator, the gas chamber, and the drainage system, wherein the separation effect of the three-phase separator directly affects the treatment effect of UASB.

The bottom of the UASB reactor is covered with a larger amount of anaerobic sludge to form a sludge bed. The wastewater flows into and fully contacts with the sludge bed at the bottom of the reactor and the organic contaminants in wastewater are decomposed into biogas by the microorganisms in the sludge bed. The biogas and the treated wastewater rise together with the suspended sludge and enter the three-phase separator and finally produce biogas and graywater, respectively. The sludge suspended in the treated wastewater is coagulated in the three-phase separator and settled back to the reactor under the action of gravity to complete the wastewater purification process. The advantages of UASBs are simple structure, high volume load rate, short hydraulic retention time, low energy consumption, and no require setting up sludge return device. This not only greatly reduces the scale of UASB to reduce the investment cost but also makes the UASB suitable for the treatment of high-concentration organic wastewater.

However, HRGs are not suitable for installing UASBs to treat wastewater because anaerobic biological treatment process is less capable of handling organics and surfactants, which are major contaminants in domestic wastewater in comparison to aerobic biological treatment process [2]. Previous studies have found that anaerobic biological treatment can only remove 51% of COD, 24% of anionic surfactants, 22% of total nitrogen, and 15% of total phosphorus from wastewater [58, 72].

2.2.3 Components of disinfection equipment

Rainwater and graywater contain a variety of bacteria and viruses that may not be removed completely by physical, chemical, and biological treatment. These bacteria and viruses lurking in the treated rainwater and graywater that are reused as non-potable water can cause odors and even disease. There, a mandatory disinfection process of treated rainwater and graywater is required to remove pathogens and odors and reduce the health risks of using these alternative water sources. Common disinfection processes mainly include chlorination, ozone disinfection, and ultraviolet disinfection.

Chlorination disinfection is the process of disinfecting treated rainwater and graywater using chlorine and chlorine preparations such as liquid chlorine, sodium hypochlorite, calcium hypochlorite, and bleaching powder [8, 73]. Chlorination is one of the most common disinfection processes because chlorine is widely available, inexpensive, and does not have strict dosage limits in comparison to conventional disinfection processes [74]. In addition, chlorination disinfection has the unique characteristic that chlorine will leave residual substances in treated rainwater and graywater, which is called residual chlorine. The residual chlorine can prolong the retention time of treated rainwater and graywater by preventing bacterial regeneration. However, the content of residual chlorine needs to pass strict requirements because excess residual chlorine will bring odor to treated rainwater and graywater, whereas insufficient residual chlorine will lose the ability of continuous sterilization.

The principle of chlorination disinfection is that chlorine can ionize hypochlorite in water and generate hypochlorous acid. The hypochlorous acid can disrupt cell function in bacteria and cause bacterial death. Therefore, proper hydraulic retention time can ensure the disinfection efficiency of chlorination. In addition, the amount of hypochlorous acid generated is affected by the pH of treated rainwater and graywater. Generally, the lower the pH of treated rainwater and graywater, the higher the hypochlorous acid concentration generated by chlorine, the better the disinfection effect. On the other hand, the efficiency of chlorination disinfection is inversely proportional to the particle size of suspended solids in treated rainwater and graywater [75]. Therefore, chlorination disinfection is recommended for the final stage of the HRGs treatment chain. Table 2-2 lists the common method of chlorination disinfection.

Table 2-2 The common method of chlorination disinfection

Disinfection method	Illustration	Advantage	Disadvantage
Ordinary chlorination disinfection	Disinfection can be achieved by adding a small amount of chlorine to the raw water	The retention time is short; The disinfection effect is reliable.	The quality of raw water is required to be less polluted and without phenolic substances.
Chloramine disinfection	Ammonia and chlorine are artificially added to the raw water at a ratio of 1:3 to 1:6;	The disinfection by-products of chloramine disinfection are significantly lower than that of ordinary chlorination disinfection; Adding ammonia first can prevent the occurrence of chlorophenol odor; Adding chlorine first can ensure the residual chlorine concentration at the end of the pipeline.	Long retention time is required by chloramine disinfection; The residual chlorine concentration is high; The operation cost is high
Folding point chlorination disinfection	Adding a sufficient amount of chlorine to raw water to convert ammonia nitrogen into nitrogen gas for removing nitrogen from raw water.	Reliable disinfection effect; Significantly remove manganese, iron, phenol, and organic matter from raw water; Reduce the odor and color of raw water.	Consume more chlorine and produce more disinfection by-products; Alkaline substances may be required to add to the raw water to adjust the pH of raw water.
Excess chlorination disinfection	Adding excess chlorine to the raw water.	It is suitable for raw water with higher organic contaminant concentration.	The effluent needs to be dechlorinated with sulfur dioxide or activated carbon.

However, chlorination disinfection will produce teratogenic, carcinogenic, and mutagenic haloalkanes, such as chloroform, and other disinfection by-products in water. Therefore, alternative disinfectants or disinfection processes is essential for disinfecting treated rainwater and graywater.

As a new disinfectant, ozone has gradually become a substitute for chlorination disinfection and is one of the most effective disinfectants. Ozone disinfection is a strong oxidant and the ability to kill viruses and cysts of ozone is higher than that of chlorination disinfection. In addition, ozone can effectively remove mold and chlorine-resistant Cryptosporidium oocysts commonly found in rainwater and wastewater. Thirdly, ozone disinfection has lower consumption of disinfectant amount, faster disinfection speed, and better disinfection effect than that of chlorination disinfection [76]. Finally, ozone disinfection can improve the odor of treated rainwater and graywater. Ozone dissolved in water can generate a large number of hydroxyl radicals to oxidize inorganic and organic matters in treated rainwater and graywater. At the same time, ozone can enter the bacterial cells and virus to oxidize and decompose the enzymes and lipopolysaccharides inside the cells and destroy the genetic material of the cells, which will cause the bacteria and virus to die.

However, the disadvantage of ozone disinfection is that there is no residual disinfectant in treated rainwater and graywater because ozone is very automatically reduced to oxygen after 30 to 40 minutes, which will result in the regeneration risks of microbial in treated rainwater and graywater disinfected with ozone. Therefore, when HRGs use ozone for disinfection, a subsequent chlorination step is recommended to prevent microbial regeneration and prolong the storage time of treated rainwater and graywater. In addition, ozone disinfection has disadvantages such as expensive investment and operation costs because ozone often requires special equipment to generate.

Ultraviolet disinfection is a disinfection process that utilizes ultraviolet lamps to irradiate treated rainwater and graywater to remove pathogens in the raw water. Ultraviolet disinfection does not require the addition of chemicals, thus ultraviolet disinfection will not increase the odor and will not produce toxic disinfection by-products of treated rainwater and graywater. Secondly, ultraviolet disinfection has a fast disinfection speed and high disinfection efficiency and is not affected by the temperature and pH of treated rainwater and graywater. Finally, ultraviolet disinfection is economical because it does not require metering pumps and plumbing systems and the process of ultraviolet disinfection is simple to operate.

Ultraviolet disinfection is effective in removing E. coli from treated rainwater and treated graywater [77]. In addition, ultraviolet disinfection can elevate the temperature of treated rainwater and treated graywater to inactivate microorganisms [78]. However, previous studies have shown that fecal coliforms, heterotrophic plate counts (HPCs), Pseudomonas aeruginosa, and Staphylococcus aureus are extremely resistant to ultraviolet light and thus require stronger exposure of ultraviolet to ensure complete removal of these substances from treated rainwater and graywater [46].

However, ultraviolet disinfection has deed spots because of its limited irradiation area. In addition, the penetrating power of ultraviolet light in treated rainwater and treated graywater will gradually weaken, whereas the ultraviolet lamp with stronger irradiation intensity has a shorter life cycle. Last but not least, suspended solids in treated rainwater and treated graywater require to be removed before ultraviolet disinfection because such substances will block the exposure of ultraviolet to affect the efficiency of disinfection [38]. Table 2-3 shows the commonly used disinfection process of HRGs and the operating conditions of these processes.

Table 2-3 Commonly used disinfection processes and their operating conditions

Disinfection process	Operating condition	Cite
Chlorination disinfection	Hypochlorite: 0.5 mg/L; Hydraulic retention time: 0.5 h.	[8]
Chlorination disinfection	Hypochlorite: 0.5 mg/L; Hydraulic retention time: 3 h.	[8]
Chlorination disinfection	Hypochlorite: 0.5 mg/L; Hydraulic retention time: 6 h.	[8]
Chlorination disinfection	Hypochlorite: 1 mg/L; Hydraulic retention time: 0.5 h.	[8]
Chlorination disinfection	Hypochlorite: 1 mg/L; Hydraulic retention time: 3 h.	[8]
Chlorination disinfection	Hypochlorite: 1 mg/L; Hydraulic retention time: 6 h.	[8]
Chlorination disinfection	Hypochlorite: 5 mg/L to 10 mg/L; Hydraulic retention time: 36 s.	[79]
Hydrogen peroxide disinfection	Concentration: 125 mg/L; Contact time: 35 min	[80]
Hydrogen peroxide disinfection	Concentration: 1 mL/L.	[81]
Photocatalytic Photon-Fenton	Wavelength: 254 nm; Concentration: 150 mg/L H_2O_2;	[82]
Ultraviolet disinfection	Wavelength: 254 nm; Intensity: 250 mJ/cm^2; Flow rate of treated rainwater and claimed water: 2.4 m^3/d.	[79]
Ultraviolet disinfection	Wavelength: 254 nm; Intensity: 2.8 mV s/cm^2; Flow rate of treated rainwater and claimed water: 0.036 m^3/d to 2.16 m^3/d.	[83]
Ultraviolet disinfection	Ultraviolet: 36 W; Intensity: 39 mW/cm^2; Flow rate of treated rainwater and claimed water: 0.28 m^3/d.	[46]
Solar disinfection	Intensity: 518 W/m^2; Hydraulic retention time: 24 h.	[84]
Solar disinfection	Intensity: 518 W/m^2; Continuous operation: 24 h.	[84]

In addition to the common processes of disinfection, there are several other disinfection techniques that can be used to disinfect treated rainwater and graywater, such as the electro-coagulation disinfection using electrolytic cells. However, electro-coagulation disinfection cannot effectively disinfect the water with high soluble contaminants. The use of Ag as a disinfectant can effectively inhibit the growth of E. coli in treated rainwater and graywater. However, the use of Ag as a disinfectant is not only expensive but increases the concentration of Ag element in the effluent to increase the health risks and environmental impacts of reusing non-potable water [85]. Finally, boiling or pasteurization can effectively inactivate viruses, parasites, and bacterial pathogens in treated rainwater and graywater, whereas these disinfection process requires high energy consumption. These limitations make these disinfection processes are unfeasible in HRGs.

2.3 Introduction to the study object

2.3.1 Kitakyushu Science and Research Park

Kitakyushu Science and Research Park (KSRP) is located in the western part of Wakamatsu District, Kitakyushu City, Fukuoka, Japan, which is one of the industrial cities in Japan. KSRP concentrates on educational organizations, scientific research organizations, and enterprises related to advanced science and technology to realize the organic integration of production, learning, and research for striving to build a core academic research center in Asia. The total development area of KSRP is approximately 335 hectares and has been developed since April 2001. The development plant for KSRP was implemented in three phases. Among them, the area of the first phase is approximately 121.4 hectares, the second phase is approximately 135.5 hectares, and the third phase is approximately 67.9 hectares. In addition, KSRP has planned approximately 10 hectares of river works [86]. Fig 2-12 shows the location and boundary of KSRP. Fig 2-13 shows the land planning of KSRP.

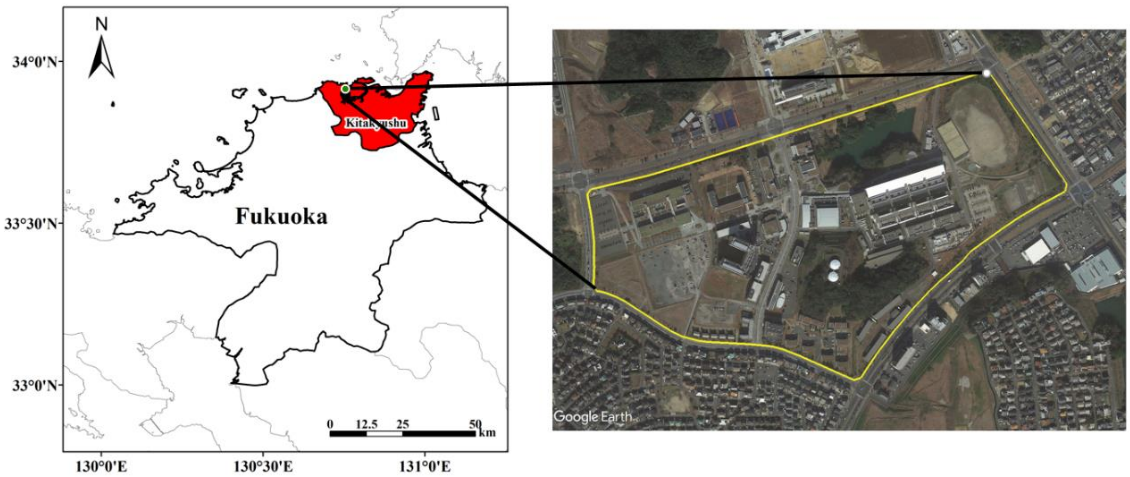

Fig 2-12 The location and boundary of Kitakyushu Science and Research Park

Table 2-4 lists the major organizations and their business contents of KSRP. The original intention of KSRP is to become a future creative research center and a core academic research center in Asia. So far, several open teaching and research organizations including the Department of Environmental Engineering of the University of Kitakyushu, the Kyushu Research Institute of the Science and Technology Research Center of Waseda University, and the Department of Life Science of Kyushu Institute of Technology have joined KSRP. In addition, KSRP also has public buildings such as Semiconductor Center, Collaboration Center, IT Advancement Center, and Business Venture Support Center for enterprises settle in and has can provide portable, diverse living environments and entertainment venues such as Media Center, Conference Center, Gym, and Canteen.

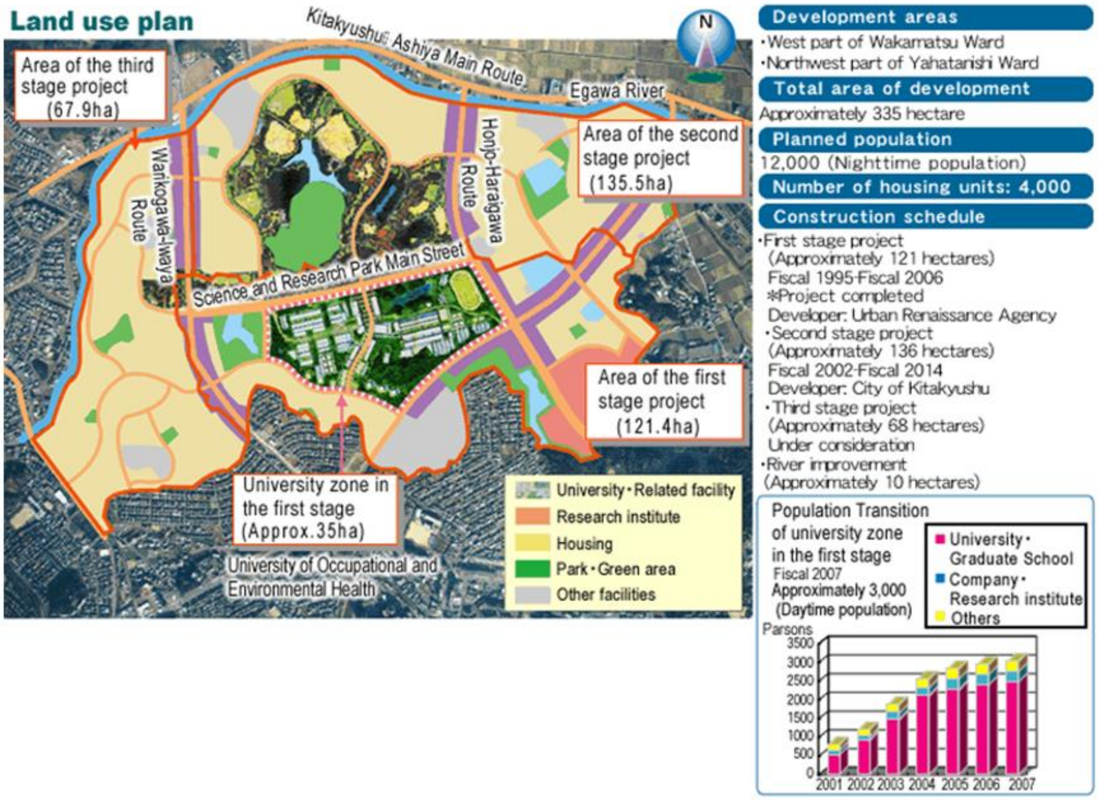

Fig 2-13 The land planning of Kitakyushu Science and Research Park [86]

Table 2-4 The organizations of Kitakyushu Science and Research Park [86]

Organizations	Composition of the organization	Business contents
The University of Kitakyushu	Teaching Building; Experiment Building; Instrumentation Center	Department of Chemical and Environmental Engineering; Department of Mechanical Systems Engineering; Department of Information and Media Engineering; Department Architecture; Department of Life and Environment Engineering; Graduate Programs in Environmental Systems; Graduate Programs in Environmental Engineering; Graduate Programs in Information Engineering.

Continued from Table 2-4

Organizations	Composition of the organization	Business contents
Kyushu Institute of Technology	Graduate School of Life Science and Systems Engineering	Department of Biological Functions Engineering; Department of Human Intelligence Systems; Department of Life Science and Systems Engineering.
Waseda University	Graduate School of Information, Production and Systems	Information Architecture; Production Systems; Integrated System.
Fukuoka University	Graduate School of Engineering	Graduate Program of Recycling and Eco-Technology; Energy and Environment Systems.
Energy Center		Manages and provides heating, cooling, electricity, potable and non-potable water for the University of Kitakyushu.
Gym and Canteen		Provide a place to eat and exercise for the KSRP
Semiconductor Center	Laboratories; Shared micromachining devices for ICs and MEMs	Provide implementation of research and development in the field of semiconductor manufacturing related to companies and universities; Provides a research site for testing and preparing ICs and MEMs; Internships accepted for IC trial production.
Collaboration Center	Laboratories; Conference room and seminar room.	A gathering of cutting-edge research companies; Provide conference rooms and seminar rooms that can accommodate 100 participants.
IT Advancement Center	Laboratories; Facilities for R&D of semiconductor design.	Provides laboratories for companies and universities to conduct research and development for advanced information communication technology and semiconductor design technology.
Business Venture Support Center	Laboratories; Conference room; Collaborative Laboratory; Share office	Provides offices for general affairs; Provides research laboratories in the Department of Mechanics and the Department of Chemistry.
Media Center	Library	Provide a variety of information and communication services using the large-capacity network system prepared by the campus.
Conference Center.		Provide a venue for small exhibitions.

On the other hand, KSRP also makes full use of geographical conditions, natural resources, and urban environment and adopts a number of technologies and measures to develop and build the campus with environmentally friendly, net-zero water, and net-zero energy consumption. For example, the University of Kitakyushu in KSRP focuses on reducing building carbon emissions and wastewater discharge to the greatest extent possible by making full utilization of natural light, wind, heat, wastewater, and other resources, which reduces the environmental load and improves the waste of resources. The University of Kitakyushu adopts light galleries and solar chimneys to make full utilization of natural wind and natural light to achieve ventilation and full lighting of the whole campus. The solar chimney is a cleaner measure that utilizes the chimney effect of solar power and the excitation of the outside wind to promote natural ventilation. Furthermore, the outside air of the University of Kitakyushu is drawn from the cool pit in the basement to pre-cool the campus in summer and pre-warm in winter. Secondly, the campus has installed 156 monocrystalline silicon solar panels and 912 poly monocrystalline silicon solar panels on the top of the teaching building to make full use of solar power to provide electricity for the campus. Then, the campus is equipped with distributed energy resource systems, which can independently provide power generation, heating, and cooling for the campus without relying on the public grid and energy sources. Finally, the campus utilizes rainwater harvested on the surfaces of the capture roof in all buildings and treats wastewater from individual buildings to maximize conserve potable water.

The distributed energy resource systems and the HRG for the treatment and distribution of rainwater and graywater are centrally located in the Energy Center, which is the main part of building an environmentally friendly campus. Therefore, the Energy Center has the responsibility to manage and maintain these systems. Fig 2-14 shows the eco-campus of the University of Kitakyushu.

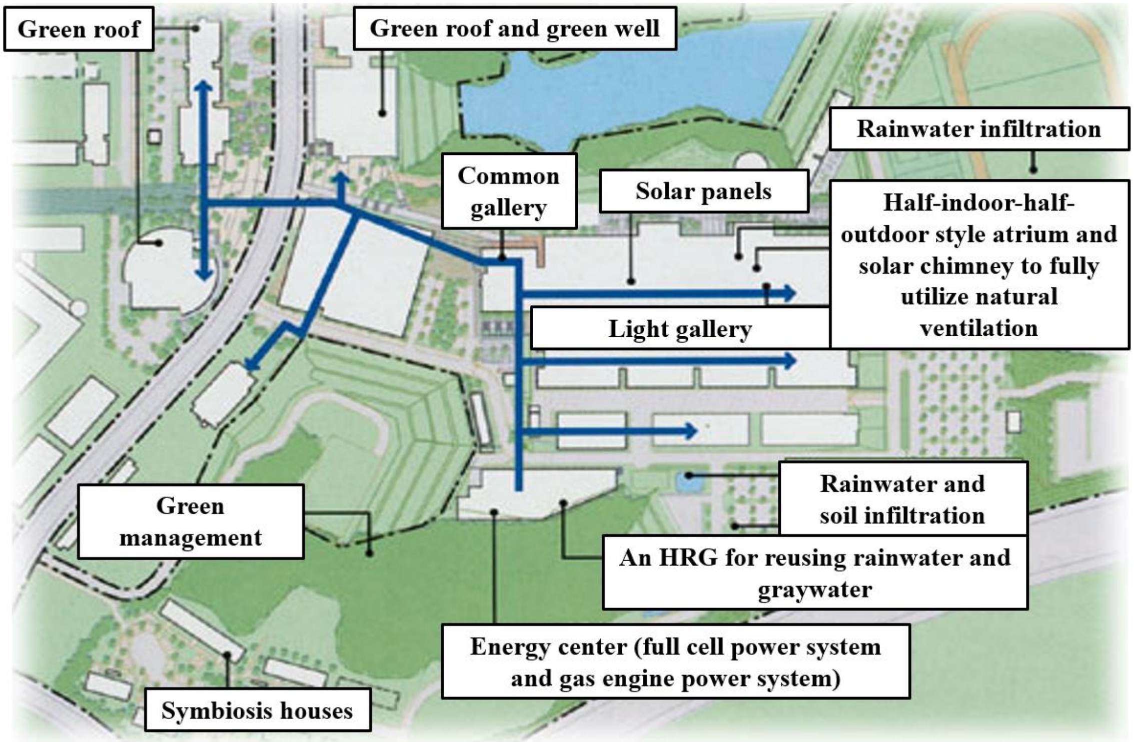

Fig 2-14 The eco-campus of the University of Kitakyushu [86]

2.3.2 The HRG in the University of Kitakyushu

Because the KSRP is committed to maximizing the utilization of alternative water sources to conserve water, an HRG was implemented in Energy Center. However, the HRG in Energy Center only serves some buildings and facilities within the KSRP and is concentrated on conserving potable for the University of Kitakyushu, whereas other buildings and facilities in the KSRP are still using potable water from main water plants. Fig 2-15 shows the service area of the HRG. Therefore, the HRG on the campus provides water to 53,214.35 m^2 of building space, including a teaching building, experiment building, gym with canteen, media center, collaboration center, and conference center.

Fig 2-15 The service area of the HRG in the University of Kitakyushu
(A. Energy Center; B. Teaching Building; C. Experiment Building; D. Gym and Canteen; E. Media Center; F. Collaboration Center; G. Conference Center.)

The water end uses of the campus include washbasins, kitchens, showers, toilets, cooling towers for space cooling and heating devices, irrigation, chiller-heater water tank supplements, fire water tank supplements, and the water supply for the energy systems. The detailed information of these buildings on the campus is shown in Table 2-5. The plan for KSPR is to replace all the water demand with non-potable water, except for washbasins, showers, and kitchens. Therefore, each building in KSRP is equipped with independent rainfall capture and rainwater tanks to ensure sufficient alternative water sources. Each building can harvest rainwater for the rainfall capture roof into rainwater tanks for storage. Then, the harvested rainwater flows from the rainwater tanks to the Energy Center through a common gallery and are re-transmitted to each building after being centrally treated. The common gallery includes the electricity, water, and information networks of the campus. The harvested rainwater is mainly reused to the non-potable water demand of cooling towers, irrigation, and the supplement of chiller-heater water and fire water tanks because the water consumption of these water uses will be affected by evaporation, especially the water consumption of cooling towers in summer. Therefore, cleaner and cheaper rainwater is the best choice for these non-potable water demands to reduce the loss by the evaporation.

These buildings on the campus also installed independent wastewater tanks to ensure sufficient graywater for reuse. All wastewater generated from these buildings, which includes light wastewater generated from washbasins and dark wastewater generated from toilet flushing, is stored in their own wastewater tanks and will be uniformly transported to the Energy Center to be treated as graywater after the accumulated amount of wastewater reaches a certain amount. The standard of reusing graywater is that the graywater does not allow to threaten humans as long as it is not swallowed by mistake because the quality of graywater is often between the water quality of potable water and wastewater. On the other hand, it is required that the graywater does not damage the function of water uses during reuse. Therefore, graywater is only considered to meet the non-potable water demand of toilet flushing on the campus. It is worth pointing out that the amount of collected wastewater is often greater than the amount of graywater because each water uses can produce graywater, whereas the such graywater can only be used for non-potable water reuse.

Table 2-5 Basic information of the buildings on the campus

Types	Construction areas	Potable water sources	Rainwater harvesting	Wastewater collecting	Water end-use
Energy Center	-	Main water plants	No	No	Washbasins, toilets, cooling towers, irrigation, chiller-heater water tanks, fire water tanks, and energy systems
Teaching Building and Experiment Building	35,060.00 m^2	Energy Center [a]	Yes	Yes	Washbasins, toilets
Gym	1,661.50 m^2	Energy Center [a]	Yes	Yes	Washbasins, toilets, showers
Canteen	1,109.00 m^2	Main water plants	Yes	Yes	Washbasins, toilets, kitchens
Media Center	7,250.55 m^2	Energy Center [a]	Yes	Yes	Washbasins, toilets
Collaboration Center	5,844.86 m^2	Energy Center [a]	Yes	Yes	Washbasins, toilets
Conference Center	2,288.44 m^2	Main water plants	Yes	Yes	Washbasins, toilets

Note: [a] The potable water supplied by the main water plants is first collected in the potable water tanks of the Energy Center and then distributed to each building by the Energy Center.

The potable water consumption of these target buildings (hereinafter referred to as Kitakyushu City University or campus) is also purchased from main water plants, but the potable water is first flow in a potable water tank in Energy Center and is managed and distributed by Energy Center.

The potable water tank in Energy Center is 120 m^3. The prolonged storage of potable water in potable water tanks may lead to the deterioration of water quality and increase the health risks of using potable water. Therefore, the weekly inspection of potable water is required to keep the stability of potable water quality. In addition, the excess potable water will spill out from the potable water tank when the potable is ingested in large quantities in a short period of time. On the other hand, the potable water demand of the Canteen and the Conference Center requires large quantities because of cooking, which results in providing potable water to these buildings will over the load of the potable water tank. Therefore, the potable water of the Canteen and the Conference Center is directly supplied by main water plants, whereas the non-potable water of both is supplied by the Energy Center.

The HRG on the campus adopts the configuration that separately treats rainwater and wastewater. The layout of the HRG on the campus is shown in Fig 2-16.

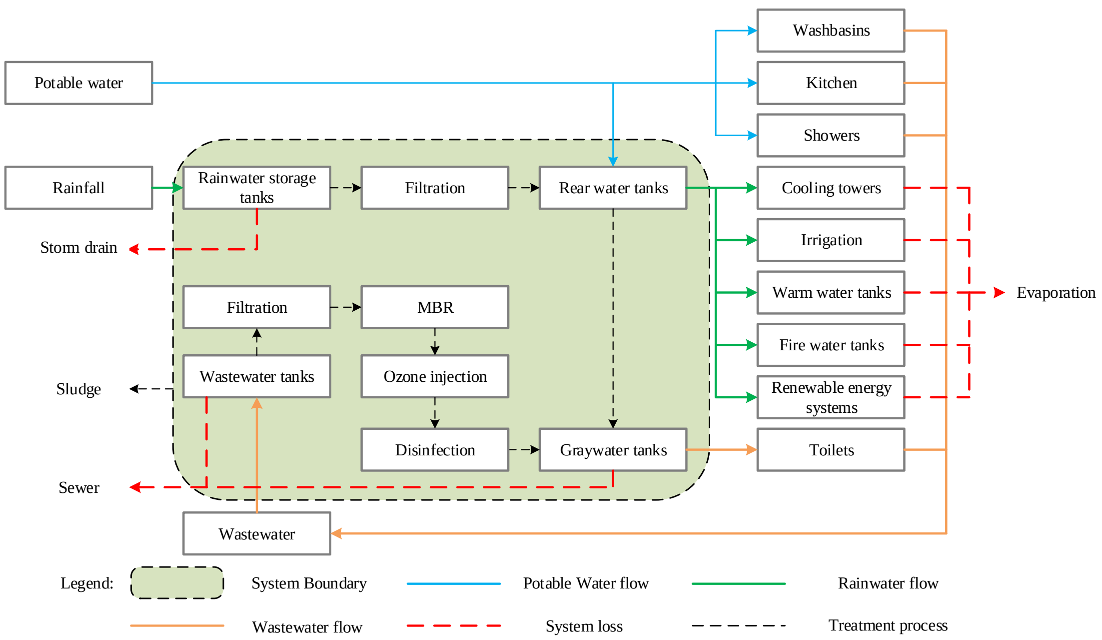

Fig 2-16 Layout of the HRG on the campus

The rainwater subsystem of the HRG includes rainwater storage tanks, a filtration device, rear water tanks for storing the filtered rainwater, and the corresponding pumps and plumbing systems. When the water yielded from the HRG cannot meet the non-potable water demand, the shortages will be supplied by the primary water supply from main water plants. Meanwhile, a one-way plumbing system for transporting water into the graywater subsystem is installed on the rear water tanks to cope with insufficient water supply due to the substandard effluent quality of the graywater subsystem.

The rainwater subsystem of the HRG does not include the first flushing device to maximize harvest rainwater. A high-efficiency new suspension filter, the FM filter, was used to replace the first flush device to treat rainwater and has been shown in Fig 2-17. FM filters are filled polyethylene filter media in the bottom for extreme durability and the filter media will not be stuck when treating rainwater with highly viscous suspended. The polyethylene filter media can also effectively provide clean and hygienic rainwater. A mixer is implemented inside the FM filter to ensure that the rainwater and the filter media are fully mixed. In addition, the investment cost of FM filters is inexpensive because such filters do not require large diameter cleaning pumps. Finally, FM filters do not require to supplement backwash water, which can greatly reduce the generation of cleaning wastewater.

On the other hand, the rainwater subsystem of the HRG is not equipped with disinfection processes because the water end uses supplied by rainwater in the campus require to be cooled such as the non-potable water demands of air-conditioning cool towers, irrigation, and chiller-heater water tank supplements and the high temperature of these water end uses can play a role in disinfection.

Fig 2-17 The FM filters in the rainwater subsystem of the HRG

The graywater subsystem of the HRG includes wastewater tanks, an MBR with seven sets of hollow fiber membranes, an aeration system, an ozone decomposition device, a sodium hypochlorite dosing device, graywater tanks for storing the treated wastewater (the treated graywater), a set of sludge recovery devices, and the corresponding pumps and plumbing systems. In addition, rainwater and graywater are not mixed in the same water tank because of different water qualities. The toilet water is supplied by graywater only, and the remaining non-potable water demand is supplied by rainwater. All the water tanks of the HRG are concentrated underground, and the materials of the water tanks and pipes are listed in Table 2-6 and the related pumps are listed in Table 2-7.

Table 2-6 The material of the water tanks and pipes of the HRG and the potable water system on the campus

Types	Components	Materials	Specifications
Rainwater subsystem	Rainwater storage tanks	Reinforced concrete	640 m^3
	Filtration device	Floating filtration device with vortex pumps	33 m^3/h
	Rear water tanks	Reinforced concrete	360 m^3
	Rainwater pipes	Steel gas pipe	—
Graywater subsystem	Wastewater tanks	Reinforced concrete	380 m^3
	Membrane bioreactor	Hollow fiber membrane	7 units with 56 m^3 contact areas
	Graywater tanks	Reinforced concrete	475 m^3
	Wastewater pipes	Polyvinylchloride pipe	—
	Aeration pipes	Polyvinylchloride pipe	—
	Graywater pipes	Steel gas pipe	—
Potable water system	Potable water tanks	Fiber-reinforced plastics	120 m^3
	Potable water pipes	Steel gas pipe	—
	Warm water pipes	Heat resistant polyvinylchloride pipe	—

In addition, excess rainwater of the rainwater subsystem is discharged into storm drains from the rainwater storage tanks, and excess wastewater and graywater of the graywater subsystem are discharged into the sewers from the wastewater tanks and the graywater tanks, respectively.

The wastewater generated from buildings flows into the HRG and first passes through coarse and fine grids to remove the large and small suspended solids in the wastewater. The remaining suspended solids are then removed by an aerated grit chamber installed in front of the wastewater tanks because these suspended solids will not only deposit in the pipes and subsequent treatment equipment to hinder the flow of wastewater but also accelerate the wear of pumps. The aerated grit chamber can aerate the tanks to prevent the wastewater from spoiling and improve the solid-liquid separation effect of wastewater. The wastewater then enters the wastewater tanks to adjust the quantity and quality to a stable level. Finally, the stable wastewater enters the final treatment process. The sludge generated from above treatment processes is discharged to the sludge recovery equipment.

However, the pollution of the collected wastewater is quite serious because the HRG collects and treats all domestic wastewater on the campus including the dark wastewater generated from toilets. Therefore, MBR is selected by the graywater subsystem of the HRG for biological treatment and final solid-liquid separation of wastewater because it is difficult to ensure that the quality of the obtained graywater meets the non-potable water reuse standard by the ordinary treatment processes.

Table 2-7 Parameters of the main pumps in the HRG on the campus

Pumps	Types	Flows	Heads	Rated power	Number of pumps
Pumps for rainwater input	50DS6.75	100 L/min	12 m	0.75 KW	2
Pumps for rainwater output from the FM filter	50DS6.75	100 L/min	12 m	0.75 KW	2
Pumps for the FM filter	65BMSP61.5A	550 L/min	8 m	1.5 KW	2
Pumps for sending rainwater to water uses	50BNBMD	800 L/min	60 m	7.5 KW	2
Pumps for sending rainwater to graywater tanks	50BNBMD	530 L/min	44 m	5.5 KW	2
Pumps for wastewater tanks	80DL62.2	120 L/min	12 m	2.2 KW	2
Pumps for sludge	50DVS61.5	200 L/min	12 m	1.5 KW	2
Pumps in wastewater tanks for stirring	50DVS6.75	100 L/min	8 m	0.75 KW	2
Pumps for graywater tanks	65DVS6.75	380 L/min	11 m	0.75 KW	2
Pumps for sending graywater to water uses	65BNLMD	1550 L/min	50 m	7.5 KW	3

A total of 7 units of hollow fiber membranes are selected by the HRG to treat wastewater and each unit of hollow fiber membrane has a contact area of approximately 56 m^3 and treatment efficiency of approximately 12 m^3/d. Hollow fiber membrane are widely used in the domestic water purification because of their high packing density, large effective membrane area, high flux, simple operation, and easy cleaning. Fig 2-18 shows the hollow fiber membrane (part) in the MBR of the HRG.

The hollow fiber membrane microfiltration is a precision filtration process. The hollow fiber membrane can pass a large amount of wastewater and small molecular solutes through the membrane by the operating pressure to achieve the purpose of separation, concentration, and purification, whereas the contaminants such as sand, clay, algae, and bacteria in the wastewater are trapped outside the membrane. The operating pressure of the hollow fiber membrane is generally 0.7 KPa to 7 KPa, the pore size range is from 0.1 μm to 75 μm, and the membrane thickness is from 120 μm to 150 μm.

In addition, the MBR of the HRG adopts the external pressure filtration method to treat wastewater because the effective area of the external pressure filtration method is larger than that of the internal pressure filtration method. Using the external pressure filtration method to treat wastewater can also ensure the rapid flow of graywater inside the membrane and ensure the treatment efficiency. Simultaneously, the external pressure filtration method can trap the sludge on the outside of the hollow fiber membrane for easy cleaning.

Fig 2-18 The hollow fiber membrane (part) in the MBR of the HRG

The life cycle of the hollow fiber membranes is 5 years. Therefore, it is not only necessary to regularly clean the MBR every year but also to replace the new hollow fiber membrane with 5 years to ensure the treatment efficiency of the MBR. The cleaning process will be divided into 4 times because 7 units of hollow fiber membranes are installed in the MBR tanks to ensure that the MBR can simultaneously treat wastewater and replace hollow fiber membranes. The regular cleaning of hollow fiber membranes can effectively improve the treatment efficiency of MBR. Table 2-8 shows the performance of the MBR before and after the cleaning processes under the test pressure of 25 L/min.

Table 2-8 The performance of the MBR before and after the cleaning processes (the flow of test pumps is 25 L/min)

	First time		Second time		Third time		Fourth time	
	Flows (L/min)	Pressure difference (MPa)	Flows (L/min)	Pressure difference (MPa)	Flows (L/min)	Pressure difference (MPa)	Flows (L/min)	Pressure difference (MPa)
Before	4.5	0.035	3.1	0.047	8.0	0.041	4.0	0.039
After	9.0	0.022	5.0	0.039	11.0	0.022	8.0	0.027

Subsequently, ozone is injected into the treated wastewater for disinfection and decolorization. In addition, it is necessary to continue adding hypochlorite to the treated wastewater for chlorination disinfection after ozone disinfection because ozone cannot remain in the raw water for a long time. Carrying out the chlorination disinfection can effectively prevent the regeneration of microorganisms in the graywater.

Ozone must be generated on-site because of the instability of ozone. The ozone generator is a device that uses a high-voltage alternating current (generally 10,000 V-20,000 V) to generate ozone (Fig 2-19). The electrodes inside the ozone generator are covered with an electrolyte of uniform thickness. When the air passed through the electrode gap, the oxygen molecules are activated and decomposed into oxygen atoms. Then, the activated oxygen atoms can combine by themselves or combine with oxygen molecules in the air to form ozone, which is a process of oxygen allotrope transformation. The ozone generator can quickly generate ozone at a working pressure of 0.05 MPa- 0.1 MPa, an air flow of 24 L/min, a cooling water flow of 18 L/min, and a temperature of 50 ℃.

Fig 2-19 The ozone generator in the HRG

In summary, rainwater and graywater can meet the non-potable water reuse standard for reuse after a series of treatment processes by HRG, which is an important prerequisite for evaluating the feasibility of decentralized HRGs in buildings. Table 2-9 and Table 2-10 show the water quality of treated rainwater and graywater yielded by the HRG on the University of Kitakyushu, respectively.

Table 2-9 Water quality of the treated rainwater in the HRG

	Standard	The HRG
pH	5.8-8.6	6.3
BOD (mg/L)	≤ 5.0	4.0
COD (mg/L)	≤ 15.0	8.0
SS (mg/L)	≤ 5.0	≤ 1.0
Coliforms (#/cm^3)	≤ 10.0	0.0
Activated sludge concentration	≤ 12000	6900

Table 2-10 Water quality of the graywater in the HRG

Items	Standard (mg/L)	HRG (mg/L)	Items	Standard (mg/L)	HRG (mg/L)
Cadmium	0.03	< 0.001	Thiobencarb	0.2	< 0.002
Cyanide	1.0	< 0.1	Benzene	0.1	< 0.001
Organophosphate	1.0	< 0.1	Selenium and its compounds	0.1	< 0.001
Lead and its compounds	0.1	0.001	Boron and its compounds	10.0	< 0.1
Hexavalent chromium compound	0.5	< 0.01	Fluorine and its compounds	8	0.23
Arsenic and its compounds	0.1	< 0.001	*pH (Dimensionless)	5.8-8.6	7.8
Mercury and its compounds	0.005	< 0.0005	BOD	120 per day	3.3
Alkyl Mercury Compound	NAN	< 0.0005	COD	120 per day	6.2
PCBs	0.003	< 0.0005	SS	150 per day	< 1
Trichloroethylene	0.1	< 0.003	N-hexane extractable content	5	< 1

Continued from Table 2-10

Items	Standard (mg/L)	HRG (mg/L)	Items	Standard (mg/L)	HRG (mg/L)
Perchloroethylene	0.1	< 0.001	The substance content of normal hexane extract	30	< 1
Dichloromethane	0.2	<0.002	Phenol	5.0	<0.05
Carbon tetrachloride	0.02	< 0.0002	Copper	3.0	0.02
1,2-Dichloroethane	0.04	< 0.0004	Zinc	2.0	0.14
1,1-Dichloroethylene	1.0	< 0.002	Soluble iron	10.0	0.02
Cis 1,2-dichloroethylene	0.4	< 0.004	Soluble Manganese	10.0	< 0.01
1,1,1-Trichloroethane	3.0	< 0.1	Chromium	2.0	< 0.01
1,1,2-Trichloroethane	0.06	< 0.0006	*Escherichia coli (number)	3000 /cm^3 per day	0.0
1,3-Dichloropropene	0.02	< 0.0002	Nitrogen	60 per day	2.7
Thiuram	0.06	< 0.0006	Phosphorus	8 per day	0.7

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Chapter 3

SIMULATION MODEL OF HRGS BASED ON THE WATER BALANCE MODEL

Contents

3.1 Content

Rainwater and graywater are the most common alternative water sources for building water conservation. Compared with stable graywater, recycling rainwater has been hindered by random and varied precipitation patterns, which requires reasonable design before equipment installation to avoid insufficient water supply. However, only harvesting rainwater is not meet expectations in some regions. A piece of efficient water-saving equipment, hybrid rainwater-graywater systems, is derived for greening buildings or net-zero city water. The systems can minimize the water consumption of the target building and can reduce the sewage discharge of the building. Previous studies simulated the rainwater sub-system and the graywater sub-system independently for the designing of HRGs and made simple water balance assumptions for the graywater sub-system, which ignored the integrity of HRGs and made insufficient precision in subsequent calculations. There is still no suitable model to effectively simulate the operation state of HRGs. This chapter aims to establish an integrated model for HRGs based on the water balance model to evaluate and optimize HRGs. The actual monitoring data of an HRG on campus was used to test the integrated model. Modeling results show that the integrated model can reflect the operating state of HRGs well and can accurately simulate the equipment scale of HRGs. The proposed model can provide a new method for the design and optimization of HRG in the future and simplify the calculation process of HRG.

3.2 Introduction

Rainwater and graywater are the most common alternative water sources to conserve water in buildings. Rainwater and graywater can be recollected, retreated, and redistributed in buildings by rainwater harvesting systems (RWHs) and graywater recycling systems (GWRs), respectively. Compared with stable graywater, recycling rainwater has been hindered by random and varied precipitation patterns, which requires reasonable design before equipment installation to avoid insufficient water supply. Conversely, recycling graywater has been hindered by the characteristics of non-potable water demand and the amount of graywater generation, which is related to wastewater quality characteristics and the number of users, respectively. However, only harvesting rainwater or recycling graywater is not meet expectations in some regions and the requirements of water conservation in some buildings, especially in buildings that aim to achieve net-zero water. A piece of efficient water-saving equipment, hybrid rainwater-graywater systems (HRGs), is derived for such scenarios. HRGs can simultaneously supply rainwater and graywater to achieve more significant water-saving efficiency to minimize the potable water consumption of the target building. Therefore, HRGs have a significant implementation potential to conserve water in buildings.

In order to implement HRGs in buildings more effectively and reasonably, a comprehensive evaluation of HRGs is required before the implementation of such systems. However, the development of evaluation models for the hydraulic conditions of HRGs is currently still infant, which hindered the understanding of such systems. Previous studies of evaluating HRGs simplified the simulation processes of such systems by dividing the simulation into the simulation of the rainwater subsystem and the simulation of the graywater subsystem, which determined the performance of HRGs by independently designing the rainwater subsystem and making simple water balance assumptions for the graywater subsystem. In general, the simulation of HRGs is often carried out by combination with the model for evaluating RWHs and the model for evaluating GWRs. The evaluation models of RWHs are various because the RWHs are climate-sensitive, including analytical probabilistic model [1-3], optimization formulation [4], linear programming [5, 6], stochastic model [7], life cycle assessment [8-11], and water balance model [12-15]. However, the evaluation models of GWRs are concentrated on life cycle assessment [16-18] because of the stable hydraulic condition. Generally, when evaluating the performance of HRGs, the simplified model refers to the fact that previous studies often rely on the simulation model of RWHs, such as the water balance model, to determine the optimal scale to achieve the maximum water-saving efficiency when simulating the rainwater subsystem of HRGs, whereas only the wastewater generated from buildings and the graywater demand of water uses are assumed to equal when simulating graywater subsystems of HRGs. This simulation method ignored the integrity of HRGs and the relationship between the rainwater subsystem and the graywater subsystem to make insufficient precision in subsequent calculations and cause errors in the simulation results [19-23].

However, there is still no suitable model to effectively simulate the operation state of HRGs, which may overestimate and underestimate the water-saving efficiency and the economic benefits of HRGs. For example, Naserisafavi, N., et al, proposed reusing rainwater to toilet flushing and reusing graywater for irrigation when evaluating an HRG in buildings for conserving water [24]. The authors assumed that all wastewater generated from the building was collected by the HRG for irrigation and found that this non-potable water supply method of the HRG had the best water-saving efficiency and a better economic benefit. However, under this assumption, the evaluation of the HRG ignored the large waste of treated graywater on rainy days and winter because the non-potable demand for irrigation is seasonal and climate-dependent and the irrigation was not required to be supplied by graywater during rainy days and winter. This results in the stable wastewater treatment in HRGs inevitably waste treated graywater during periods of low non-potable demand, which will damage economic benefits and waste resources of HRGs. Similarly, the evaluation result obtained by HRGs that supply graywater to air conditioning cooling in buildings cannot be suitable for HRGs that supply treated graywater to toilets in buildings because the non-potable water demand for toilet flushing is more stable than air conditioning cooling throughout the year, and a simple model of graywater subsystems of HRGs cannot cope with both scenarios simultaneously [25]. Therefore, the development of an integrated simulation model for evaluating HRGs is essential for the effective implementation of such systems.

In order to precisely evaluate and optimize the performance of HRGs, an integrated simulation model based on the water balance model was proposed in this chapter. Then, the simulation results obtained from the integrated model of HRGs were compared to the actual monitoring data of an HRG on campus to test the feasibility of the simulation model. The integrated model of HRG proposed in this chapter can not only provide a new method for the design and optimization of HRGs in the future and simplify the calculation process of HRGs but also provide new ideas for developing other simulation models for evaluating and optimizing HRGs in buildings.

3.3 Water balance model

The water balance principle is used for designing decentralized water reuse systems, which requires the volume input to be equal to the output, and the water balance model is widely used to optimize and evaluate rainwater harvesting systems because the random precipitation pattern will result in a dynamic change of the storage volume in rainwater tanks [26-28]. The equation for the water balance model is as follows:

$$I_t + R_{t-1} + SU_t = Y_t + R_t + SP_t \tag{3-1}$$

where I_t is the water harvested by the systems at the beginning of time step t (m^3), R_{t-1} is the water remaining in the systems before time step t (m^3), SU_t is the water supplemented from external water sources when the water supplied by the systems cannot meet the demand at time step t (m^3), Y_t is the water output from the systems at time step t (m^3), R_t is the water remaining in the systems at the end of time step t (m^3), and SP_t is the water overflow from the systems at time step t (m^3).

When the water balance model is used to evaluate RWHs, I can be modified using Q_R, which denotes the rainwater that is captured on the roofs of buildings and is calculated using the following equation:

$$Q_{Rt} = \frac{\varphi A H_t}{1000} \tag{3-2}$$

where φ is the runoff coefficient (dimensionless, 0–1) (a value of 0.8 is used in this study according to the recommendation of Marinoski, Rupp [29], Musayev, Burgess [30], and Sepehri, Malekinezhad [31]), A is the area capturing rainwater on the roof of a building (m^2), and H_t is the precipitation at time step t (mm).

Two algorithms can be executed to calculate the water balance model, which are the "yield before spillage" (YBS) and "yield after spillage" (YAS) [32]. The difference between the operational logic of the two algorithms is whether overflow occurs before or after water output from the systems. The YBS algorithm emphasizes that the water output from the corresponding water tanks occurs before the water overflow from the systems. The flow chart of the YBS algorithm is shown in Fig 3-1.

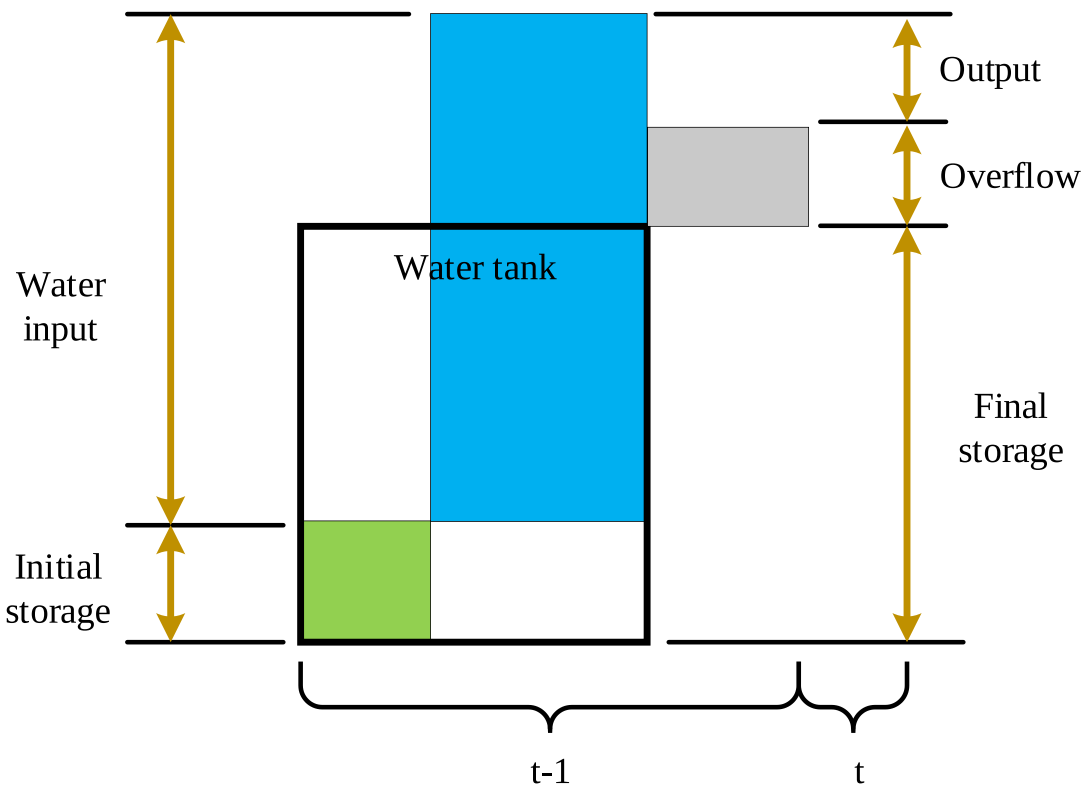

Fig 3-1 The flow chart of the YBS algorithm

The equation for the YBS algorithms is expressed as equation (3-3) to equation (3-6):

$$Y_t = \begin{cases} R_{t-1} + I_t & R_{t-1} + I_t \le D_t; \\ D_t & R_{t-1} + I_t > D_t; \end{cases} \tag{3-3}$$

$$R_t = \begin{cases} R_{t-1} + I_t - Y_t & R_{t-1} + I_t - D_t \le V; \\ V & R_{t-1} + I_t - D_t > V; \end{cases} \tag{3-4}$$

$$SU_t = \begin{cases} D_t - R_{t-1} - I_t & R_{t-1} + I_t \le D_t; \\ 0 & R_{t-1} + I_t > D_t; \end{cases} \tag{3-5}$$

$$SP_t = \begin{cases} 0 & R_{t-1} + I_t - D_t \le V; \\ I_t + R_{t-1} - D_t - V & R_{t-1} + I_t - D_t > V; \end{cases} \tag{3-6}$$

where D_t is the non-potable water demand at time step t (m^3), and V is the size of the water tank used in a system (m^3).

The YAS algorithm emphasizes that the water output from the corresponding water tanks occurs after the water overflow from the systems. The flow chart of the YAS algorithm is shown in Fig 3-2.

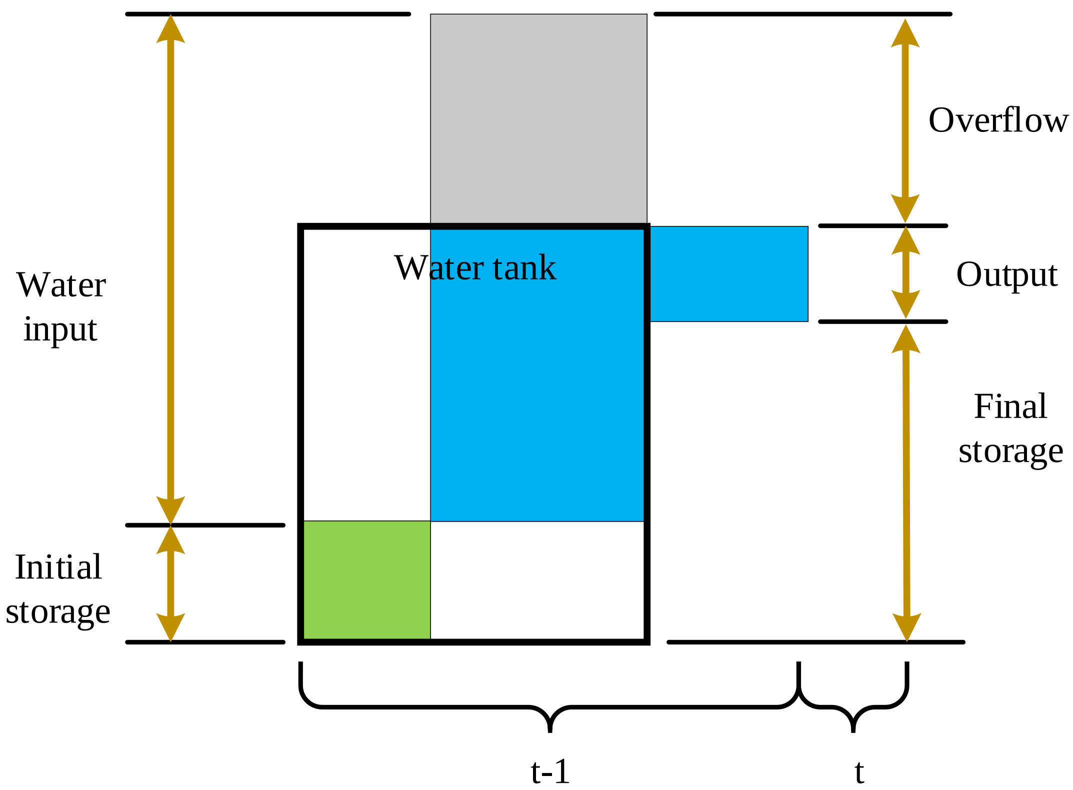

Fig 3-2 The flow chart of the YAS algorithm

The equation for the YAS algorithms is expressed as equation (3-7) to equation (3-10):

$$Y_t = \begin{cases} R_{t-1} + I_t & R_{t-1} + I_t < D_t; \\ D_t & R_{t-1} + I_t \geq D_t; \end{cases} \tag{3-7}$$

$$R_t = \begin{cases} R_{t-1} + I_t - Y_t & R_{t-1} + I_t < V; \\ V - Y_t & R_{t-1} + I_t \geq V; \end{cases} \tag{3-8}$$

$$SU_t = \begin{cases} D_t - R_{t-1} - I_t & R_{t-1} + I_t < D_t; \\ 0 & R_{t-1} + I_t \geq D_t; \end{cases} \tag{3-9}$$

$$SP_t = \begin{cases} 0 & R_{t-1} + I_t < V; \\ R_t + I_t - V & R_{t-1} + I_t \geq V; \end{cases} \tag{3-10}$$

According to the water balance model of evaluating RWHs, the simulation model of HRGs in buildings was proposed in this chapter based on the YBS and YAS algorithms and the simulation model will be introduced in the next section.

3.4 Simulation model of HRGs

Three types of water tanks—rainwater tanks, wastewater tanks, and graywater tanks—need to be respectively simulated to evaluate the performance of HRGs, which will complicate the evaluation process. Therefore, an integrated simulated model was proposed in this chapter.

3.4.1 Water balance for wastewater tanks

The first step of the simulation model is to set the daily treatment capacity of the graywater subsystem and the size of wastewater tanks. The daily treatment capacity is dependent on the amount of wastewater collected and graywater demand, whereas the size of wastewater tanks is dependent on the daily treatment capacity of graywater subsystems because the size of wastewater tank used in HRGs is not for long-term storage and has less effect on the performance. Therefore, the size of wastewater tanks only needs to provide the wastewater that can meet the subsequent treatment and ensure that the wastewater is not accumulated for more than 24 h to avoid bacterial growth [33]. On the other hand, the actual treatment capacity refers to that graywater subsystems will output less graywater during the low wastewater generation period because of holidays and at night. The actual treatment capacity is calculated as equation (3-11):

$$D_{Tt} = \begin{cases} R_{Gt-1} + Q_{Gt} & R_{Gt-1} + Q_{Gt} - T_{Tt} < 0; \\ T_{Tt} & R_{Gt-1} + Q_{Gt} - T_{Tt} \geq 0; \end{cases} \tag{3-11}$$

Where D_{Tt} is the actual treatment capacity (m^3/d); R_{Gt-1} is the wastewater remaining in wastewater tank (m^3); Q_{Gt} is the wastewater input (m^3); T_{Tt} is the theoretical treatment capacity (m^3/d).

The YBS algorithm is used to simulate the catchment capacity of wastewater tanks because the treatment process of graywater subsystems runs continuously, whereas wastewater is generated discontinuously throughout the day. Therefore, the wastewater tanks will continuously output wastewater and relatively intermittently collect the wastewater generated from the building. Wastewater output takes precedence over wastewater overflow, especially during the period of low wastewater input. The water balance for the wastewater tanks is calculated as followed:

$$Y_{Gt} = \begin{cases} R_{Gt-1} + Q_{Gt} & R_{Gt-1} + Q_{Gt} - D_{Tt} < 0; \\ D_{Tt} & R_{Gt-1} + Q_{Gt} - D_{Tt} \geq 0; \end{cases} \tag{3-12}$$

$$R_{Gt} = \begin{cases} R_{Gt-1} + Q_{Gt} - Y_{Gt} & R_{Gt-1} + Q_{Gt} - D_{Tt} - V_g < 0; \\ V_g & R_{Gt-1} + Q_{Gt} - D_{Tt} - V_g \geq 0; \end{cases} \tag{3-13}$$

$$SP_{Gt} = \begin{cases} 0 & R_{Gt-1} + Q_{Gt} - D_{Tt} - V_g < 0; \\ R_{Gt-1} + Q_{Gt} - D_{Tt} - V_g & R_{Gt-1} + Q_{Gt} - D_{Tt} - V_g \geq 0; \end{cases} \tag{3-14}$$

Where V_g is the size of wastewater tanks (m^3); Y_{Gt} is the wastewater output of wastewater tanks (m^3), and SP_{Gt} is the overflow of wastewater tanks (m^3).

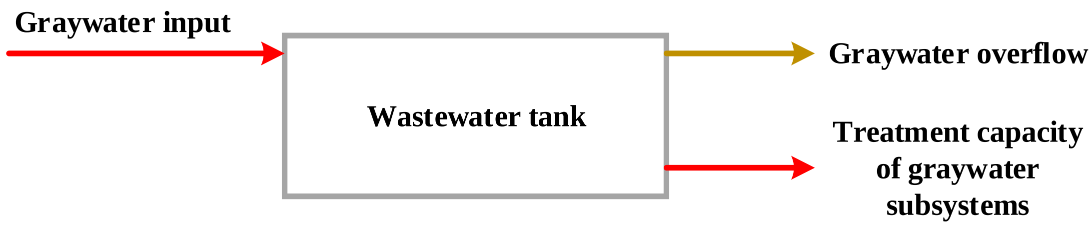

Fig 3-3 Calculation process of wastewater tanks

3.4.2 Water balance for graywater tanks

Different from wastewater tanks, the YAS algorithm is used to simulate the performance of graywater tanks because the daily water demand of buildings is discontinuous, and the continuous input of treated water will cause the systems to overflow water before it is used. The calculation process of graywater tanks is shown in Fig 3-4 and the water balance for the graywater tanks is calculated as followed:

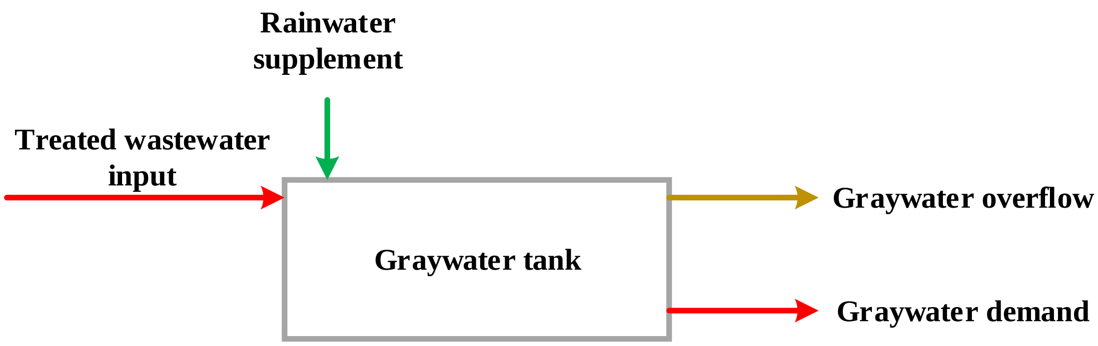

Fig 3-4 Calculation process of graywater tanks

$$Y_{Et} = \begin{cases} R_{Et-1} + Y_{Gt} & R_{Et-1} + Y_{Gt} - D_{Et} < 0; \\ D_{Et} & R_{Et-1} + Y_{Gt} - D_{Et} \geq 0; \end{cases} \tag{3-15}$$

$$R_{Et} = \begin{cases} R_{Et-1} + Y_{Gt} - YRW_t & R_{Et-1} + Y_{Gt} - V_e < 0; \\ V_e - Y_{Et} & R_{Et-1} + Y_{Gt} - V_e \geq 0; \end{cases} \tag{3-16}$$

$$SU_{Et} = \begin{cases} D_{Et} - R_{Et-1} - Y_{Gt} & R_{Et-1} + Y_{Gt} - D_{Et} < 0; \\ 0 & R_{Et-1} + Y_{Gt} - D_{Et} \geq 0; \end{cases} \tag{3-17}$$

$$SP_{Et} = \begin{cases} 0 & R_{Et-1} + Y_{Gt} - V_e < 0; \\ R_{Et-1} + Y_{Gt} - V_e & R_{Et-1} + Y_{Gt} - V_e \geq 0; \end{cases} \tag{3-18}$$

Where V_e is the size of graywater tanks (m^3); Y_{Et} is the graywater output from graywater tanks at the time step t (m^3); R_{Et-1} is the graywater remaining in the graywater tank before time step t (m^3); R_{Et} is the graywater remaining in graywater tanks at the end of time step t (m^3); D_{Et} is the graywater demand of buildings (m^3); SU_{Et} is the rainwater supplemented when the graywater supplied by the graywater subsystem cannot meet the demand at time step t (m^3), and SP_{Et} is the graywater overflow from reclaimed water tanks at time step t (m^3)

3.4.3 Water balance for rainwater tanks

Similar to the water balance for reclaimed water tanks, the YAS algorithm is used to simulate the performance of rainwater tanks because the daily water demand of buildings is discontinuous, and instantaneous precipitation will cause the systems to spill rainwater before it is used. Furthermore, the YAS algorithm is more accurate and conservative than the YBS algorithm when simulating the performance of rainwater tanks [34]. The calculation process of rainwater tanks is shown in Fig 3-5 and the water balance for rainwater tanks is calculated as followed:

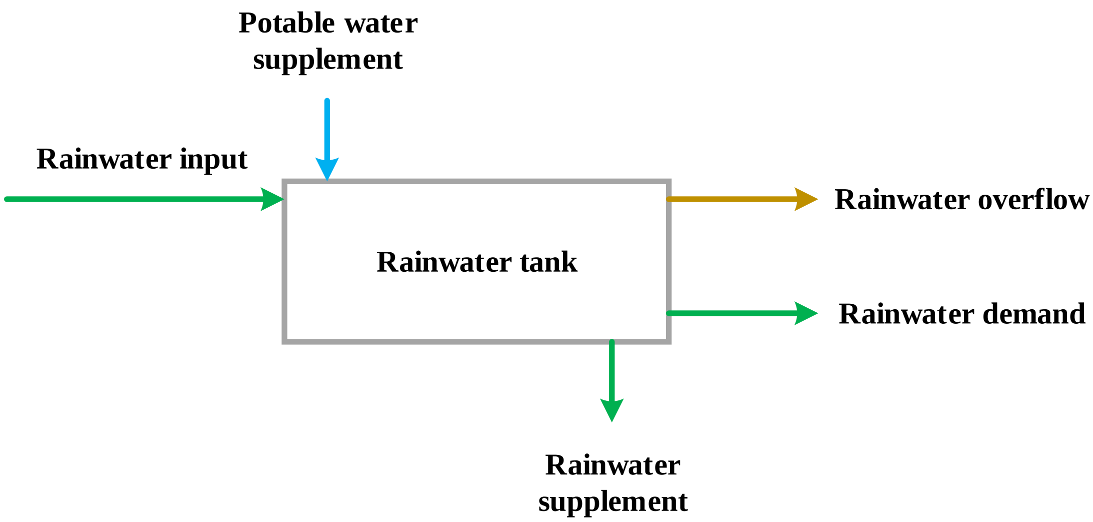

Fig 3-5 Calculation process of rainwater tanks

$$Y_{Rt} = \begin{cases} R_{Rt-1} + Q_{Rt} & R_{Rt-1} + Q_{Rt} - D_{Rt} < 0; \\ D_{Rt} & R_{Rt-1} + Q_{Rt} - D_{Rt} \geq 0; \end{cases} \tag{3-19}$$

$$R_{Rt} = \begin{cases} R_{Rt-1} + Q_{Rt} - Y_{Rt} & R_{Rt} + Q_{Rt} - V_r < 0; \\ V_r - YR_t & R_{Rt} + Q_{Rt} - V_r \geq 0; \end{cases} \tag{3-20}$$

$$SU_{Rt} = \begin{cases} D_{Rt} - R_{Rt-1} - Q_{Rt} & R_{Rt-1} + Q_{Rt} - D_{Rt} < 0; \\ 0 & R_{Rt-1} + Q_{Rt} - D_{Rt} \geq 0; \end{cases} \tag{3-21}$$

$$SP_{Rt} = \begin{cases} 0 & R_{Rt} + Q_{Rt} - V_r < 0; \\ R_{Rt} + Q_{Rt} - V_r & R_{Rt} + Q_{Rt} - V_r \geq 0; \end{cases} \tag{3-22}$$

Where D_{Rt} is the rainwater demand (m^3); Y_{Rt} is the rainwater output from rainwater tanks at time step t (m^3); R_{Rt-1} is the rainwater remaining in rainwater tanks before time step t (m^3); R_{Rt} is the rainwater remaining in rainwater tanks at the end of time step t (m^3); V_r is the size of rainwater tank (m^3); SU_{Rt} is the potable water supplemented from main water plants when the rainwater supplied by the rainwater subsystem cannot meet the demand at time step t (m^3), and SP_{Rt} is the rainwater overflow from rainwater tanks at time step t (m^3).

The integrated algorithm was coded using MATLAB, and the diagram is shown in Fig 3-6. The flow of operation in MATLAB is shown in Fig 3-7. The integrated simulation model of HRGs can not only effectively obtain the optimal scale of such systems including the optimal rainwater tank sizes and the optimal treatment capacity of graywater subsystems by inputting the non-potable water demand of buildings, wastewater generated from buildings, volume of wastewater treated, and precipitation data, but also can comprehensively evaluate the performance and feasibility of HRGs because the performance indexes such as potable water-saving efficiency, non-potable water-saving efficiency, rainwater utilization rate, and graywater utilization rate of HRGs can be calculated from the results obtained from the integrated simulation model. In addition, the integrated simulation model can also obtain the design curves for RWHs, GWRs, and HRGs as follows: (1) The wastewater treatment volume was set to 0 to obtain design curves for RWHs. (2) Precipitation was set to 0 to obtain design curves for GWRs. (3) The non-potable water demand of buildings was separated into that demanded for use in flushing toilets and other non-potable water uses to obtain design curves for HRGs.

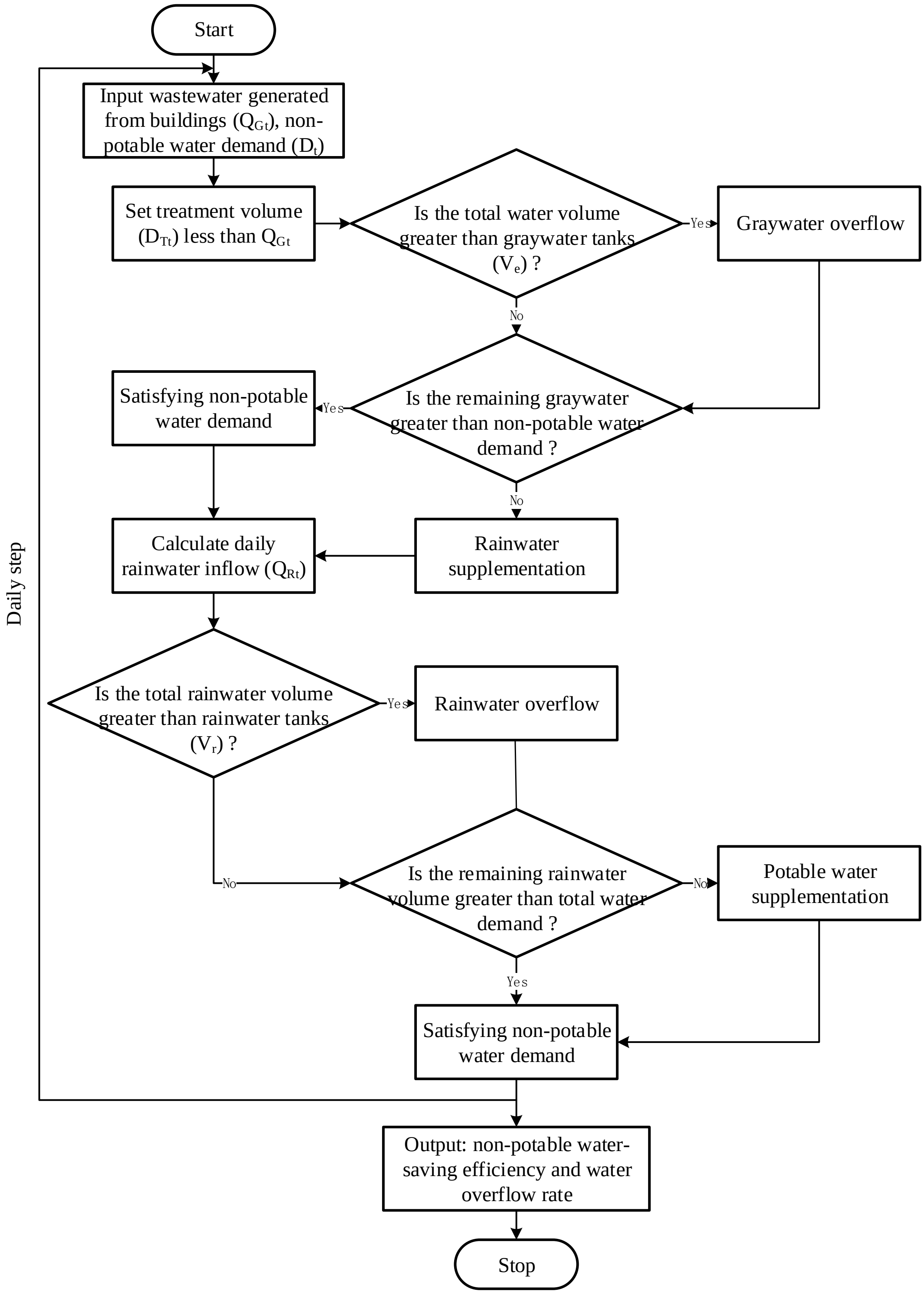

Fig 3-6 Diagram of the integrated simulation model

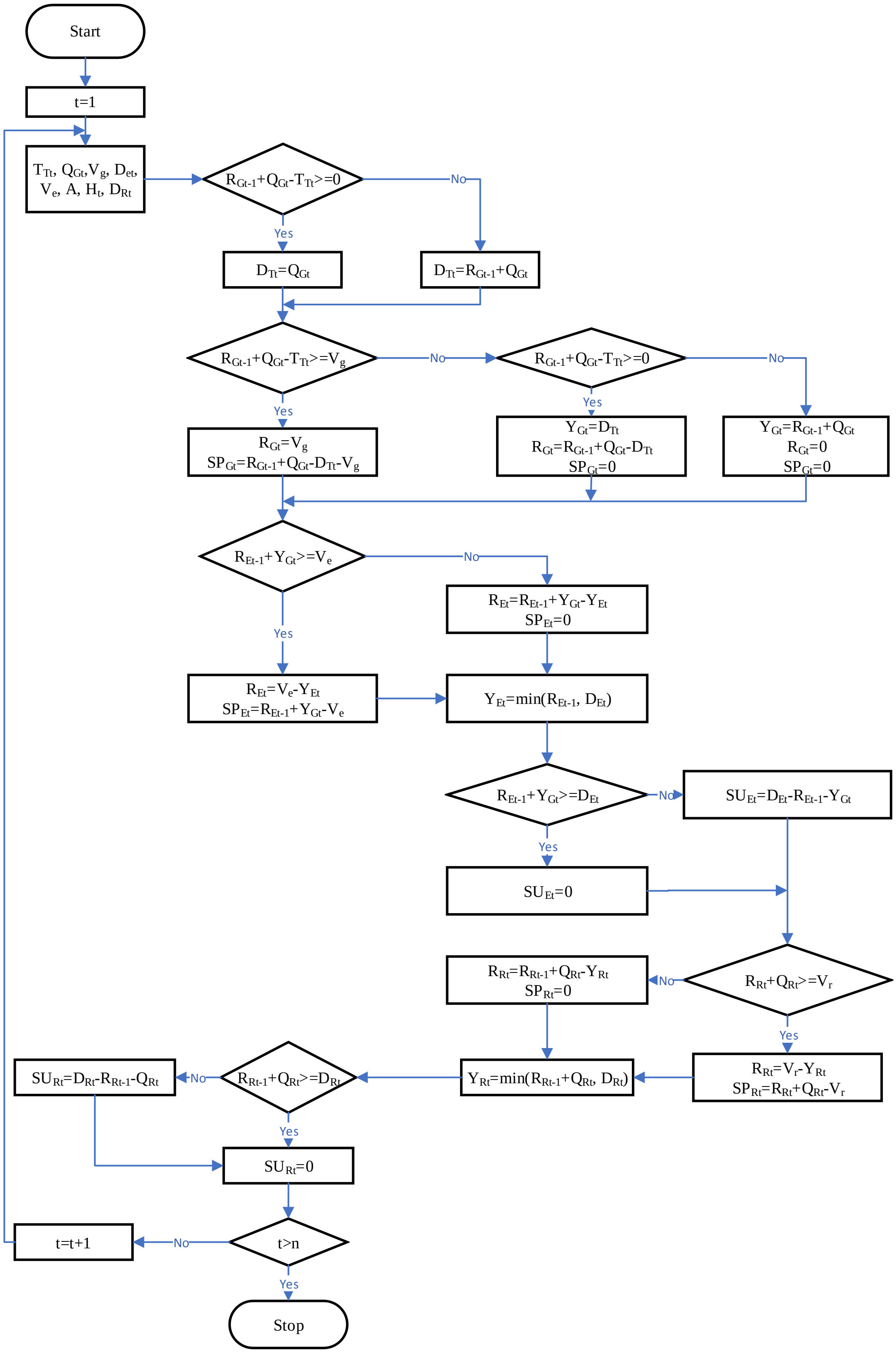

Fig3-7 Operation flow of the integrated simulation model in MATLAB

3.5 Modeling accuracy test based on actual monitoring data

According to the introduction of the simulation model, the precipitation data, capture areas, wastewater generation data, and water demand data are required to evaluate the performance of HRGs. Therefore, the simulation results obtained from the simulation model were fitted with the actual monitoring data from an HRG on the University of Kitakyushu to verify the accuracy of the model.

3.5.1 Data sources

The actual monitoring data was obtained from a running HRG on the University of Kitakyushu. An on-site survey was carried out on the campus, and a 15-year Excel formed water consumption bill of the campus and Excel formed hourly actual monitoring data of the HRG were obtained from 2002 to 2017. The above data includes the water consumption data of each water uses, rainwater and wastewater input data of the HRG, rainwater and graywater output data of the HRG, potable water supplement to rainwater tanks and rainwater supplement to graywater tanks data, and water treatment data of the rainwater and graywater subsystems. The uncertain and missing data was modified by consulting the manager of the Energy Center who is the charge of the HRG.

Fig 3-8 shows the definition of the water demand and water consumption in this study and the classification of the above data. Water demand refers to the theoretical water consumption of the water uses that need to be supplied by potable water, rainwater water, and graywater. For example, potable water demand refers to the total water for washbasins, kitchens, and showers on the campus. Rainwater demand refers to the total water for the water uses that are planned to supply by rainwater such as cooling towers, irrigation, warm water tanks, fire water tanks, and renewable energy systems. Graywater demand refers to the total water for toilets, which are planned to supply by graywater. The rainwater demand and graywater demand constitute the non-potable water demand. Among the obtained data, the water consumption data of each water use is considered as the water demand in this study.

However, due to the irregular precipitation or substandard wastewater, the HRG is often unable to provide adequate rainwater and graywater for these non-potable demands. At this time, rainwater and main water from the main water plants will be used to replenish water for these water uses to ensure a stable water supply. Therefore, water consumption refers to the actual water consumption of potable water, rainwater, and graywater. Among them, potable water is not only used to supply the water demands of washbasins, kitchens, and showers but also supply to the rainwater tanks for insufficient non-potable water demands. Rainwater is not only used to supply the water demands of cooling towers, irrigation, warm water tanks, fire water tanks, renewable energy systems but also supply to the graywater tanks for insufficient water demand for toilets. The rainwater consumption and graywater consumption constitute the non-potable water consumption. Among the obtained data, the potable water consumption consists of the potable water demand of washbasins, kitchens, and showers and the main water supplement to rainwater tanks, whereas the rainwater consumption consists the data of rainwater yielded from the HRG and the data of rainwater supplement to graywater tanks. The graywater consumption is the graywater output from the HRG.

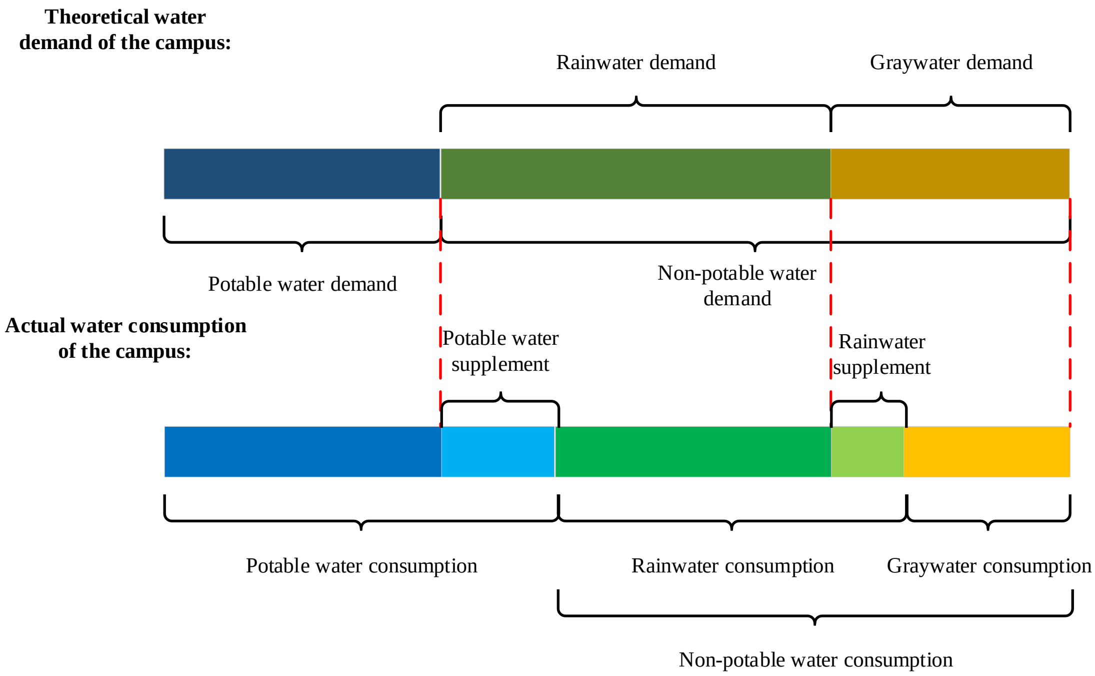

Fig 3-8 Schematic diagram of water demand and water consumption on the campus

The HRG has been running since June 2001, and the graywater subsystem of the HRG was stopped in October 2019. However, the graywater subsystem of the HRG failed frequently since 2010, resulting in substandard treated graywater production and requiring a large supplement amount of rainwater to meet the graywater demand. Therefore, the HRG provides an increasing amount of rainwater instead of providing graywater to meet the non-potable water demands of the campus.

The potable water consumption of the campus is shown in Fig 3-9. As shown in Fig 3-9, the potable water demand of the campus is affected by social activities in schools, which generally varies between 10,000 m^3 to 14,000 m^3 throughout the year. However, the amount of potable water supplement is affected by the precipitation. The highest amount of main water supplement to the HRG appeared in 2005, which is 7,772 m^3 throughout the year, because this year had the lowest precipitation from 2001 to 2017.

The rainwater consumption of the campus is shown in Fig 3-10. As shown in Fig 3-10, the HRG can stably provide approximately 6,500 m^3 to 9,700 m^3 of rainwater for non-potable water reuse before 2010. However, because of the frequent failure of the graywater subsystem, the treated rainwater has been rarely used to meet the rainwater demands of the campus since 2010 but is replenished to the reclaimed water tank of the graywater subsystem for graywater demands of the campus. This is also the reason why the amount of potable water supplement has increased year by year since 2010, although there is sufficient precipitation (Fig 3-9). From 2011 to 2017, the rainwater supplement to the graywater tanks has been increased from 3,639 m^3 to 6,511 m^3 throughout the year. The rainwater output from the HRG will be used to meet all non-potable water demands of the campus since the graywater subsystem of the HRG was completely stopped in 2019.

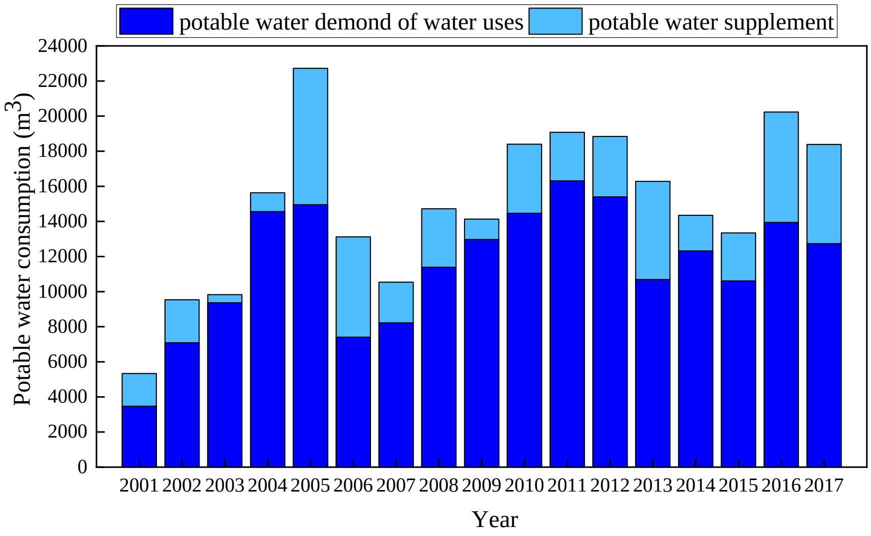

Fig 3-9 Potable water consumption of the campus from 2001 to 2017

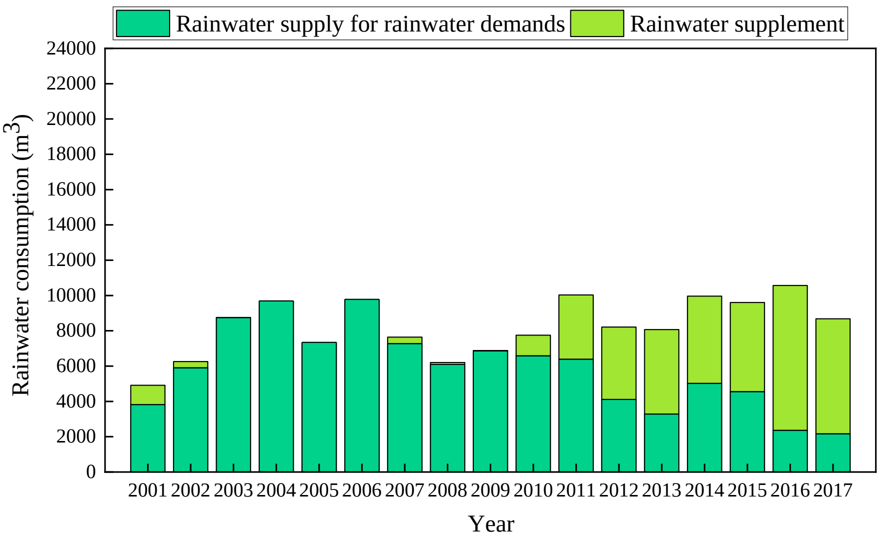

Fig 3-10 Rainwater consumption of the campus from 2001 to 2017

The graywater consumption of the campus from 2001 to 2017 is shown in Fig 3-11. The HRG can almost meet all graywater demands of the campus from 2001 to 2010, which outputs approximately 9,500 m^3 of graywater throughout the year. However, the HRG cannot provide qualified graywater since 2010 because the graywater subsystem failed frequently, and most graywater was discharged into the sewers. According to the on-site survey and consult with the manager of the HRG, the major problem of the graywater subsystem is that the aeration holes of the MBRs are blocked. Therefore, frequent cleaning of the graywater subsystem, especially the treatment unit and plumbing systems, is essential for ensuring the operational efficiency of the HRG.

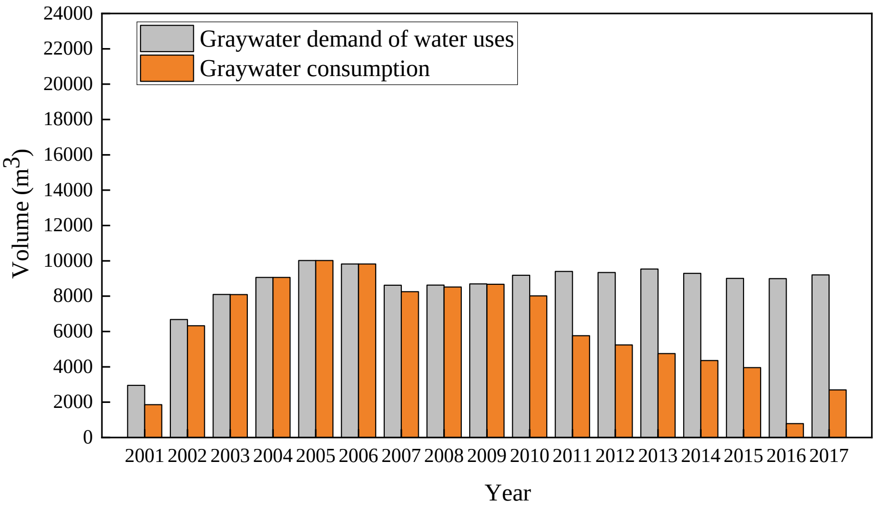

Fig 3-11 Graywater consumption of the campus from 2001 to 2017

Therefore, the non-potable water consumption of the campus is shown in Fig 3-12 and the Graywater and rainwater reuse rate of the HRG is shown in Fig 3-13. The HRG can provide non-potable water for the campus from approximately 11,356 m^3 to 19,604 m^3 throughout the year. The non-potable water supply by the HRG shows a downtrend from 2010 to 2017 because, during this period, rainwater has to meet the rainwater demand and a part of graywater demand, whereas there is not sufficient rainfall to meet the increasing demands of the campus. In the non-potable water provided by the HRG, the proportion of rainwater is approximately 42% to 52%, whereas the proportion of graywater is approximately 48% to 58%. However, since 2010, the proportion of rainwater has gradually increased from 49% to 76%, whereas the proportion of graywater has gradually decreased from 51% to 24%.

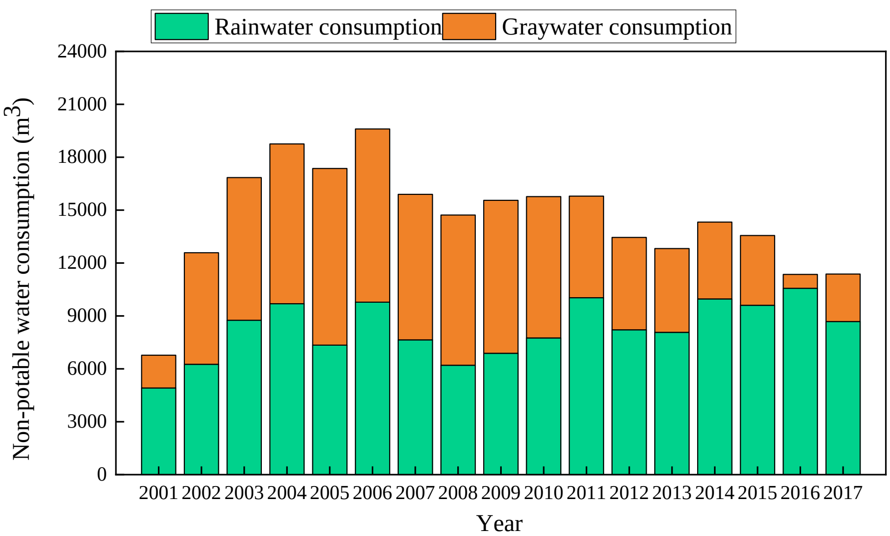

Fig 3-12 Non-potable water consumption of the campus from 2001 to 2017

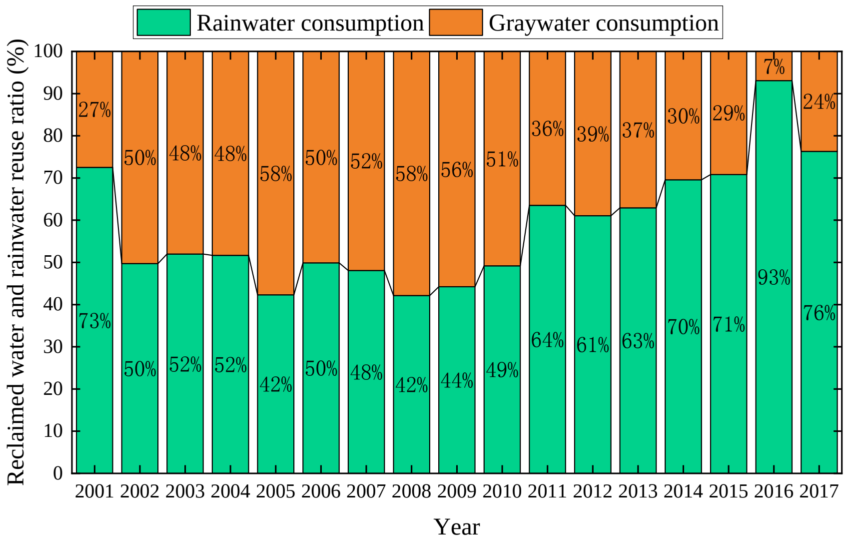

Fig 3-13 Graywater and rainwater reuse rate of the HRG from 2001 to 2017

Therefore, the actual monitoring data of the HRG can be divided into two-stage, one is from 2001 to 2010, which is the stable operation stage of the HRG, and the other is from 2011 to 2017, which is the graywater subsystem broken stage of the HRG. During the later stage, due to the frequent maintenance of the graywater subsystem, a large amount of daily actual monitoring data of the graywater subsystems was missing, although the full-year data can be calculated. Therefore, in the fitting process, the more stable data of the graywater subsystem from 2002 to 2010 was selected to fitting with the results obtained for the simulation model of HRGs because hourly or daily data is required for accurate results. Similarly, actual monitoring data of the rainwater subsystem from 2002 to 2014 was selected to fit with the results of the rainwater subsystem obtained by the simulation model to give up missing data.

According to the ranges of the actual monitoring data, the precipitation data of Kitakyushu from 2002 to 2014 was collected from Japan Meteorological Agency and was selected to simulate the performance of the HRG [35]. The trend of precipitation in Kitakyushu is shown in Fig 3-14. The study area is a precipitation-rich city and the local climate is warm and humid throughout the year, with an average annual precipitation of 1,862.5 mm. As shown in Fig 3-14 that the precipitation in Kitakyushu is unimodal, with higher precipitation in June, July, and August, and lower precipitation in December, January, and February. Kitakyushu has almost no snow all year round, thus rainwater can be effectively collected by the local buildings for non-potable water reuse throughout the year.

The capture areas of the served area by the HRG were calculated by the mapping function of Google Earths, and the calculation results are listed in Table 3-1. The capture areas of Teaching Building and Experiment Building are the highest with 6,158 m^2, whereas the capture areas of Conference Center are the smallest with 446 m^2. The total capture areas of the campus are approximately 10,632 m^2. It is worth pointing out that the capture area of all buildings on the campus is only considered the roof.

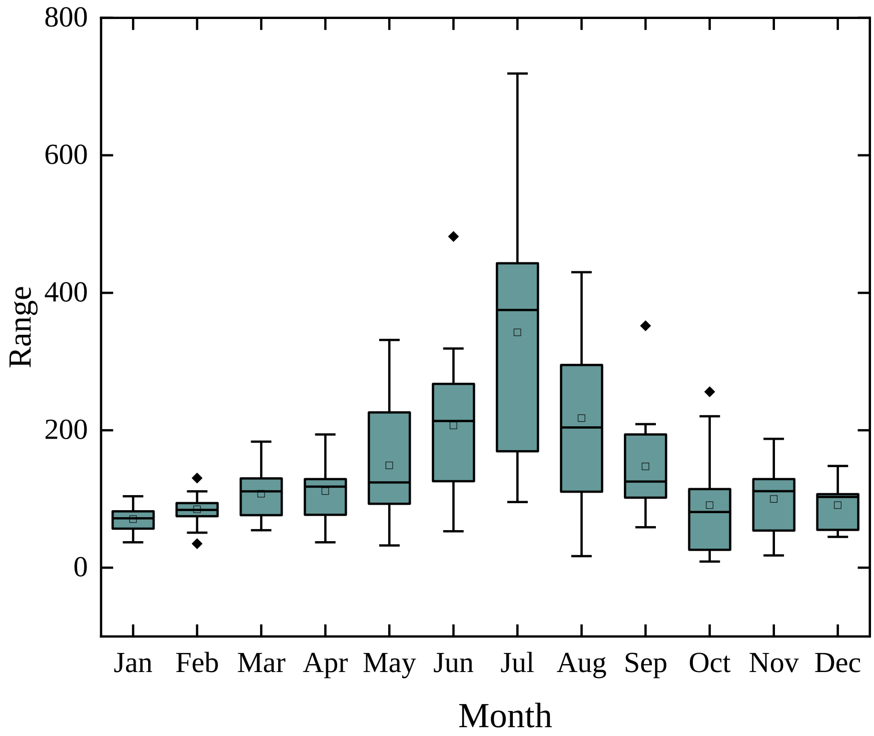

Fig 3-14 Precipitation in Kitakyushu from 2002 to 2014

Table 3-1 The capture areas of each served building by the HRG

Types	Construction areas	Capture areas	Rainwater harvesting	Graywater collecting
Energy Center	-	-	No	No
Teaching Building and Experiment Building	35,060.00 m^2	6,158 m^2	Yes	Yes
Gym	1,661.50 m^2	2,056 m^2	Yes	Yes
Canteen	1,109.00 m^2		Yes	Yes
Media Center	7,250.55 m^2	1,347 m^2	Yes	Yes
Collaboration Center	5,844.86 m^2	625 m^2	Yes	Yes
Conference Center	2,288.44 m^2	446 m^2	Yes	Yes

The actual monitoring data of each water uses and the graywater generation data from 2002 to 2010 were used to input into the MATLAB as the non-potable water demands and wastewater input, respectively, during the simulation process to obtain the simulation results of the HRG including rainwater output (rainwater consumption), potable water supplement, rainwater overflow, wastewater input (treatment capacity), wastewater overflow, graywater consumption, and graywater overflow. The rainwater output result includes the rainwater supplement because for the subsequent feasibility evaluation of HRGs, the output of the simulation model is more concerned with the total rainwater and graywater output of HRGs rather than the mutual complementation within such systems (equation (3-19)).

3.5.2 Simulation fitting

The simulation results and the fitting curves of the rainwater tank of the HRG are shown in Fig 3-15.

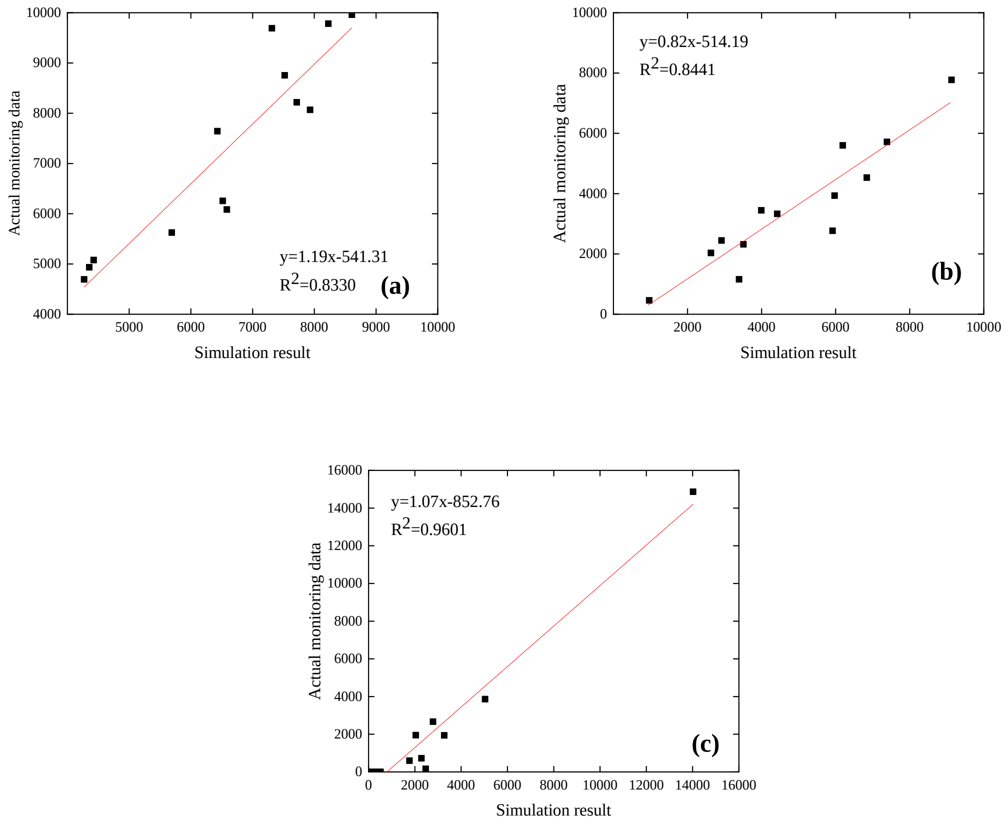

Fig 3-15 The simulation results and the fitting curves of the rainwater tank of the HRG ((a) rainwater output, (b) potable water supplement, and (c) rainwater overflow)

As shown in Fig 3-15, the simulation model of HRGs can effectively reappear the operating state of the rainwater tank. The R^2 between the simulation results of rainwater output, potable water supplement, and rainwater overflow and the actual monitoring data of the HRGs is 0.8330, 0.8441, and 0.9601, respectively. One of the factors affecting the simulation results is the measurement and assumption of the capture areas because precipitation cannot always be harvested by 100% of the capture areas and the evaporation of rainwater is assumed to be a constant value. This will overestimate or underestimate the rainwater harvesting efficiency of HRGs in buildings. In addition, the actual operation stage of the HRGs will also affect the final fitting results because the HRG will artificially empty and refill the rainwater tank according to the actual situation during the actual operation, which are processes that cannot be considered by the simulation model of HRGs.

The simulation results and the fitting curves of the wastewater tank of the HRG are shown in Fig 3-16.

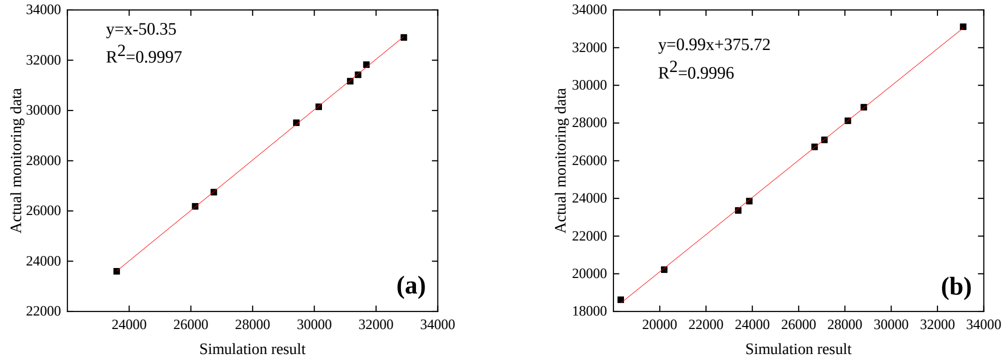

Fig 3-16 The simulation results and the fitting curves of the wastewater tank of the HRG ((a) wastewater output, (b) wastewater overflow)

As shown in Fig 3-16, the fitting results of wastewater output and wastewater overflow between the simulation results and actual monitoring data can reach 0.9997 and 0.9996, respectively because the graywater generation is stable throughout the year and the short-term artificial emptying process has fewer effects on the simulation results. In addition, the wastewater overflow of the simulation results refers to the volume of the wastewater discharged from buildings, which illustrated that light wastewater is preferentially collected from parts of water uses according to the graywater demand and the wastewater generated by other water uses can be discharged into the sewer.

The simulation results and the fitting curves of the graywater tank of the HRG are shown in Fig 3-17.

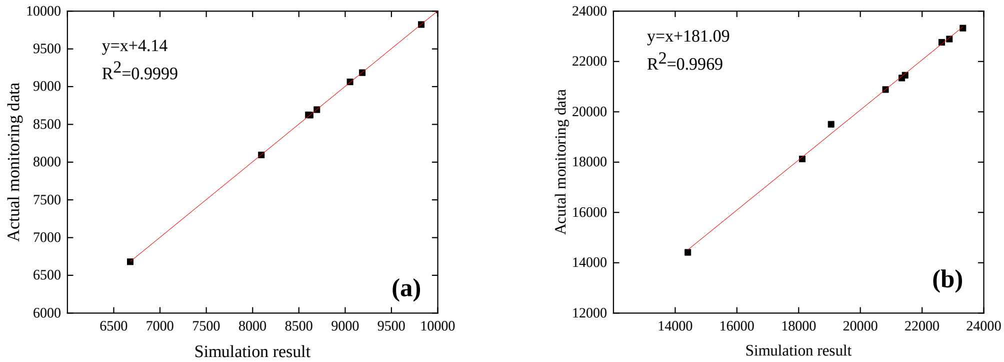

Fig 3-17 The simulation results and the fitting curves of the graywater tank of the HRG ((a) graywater output, (b) graywater overflow)

As shown in Fig 3-17, similar to the simulation of the wastewater tank, the fitting results of graywater output and graywater overflow between the simulation results and actual monitoring data can reach 0.9999 and 0.9969, respectively. Graywater overflow refers to the waste of these graywater because the graywater demand of the building will intermittently decrease during holidays and weekends, whereas the production of wastewater from water end uses will be stable throughout the year.

3.6 Summary

In this chapter, we introduce and model the basic study method, the simulation model of HRGs, and fit the simulation results with actual monitoring data of an HRG to verify the accuracy of the proposed model.

Firstly, we model the simulation model for evaluating HRGs based on the water balance model, which is tailored for evaluating RWHs in buildings. The YAS algorithm and YBS algorithm are modified for determining the water balance of the rainwater tank, wastewater tank, and graywater tank in HRGs. Therefore, the simulation model of HRGs can output the rainwater output, wastewater output, graywater output, rainwater overflow, wastewater overflow, graywater overflow, and potable water supplement for subsequent evaluating and calculating the performance of HRGs.

Secondly, the simulation model is achieved in MATLAB. The input data for simulation includes the precipitation data, capture areas, rainwater demand, graywater demand, and wastewater generated from buildings. Furthermore, the simulation model of HRGs can simultaneously evaluate the performance of RWHs, GWRs, and HRGs by setting the corresponding parameter to 0.

Finally, we carried out an on-site survey of the HRG on campus and obtained the actual monitoring data of the HRG that was used to fit with the simulation results. The results show that the simulation model of HRGs can accurately and simply reappear the operation of HRGs to evaluate and optimize the performance and scale of such systems.

The simulation model of HRGs proposed in this chapter can make the evaluation of HRGs no longer based on the simple assumption of water quantity balance and incorrectly evaluate the performance of such systems, improve the accuracy of evaluation and optimization results, and has high practical value and promotion significance.

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Chapter 4

ENVIRONMENTAL AND ECONOMICAL BENEFITS OF HRGS IN PUBLIC BUILDINGS

Contents

4.1 Content

The development of hybrid rainwater-graywater systems (HRGs) has greatly alleviated urban water scarcity. However, the HRGs in public buildings have rarely been explored, which had limited the popularity of hybrid systems. In addition, previous studies on evaluating HRGs have focused on ideal systems and hypothetical scenarios of water conservation, which may result in an overestimation of the water-saving efficiency brought by implementing HRGs. In this chapter, a campus in Japan was selected to evaluate the feasibility of HRGs in public buildings. The simulation model based on the water balance model with an hourly time step was performed to quantify the performance of the rainwater and graywater subsystems in the HRGs. Second, the electricity consumption of the HRGs was evaluated. Then, a detailed life cycle cost model was designed to calculate the economic benefit of the HRGs under the current and optimization scenarios. Finally, the results obtained are compared with HRGs in residential and commercial buildings to discuss the advantages of HRGs in public buildings. The results indicate that the promotion of HRGs in public buildings can not only achieve higher water-saving efficiency than other building types but also reduce electricity consumption in comparison with the traditional water supply methods. The economical unfeasibility of HRGs is caused by the waste of excess graywater and high maintenance costs. HRGs in public buildings has the potential to be promoted preferentially in regions where the water tariff is higher than 880 JPY/m^3 or the non-potable water tariff is set to at least 200 JPY/m^3.

4.2 Introduction

Rainwater and graywater are two common alternative water sources that can be reused in buildings because several water uses do not require high-quality water, such as toilets [1], urinals [2, 3], washing machines [4], and irrigation [5-7]. The water consumption of these water uses accounts for more than 20% of the total water consumption in a building [8], especially in a non-residential building, where these uses account for more than 50% [9, 10]. Non-potable water in a building can be appropriately substituted by rainwater or graywater to alleviate water scarcity and the pressure on the urban water supply caused by mounting population density and changing precipitation patterns [11]. Thus, the installation of water reuse systems such as rainwater harvesting systems (RWH), graywater recycling systems (GWR), or hybrid rainwater-graywater systems (HRG), is recommended or mandated in new buildings in some countries to harvest and utilize rainwater and graywater for non-potable water reuse. An insufficient evaluation of the systems before installation will result in additional failure and maintenance costs [12]. Feasibility evaluations of RWHs, GWRs and HRGs in different regions and building types is essential for promoting the implementation of water reuse systems [13-16] .

Potable water-saving efficiency is greatly limited by installing RWH and GWR separately. Ghisi and Mengotti de Oliveira [17] investigated two residential buildings in Brazil that installed RWH and GWR. The results demonstrated that the potable water-saving efficiency could reach 35.5% and 33.6% for RWH and 30.4% and 25.6% for GWR by installing the two systems separately, whereas the potable water-saving efficiency could reach 36.4% and 33.8%, respectively, by reusing rainwater and graywater together. The performance of RWH is also susceptible to the local climate conditions [18]. For example, the reliability of a water supply by RWH is not ensured due to the changes in precipitation patterns caused by global warming in the next 30 years in China until the current rainwater storage of RWH has expanded [19]. Furthermore, the economic benefits of RWH are affected by the climate-dependent water supply method in different regions. The installation and maintenance costs can be recovered by RWH in rainy Bangladesh within 2–6 years [20], whereas the benefit-cost ratio of RWH is less than 1.0 in a city in Pakistan, which is located in cold semi-arid and warm desert areas because the scarce rainfall cannot meet the water demand [21]. A similar conclusion was also found by Jing, Zhang [22] in China. The authors indicated that the economic feasibility of reasonably designed RWH is achieved in humid and semi-humid regions rather than in arid regions. Graywater, as an alternative non-potable water, is more stable than rainwater and can meet the non-potable water demand, but the water quality of graywater is poorer than that of rainwater [23]. Thus, compared with RWH, the water conservation of GWR is more reliable, but the spread of GWR is hindered by the expensive investment cost. In Syrian residential buildings, the payback period of GWR using an artificial wetland (AW) with poor effluent quality for graywater treatment is 7 years, while the payback period of using a commercial biofilter (CBF) for GWR, with higher effluent quality, is as long as 52 years [24]. A membrane reactor (MBR) is favorable for GWR because of its small scale and uses less electricity consumption [25], but the cost of graywater treatment processes combined with MBR is higher than that of other conventional processes [26]. Friedler and Hadari [27] found that the MBR-based GWR is economically feasible under a water tariff of 121 JPY/m^3 in a 40-story residential building or residential area, whereas the economic benefit of GWR with a rotating biological contactor (RBC) can be achieved within 15 years in a 7-story residential building under the same water tariff scenario. Arden, Morelli [28] determined that the cost parity of an MBR-based GWR can be realized under the water tariff of 192 JPY/m^3 in a large building in the United States. In addition, Oh, Leong [29] do not recommend reusing graywater for irrigation in Malaysia because it may have negative long-term impacts on the soil. An HRG can not only harvest and supply rainwater and graywater simultaneously to improve the potable water-saving efficiency, but also avoid the insufficient water supply of RWH during the dry monsoon period and alleviate the effects of using the lower-quality graywater. Furthermore, an HRG reduces storm runoff and wastewater volume discharged into the sewer for comprehensive environmental benefits. However, due to its complex structure and high costs, HRGs have been primarily installed on "Green Buildings" that aim to achieve the lowest environmental impact [30]. In order to apply HRG widely, it is necessary to systematically explore HRG's operating characteristics in different scenarios.

Previous studies on HRG are limited to residential and commercial buildings and have focused on its water-saving and environmental impacts. Marinoski and Ghisi [31] presented a life cycle assessment (LCA) method to evaluate the performance of an HRG in a single-family residential building in Brazil. The results indicated that a 41.9% water-saving efficiency, 40% draining reduction rate, and 36.1% energy consumption reduction rate were achieved by the HRG. Leong, Chong [32] quantified the water-saving performance of hypothetical HRGs in a commercial building and a residential building in Malaysia based on the RainTANK model for the rainwater subsystem and a simple continuous mass balance model for the graywater subsystem. The authors indicated that in terms of water-saving efficiency, the HRG in the commercial building should prioritize graywater and harvest rainwater to meet the remaining water demand, while the HRG in the residential building should primarily reuse rainwater.

The economic benefits of the HRG have not been fully evaluated. Ghisi and Mengotti de Oliveira [17] presented a simple economic model to simulate the economic benefits of using rainwater and graywater in a single family in southern Brazil. The authors indicated that the payback period of this scenario is more than 28 years. However, the result only considered that rainwater and graywater are independent water sources and cannot reflect the unique economic characteristics of an HRG. Leong, Balan [33] carried out LCA and life cycle cost (LCC) methods of water reuse systems in a commercial building and a residential building and indicated that the commercial HRG is financially attractive under the water tariff of 542 JPY/m^3, whereas a residential HRG is financially infeasible. However, the authors simplified the water demand of the buildings and the operation process of the HRG, and the results obtained may have underestimated the life cycle cost of the HRG. Public buildings, especially campus buildings, have various situations of non-potable water demand such as cleaning and sanitation [10, 34]. Water reuse systems in campus buildings may achieve greater feasibility than other building types [35]. Evaluating the environmental performance and economic benefits of HRG in public buildings, which is a largely underexplored domain, has far-reaching significance for the promotion of HRGs from “Green Buildings” to urban areas.

This chapter aims to evaluate the feasibility of HRG in a public building for extending the HRG to a wider range of building types, which is critical in the initial stages of HRG development. Therefore, the HRG mentioned in Chapter 2 was selected as a case study in this chapter. The water-saving performance, operational electricity consumption, and economic benefit of the HRG were evaluated using a water balance model and a life cycle cost model based on actual monitoring data. Finally, the results obtained were compared with those of previous studies to discuss the feasibility of HRG in public buildings. The results obtained can be used as a comparison tool for other studies and provide data support for stakeholders to popularize HRG. In addition, the models proposed can provide new ideas for the design and optimization of HRG in the future.

4.3 Methodology

4.3.1 Data sources

The location of the study area and the lay out of the HRG are shown in Fig 4-1 and Fig 4-2, respectively. An on-site survey was carried out on the campus, and a 15-year water consumption bill of the campus and hourly monitoring data of the HRG were obtained from 2002 to 2017. In addition, the economic data of the HRG from 2002 to 2017 were collected from the historical records at the Energy Center.

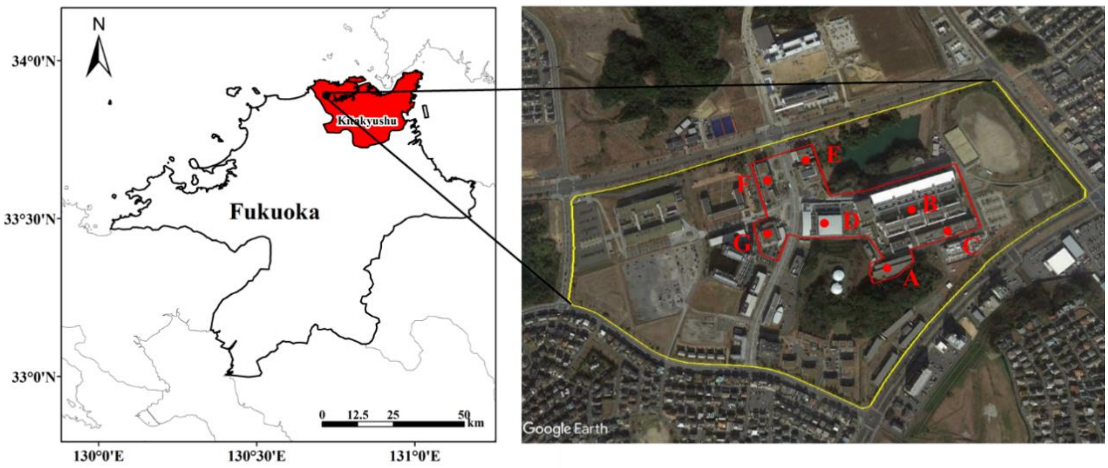

Fig 4-1 Location of the study area
(A. Energy Center; B. Teaching Building; C. Experiment Building; D. Gym and Canteen; E. Media Center; F. Collaboration Center; G. Conference Center.)

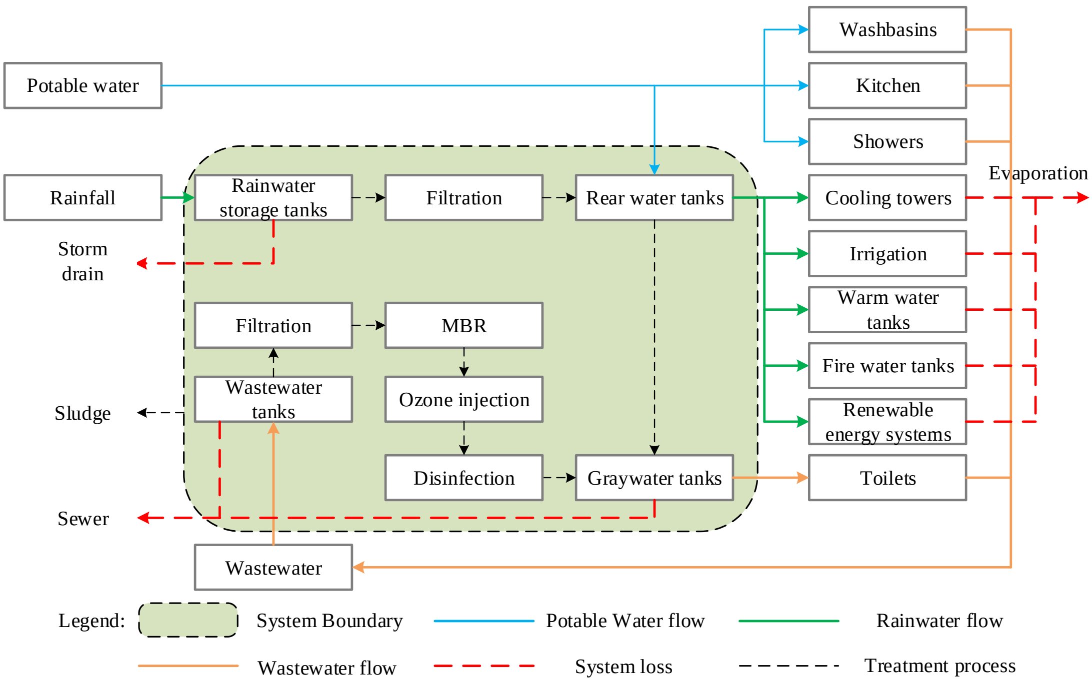

Fig 4-2 Layout of the HRG on the campus

4.3.2 Performance indicators of the HRG

The water-saving efficiency refers to the percentage of the total potable water consumption that can be reduced by the HRG (%). The non-potable water replacement rate refers to the ratio of the rainwater and reclaimed water yield of the HRG to the non-potable water demand (%). The above indices are calculated by Equations (4-1) and (4-2):

$$Water\ saving\ efficiency = 100\% \times \frac{\sum Y_{HRG}}{\sum D_p + \sum D_n} \tag{4-1}$$

$$Non-potable\ water\ replacement\ rate = 100\% \times \frac{\sum Y_{HRG}}{\sum D_n} \tag{4-2}$$

where Y_{HRG} is the non-potable water output by the HRG (m^3); D_p is the potable water demand (m^3); and D_n is the non-potable water demand of water end uses (m^3).

The non-potable water supply capability (NSC, %) is defined as the percentage of the time that the HRG can reliably provide a stabilized water supply without being supplemented by the potable water in a year:

$$NSC = 100\% \times \frac{N_{tot} - N_{sup}}{N_{tot}} \tag{4-3}$$

where N_{tot} is the total number of hours in a year of 8,760 h; N_{sup} is the number of hours that the potable water supplements to the HRG when the non-potable water output from the HRG cannot meet the demand (h).

In order to quantify the rainwater and graywater utilization efficiency of the HRG, the rainwater utilization rate (%), the wastewater utilization rate (%), the wastewater treatment rate (%), and the graywater utilization rate (%) are presented as:

$$Rainwater\ utilization\ rate = 100\% \times \frac{\sum Y_R}{\sum Q_R} \tag{4-4}$$

$$Wastewater\ utilization\ rate = 100\% \times \frac{\sum Y_E}{\sum Q_G} \tag{4-5}$$

$$Wastewater\ treatment\ rate = 100\% \times \frac{\sum Y_G}{\sum Q_G} \tag{4-6}$$

$$Graywater\ utilization\ rate = 100\% \times \frac{\sum Y_E}{\sum Y_G} \tag{4-7}$$

where Y_R is the rainwater output from the rainwater subsystem (m^3); Q_R is the rainwater input to the HRG (m^3); Y_E is the graywater output from the graywater subsystem (m^3); Q_G is the wastewater input to the HRG (m^3); and Y_G is the output of wastewater treated by the graywater subsystem and the volume of graywater input to the graywater tanks (m^3).

4.3.3 Electricity consumption

The electricity consumption of the HRG's pumps is calculated as:

$$E_p = \frac{P \times H}{\eta} + \frac{P_s \times h}{1000} \tag{4-8}$$

where E_p is the electricity consumption of the pump (kWh); P is the rated power of the pump (kW); H is the working hours of the pump (h); and η is the efficiency of the pump (%), which was 65% in this chapter [36]; P_s is the standby power of the pump (%), which is 2 W recommended by Retamal, Turner [37]; and h is the standby hours of the pump (h).

For devices that have actual monitoring data of the operation voltage and operation current, Equation (4-8) can be modified by:

$$E_p = \frac{U_{rm} \times I_{rm} \times H}{1000} + \frac{P_s \times h}{1000} \quad (4\text{-}9)$$

where U_{rm} is the actual voltage of the device (V); and I_{rm} is the current of the device (A).

4.3.4 Economic feasibility

The life cycle cost of the HRG includes the initial investment cost of the equipment, cost of the operation and maintenance (O&M), and dismantling cost of the equipment. The specific calculation is as follows:

$$COST_{HRG} = COST_{Ini} + COST_{O\&M} + COST_{Dis} \quad (4\text{-}10)$$

where $COST_{HRG}$ is the life cycle cost of the HRG (JPY); $COST_{Ini}$ is the initial investment cost (JPY); $COST_{O\&M}$ is the cost of the O&M (JPY); $COST_{Dis}$ is the disassembly cost (JPY). Because the dismantling process has less impact on the results [33] and the HRG in the campus is still operating, the dismantling cost of the HRG was not considered in this chapter.

The initial investment cost of the HRG can be determined by:

$$COST_{Ini} = COST_r + COST_g \quad (4\text{-}11)$$

where $COST_r$ is the cost of the rainwater subsystem (JPY); and $COST_g$ is the cost of the graywater subsystem (JPY).

The details of the operation and maintenance costs are as follows:

$$COST_{O\&M} = \sum COST_{Op} + \sum COST_{Ma} \quad (4\text{-}12)$$
$$COST_{Op} = \sum COST_{El} + \sum COST_{Co} + \sum COST_{Sl} + \sum COST_{Ot} \quad (4\text{-}13)$$
$$COST_{Ma} = \sum COST_{In} + \sum COST_{Re} + \sum COST_{MBR} \quad (4\text{-}14)$$

where $COST_{Op}$ is the operation cost of the HRG (JPY); $COST_{Ma}$ is the annual maintenance cost (JPY); $COST_{El}$ is the annual electricity tariffs (JPY), and the electricity fee is set as 23.7 JPY/kWh [38]; $COST_{Co}$ is the consumables cost of the HRG, including disinfectants and aeration nozzles (JPY); $COST_{Sl}$ is the cost of sludge dehydration and transportation to the sludge treatment plant (JPY); $COST_{Ot}$ is the extra budget of the HRG (JPY); $COST_{In}$ is the annual inspection of the HRG (JPY); $COST_{Re}$ is the repair costs, including the replacement costs of pumps, valves, and other accessories (JPY); $COST_{MBR}$ includes the cleaning and replacement cost of the hollow fiber membrane (JPY), and the life cycle of the hollow fiber membrane is 5 years for the MBR.

Net present value (NPV) is used to determine the economic benefits of the HRG over the life cycle:

$$NPV = \sum_{T=0}^{n} \frac{BENEFIT_T - COST_{O\&M,T} - COST_{Inv}}{(1+i)^T} \tag{4-15}$$

where n is the served life of the HRG; $BENEFIT_T$ is the annual benefit (JPY); i is the discount rate (%), which was 3.5% in this chapter [39]. The benefit of the HRG is as follows:

$$BENEFIT_T = \sum BENEFIT_W + \sum BENEFIT_D \tag{4-16}$$

where $BENEFIT_W$ is the water tariff savings (JPY), and $BENEFIT_D$ is the draining tariff savings (JPY). The water tariff and the draining tariff are listed in Table 4-1 and Table 4-2. The calculation method is based on the Kitakyushu Waterworks Bureau [40].

Table 4-1 The water tariffs of the Kitakyushu, Japan

Types	Price						
Water tariffs	Base	1 m^3-25 m^3	26 m^3-50 m^3	51 m^3-200 m^3	201 m^3-1,000 m^3	1,001 m^3-10,000 m^3	10,001 m^3
	4,500 JPY	124 JPY/m^3	158 JPY/m^3	210 JPY/m^3	290 JPY/m^3	325 JPY/m^3	335 JPY/m^3

Table 4-2 The draining tariffs of the Kitakyushu, Japan

Types	Price						
Draining tariffs	Unless 20 m^3	21 m^3-50 m^3	51 m^3-100 m^3	101 m^3-400 m^3	401 m^3-2,000 m^3	2,001 m^3-20,000 m^3	20,001 m^3
	1,268 JPY	141 JPY/m^3	208 JPY/m^3	257 JPY/m^3	307 JPY/m^3	407 JPY/m^3	412 JPY/m^3

4.3.5 Economic optimization scenarios

In order to explore the potential economic benefits of the HRG, an economic optimization analysis was performed. Four hypothesis scenarios were proposed and implemented based on the current operation status to optimize the economic benefits of the HRG on the campus.

(1) Scenarios description

1. Scenario 1: The current users of the HRG are charged non-potable water tariffs based on the water volume they use, and the excess rainwater and graywater are discharged to sewers as normal.
2. Scenario 2: The current users use the non-potable water supplied by the HRG for free, and the excess rainwater and gray water will be sold to other users or be discharged profitably to rivers.
3. Scenario 3: All the non-potable water yielded from the HRG is charged the non-potable

water tariff.

4. Scenario 4: Because the highest water tariffs in cities under the same climatic conditions in Japan are more than twice that of Kitakyushu, the potable water tariff of Kitakyushu is increased to three times the current rate at 20% intervals to hypothetically explore the economic potential of the HRG under different water tariffs.

(2) Operation assumptions

It is assumed that the annual O&M cost of the HRG cannot be changed within a certain period, and the life cycle of the HRG is 15 years.

(3) Non-potable water tariff assumptions

Given that the highest standard of water tariff in Kitakyushu is 335 JPY/m^3 (Table 4-1), the non-potable water tariff that exceeds this threshold will not be attractive for investments. Thus, the non-potable water tariff of assumption scenarios is assumed to be 0 JPY/m^3, 100 JPY/m^3, 200 JPY/m^3, 300 JPY/m^3, and 400 JPY/m^3, respectively. It should be noted that there is no basic fee for non-potable water tariffs.

4.4 Results and discussion

4.4.1 Water end-uses inventory

Marinoski and Ghisi [31] recommended obtaining at least 12 months of water consumption data to verify the seasonal impacts. Therefore, the actual monitoring data of the water bills from 2006 were selected as a typical year for analysis in this chapter, because there are no data missing throughout the year. The water demands of the campus are listed in Tables 4-3, Table 4-4, and Table 4-5.

As shown in Table 4-3, the potable water demand of the campus peaked in July and August, and the trend of the hot water demand was the opposite because hot water is predominantly consumed in the bathroom of the Gym, which is used less frequently in summer. However, the potable water demand of the Experiment Building peaked in January, and the annual potable water demand of the Experiment Building accounted for the largest share (49.33%) of total potable water demand on the campus.

Table 4-3 Potable water demands of the campus (m^3)

Month	Teaching building	Experiment Building	Collaboration Center	Energy Center	Gym	Media Center	Hot water tanks	Total
Jan.	61	971	48	27	11	46	120	1,284
Feb.	48	521	48	27	9	44	109	806
Mar.	65	118	56	29	9	47	92	416
Apr.	55	189	55	29	7	47	103	485
May.	62	177	61	28	8	52	110	498
Jun.	82	238	68	30	8	59	103	588
Jul.	78	224	72	31	6	73	92	576
Aug.	79	228	80	34	3	55	67	546

Continued from Table 4-3

Month	Teaching building	Experiment Building	Collaboration Center	Energy Center	Gym	Media Center	Hot water tanks	Total
Sep.	61	208	65	30	0	46	54	464
Oct.	82	266	67	29	0	51	107	602
Nov.	86	284	63	28	0	36	107	604
Dec.	63	230	55	28	11	26	125	538
Total	822	3,654	738	350	72	582	1,189	7,407
Percent	11.1%	49.33%	9.96%	4.73%	0.97%	7.86%	16.05%	100%
Ave.	617 m^3 per month or 20 m^3 per day							

It can be seen from Table 4-4 that the non-potable water of toilets in the Teaching Building, Media Center, and Experiment Building are higher than others, accounting for 32.44%, 23.48%, and 22.85% of the total toilet water demand on the campus, respectively. Moreover, the toilet water demand of the campus is stable but lower in March and September because the periods include holiday breaks.

As shown in Table 4-5, the cooling towers account for the highest annual water demand (95.29%) and the irrigation water demand is lower in January, November, and December. The chiller-heater water tank is primarily responsible for supplying water to the space cooling and heating system; thus, the water replenishment of the water tank in summer (July, August, and September) is usually greater than during other seasons.

Table 4-4 Non-potable water demands for toilets of the campus (m^3)

Month	Teaching building	Experiment Building	Collaboration Center	Conference Center	Gym	Media Center	Total
Jan.	239	196	100	6	41	197	779
Feb.	240	181	101	2	40	192	756
Mar.	206	160	111	15	42	152	686
Apr.	277	171	106	9	51	180	794
May.	300	206	105	6	77	211	905
Jun.	307	230	108	4	73	208	930
Jul.	284	232	99	24	58	216	913
Aug.	234	155	137	8	37	239	810
Sep.	178	135	97	5	26	116	557
Oct.	310	204	114	15	76	184	903
Nov.	309	229	113	26	75	184	936
Dec.	302	207	104	16	59	165	853
Total	3,186	2,306	1,295	136	655	2,224	9,822
Percent	32.44%	23.48%	13.18%	1.38%	6.67%	22.85%	100%
Ave.	819 m^3 per month or 27 m^3 per day						

Table 4-5 Non-potable water demands for other water uses of the campus (m^3)

Month	Cooling towers	Irrigation	Chiller-heater water tanks	Fire water tanks	Energy systems	Total
Jan.	40	1	3	0	5	49
Feb.	16	2	1	0	5	24
Mar.	73	2	2	0	8	85
Apr.	164	2	4	0	5	175
May.	211	4	6	0	2	223
Jun.	2,333	2	25	0	1	2,361
Jul.	7,064	2	42	0	3	7,111
Aug.	2,896	3	63	0	6	2,968
Sep.	1,260	2	32	3	207	1,504
Oct.	772	2	18	0	215	1,007
Nov.	25	1	3	0	5	34
Dec.	25	2	40	0	7	74
Total	14,879	25	239	3	469	15,615
Percent	95.29%	0.16%	1.53%	0.00%	3.02%	100%
Ave.	1,301 m^3 per month or 43 m^3 per day					

The monthly trend of water demand on the campus in a typical year was shown in Fig 4-3. According to Fig 4-3, the total water demand trend of the campus surges in June, July, and August, and the total water demand in the remaining months is relatively stable. Therefore, the water demand characteristics of public buildings have obvious seasonal differences.

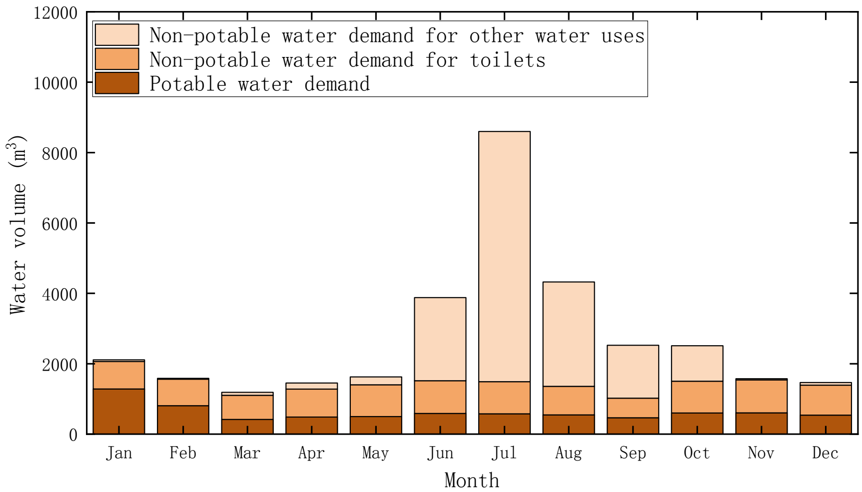

Fig 4-3 Monthly trend of water demand on the campus in a typical year

4.4.2 Water-saving performance analysis

(1) rainwater subsystem

The operating status of the rainwater subsystem during the year is shown in Fig 4-4 and Table 4-6.

Table 4-6 Water supply insufficiency and rainwater overflow of the rainwater subsystem

	Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Insufficient rainwater supply hours	10	0	0	0	0	0	299	375	0	145	0	0
Insufficient rainwater supply days	6	0	0	0	0	0	19	22	0	14	0	0
Main water supplement (m^3)	10	0	0	0	0	0	4,200	1,971	0	390	0	0
Rainwater overflow (m^3)	0	0	0	398	130	737	0	0	0	0	0	443

As shown in Fig 4-4, the monthly rainwater input and output of the rainwater subsystem are inconsistent, which has led to the inevitable situations of insufficient rainwater supply and rainwater overflow in some months. The annual NSC of the rainwater subsystem is between 29.03% (August) and 100%. Because of the large water demand of the cooling towers from July to September, the rainwater subsystem becomes unreliable and can only meet the water demand one-third of the time (12 days in July and 9 days in August). In addition, in Table 4-6, part of the harvested rainwater is overflowed to the storm drain in April (398 m^3), May (130 m^3), June (737 m^3), and December (443 m^3) due to lower demand, which caused the utilization rate of the rainwater subsystem to be 77.17% for the year.

This result is consistent with previous studies that showed that the NSC and rainwater utilizing efficiency of the RWH is lower in regions with little rainfall or more rainfall throughout a year but is not concentrated in a period of considerable water demand [21, 22, 41]. In these regions, larger rainwater tanks are needed to capture more rainfall to solve the rainwater supply insufficiency. However, a larger water tank requires more floor space and construction costs [42]. Therefore, balancing the size and the cost of the rainwater tank is a key indicator for the RWH and HRG design.

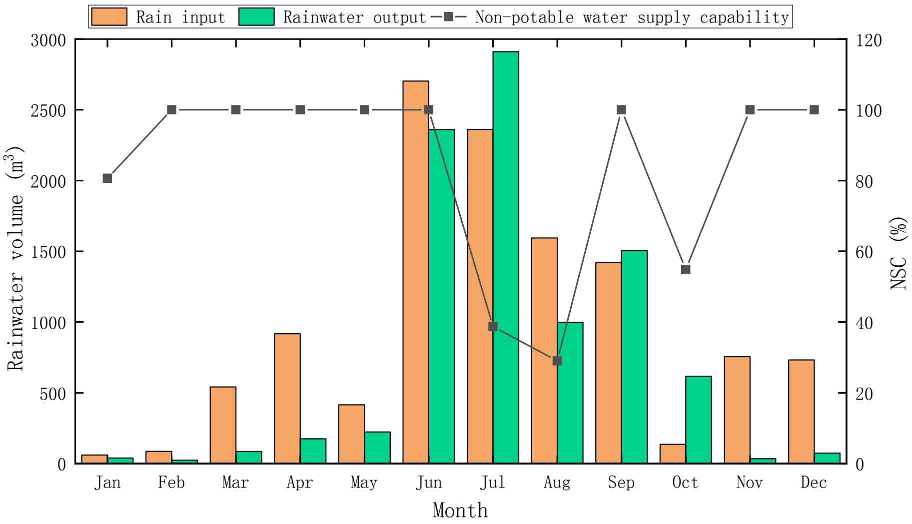

Fig 4-4 Rainwater input and output of the rainwater subsystem and the non-potable water supply capability of the HRG

(2) Graywater subsystem

The operating status of the graywater subsystem during the year is shown in Fig 4-5. According to Equation (4-6) and Fig 4-3, 51.94% of the collected wastewater was treated by the graywater subsystem of the HRG during the year. The monthly wastewater treatment rate ranges from 48.45% to 56.67%. However, the graywater reuse is only 31.52% per year (monthly graywater utilization rate is from 26.18% to 35.16%) and the wastewater utilization rate is approximately 16.37% per year, with the monthly wastewater utilization rate ranging from 14.84% to 18.85%. Because the residence time for storage of wastewater is generally below 24 h to prevent bacterial proliferation [43], excess graywater and wastewater were discharged to the sewer, causing a waste of resources.

The excess wastewater could be used to solve the insufficient water supply of the rainwater subsystem if the water quality of the graywater is up to standard. However, the design of the plumbing systems of the HRG is one-way, with higher water quality flowing into the water tank of low-quality water, which limits the feasibility of this approach. Water quality monitoring of the graywater will impose stricter requirements if two-way plumbing systems are utilized, resulting in an increased annual economic investment. This approach is unreasonable for small-scale systems. However, Kobayashi, Ashbolt [44] proposed that the excess graywater was directly discharged into the river through a sewage treatment plant via a separate rainwater pipeline or was directly discharged into the river from the system. These methods avoid the repeated consumption of resources while increasing the feasibility of the HRG by improving the draining-reduction potential and the economic benefits. However, during the life cycle of the HRG, most of the sewer network in Kitakyushu still combined rain and sewage. Although the government has formulated a series of plans to improve the sewer network from a combined system to a separate system, the extensive service areas and financial support have caused the improvement to be a long-term project [40]. Therefore, the reasonable utilization of wastewater resources in the graywater subsystem has become a critical indicator to improve the HRG performance.

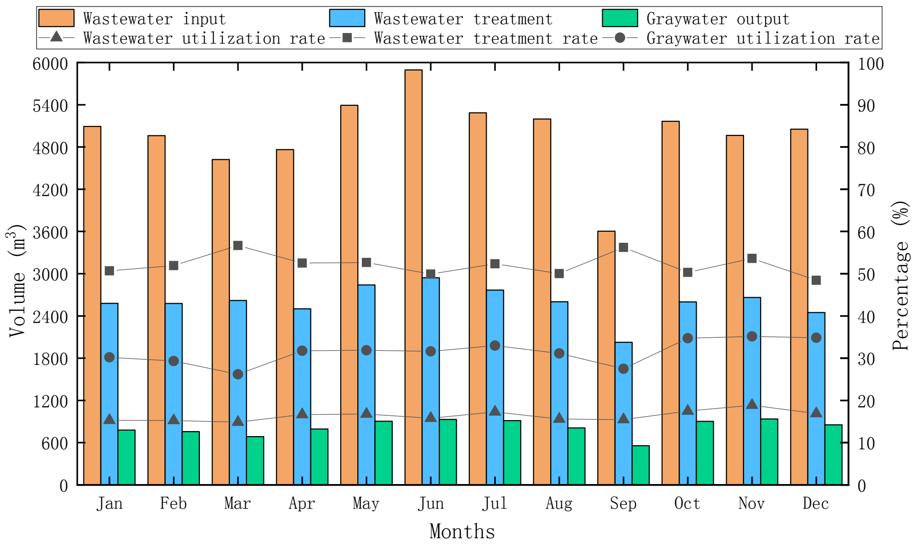

Fig 4-5 Wastewater input, treatment, and graywater output of the graywater subsystem with their performance

(3) Water-saving performance

The water-saving performance of the HRG is shown in Fig 4-6. On the campus, 57.44% (ranging from 38.73% to 84.84%) of potable water can be conserved (13,978 m^3) and 74.14% (ranging from 47.66% to 100%) of the non-potable water demand can be replaced by the HRG throughout the year. Among them, the toilet water demand is fully supplied by graywater (9,822 m^3), while 57.92% (9,044 m^3) of the other non-potable demand (15,615 m^3) is only replaced by rainwater. Because it is almost unnecessary to replenish the graywater subsystem with the potable water supply , the NSC of the HRG depends on the reliability of the rainwater subsystem, and the HRG can provide 83.29% (304 days) of the non-potable water supply during the year without relying on the potable water supplementation (Table 4-6).

There are two trends between the water-saving efficiency and non-potable water replacement rate of the HRG: one is from January to June and from October to December, where the trend of water-saving efficiency surges while the non-potable water replacement rate is stable; the other is from June to October, and the same trend is achieved between the water-saving efficiency and non-potable water replacement rate. During the former, the non-potable water output from the HRG can meet the demand. The water-saving efficiency of the HRG increases with the increasing non-potable water demand. During the latter, the non-potable water output from the HRG cannot meet the demand. In this scenario, the potable water supplement is carried out and increased the potable water consumption, which causes water-saving efficiency, while the non-potable water replacement rate of the HRG decreases simultaneously.

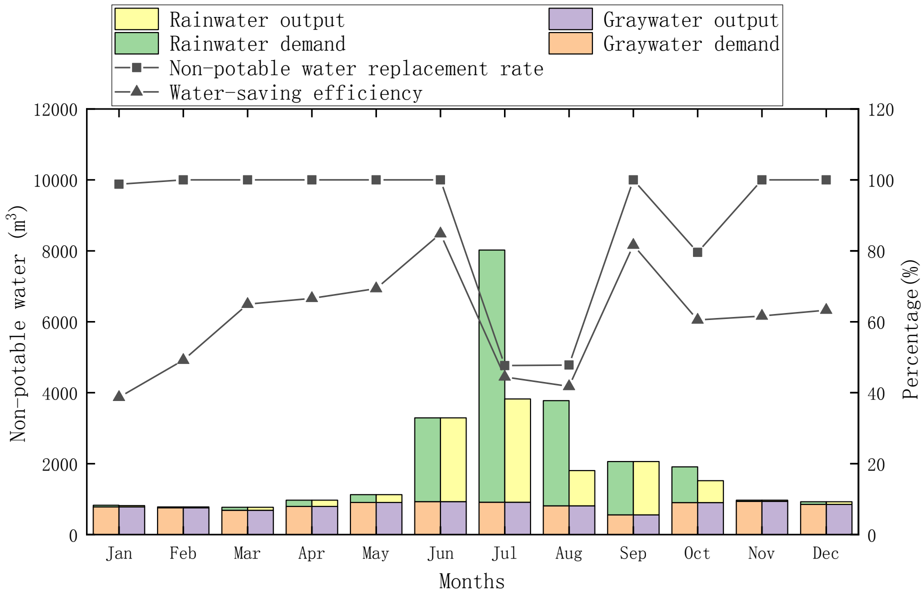

Fig 4-6 Water-saving performance of HRG in the campus

4.4.3 Electricity consumption analysis

The electricity consumption of the HRG includes the water treatment consumption of the rainwater subsystem and the graywater subsystem. Among them, the electricity consumption of the rainwater subsystem includes the pump that transports the rainwater in the rainwater storage tanks to the filtration system and the stirring consumption of the filtration system. The electricity consumption of the graywater subsystem includes the mixing pump and the wastewater lifting pump of the wastewater harvesting tanks, the aeration device and the wastewater treatment pump of the MBR system, the treated water delivery pump for disinfection, the sludge pump, the ozone decomposition device, and the deodorizing fan.

Both the HRG and the potable water supply system of the campus were equipped with water distribution pumps. In this chapter, it is assumed that the water supply of the campus is provided by the potable water tank at the Energy Center when the HRG is not installed, and it is regarded that all the water distribution pumps do not change with the installation of the water-saving facility. Therefore, the electricity consumption of the water distribution system of the campus is divided into three parts:

1. The treatment consumption of the HRG (both the rainwater and graywater subsystems),
2. The distribution consumption of the non-potable water (rainwater and graywater).
3. The distribution consumption of the potable water.

The electricity consumption of each part is shown in Table 4-7.

Table 4-7 The annual electricity consumption of the HRG and the electricity consumption per m^3 of water processed by the HRG

Items	Components	Total electricity consumption	Electricity consumption of treating 1 m^3 water
Rainwater treatment	Pumps	836.53 kWh	0.09 kWh
	FM filer	2,312.49 kWh	0.26 kWh
Wastewater treatment	MBR system and its accessory equipment and sludge system	36,142.38 kWh	1.16 kWh
Non-potable water distribution	Rainwater	2,190.99 kWh	0.24 kWh
	Graywater	1,235.77 kWh	0.12 kWh
Potable water distribution	Pumps	1,374.21 kWh	0.19 kWh

As shown in Table 4-7, treating the rainwater by the HRG requires 0.35 kWh/m^3, which accounts for 23.18% of the total electricity consumption of the HRG; and treating the graywater by the HRG requires 1.16 kWh/m^3, which accounts for 76.82% of the total electricity consumption, because the MBR requires long-term aeration and an ozone supply. In addition, the potable water supplement of the HRG is directly obtained from the main water plants, and the water pressure of which can meet the demand and does not require additional electricity from the campus.

In addition, purifying and distributing the rainwater consumes 0.59 kWh/m^3, and the graywater requires 1.28 kWh/m^3, which account for 31.55% and 68.45%, respectively, of the electricity consumption of the water distribution system in the HRG.

According to a report by the Japan Water Research Center (JWRC), to treat and distribute 1 m^3 of water in the main water plants consumes 0.50 kWh of electricity, and distribution accounts for approximately 74.17% (0.37 kWh) [45]. In addition, treating 1 m^3 sewage water in the sewage water plants require 0.49 kWh of electricity, with the water treatment device accounting for approximately 47% (0.23 kWh) [46]. Because sewage drainage is usually caused by gravity flow, the electricity consumption of sewage drainage is ignored.

Considering that installation of the HRG can reduce the water supply pressure of the main water plants and the water treatment pressure of the sewage treatment plants simultaneously, 0.64 kWh/m^3 of electricity consumption will be reduced when installing the HRG in public buildings for treating rainwater, whereas the electricity consumption will be increased by 0.17 kWh/m^3 when treating graywater in the HRG. In this chapter, if only reused graywater is considered, the average annual electricity consumption of installing the decentralized HRG on the campus (14,558.92 kWh per year) is 22.05% lower than the average annual electricity consumption of the centralized main water plants and sewage treatment plants (18,677.34 kWh per year). Marinoski and Ghisi [31] reached a similar conclusion when assessing the environmental impact of the installation of a hypothetical HRG system in 48 residential buildings in Brazil. The authors found that the installation of an HRG can reduce the total electricity consumption by 36.1% compared with conventional water supply systems

4.4.4 Economic analysis

(1) Economic benefits analysis

The cumulative O&M cost of the HRG is shown in Fig 4-7. The inspection cost accounted for most (35.66%) of the total O&M costs of the HRG. Because the hollow fiber membrane must be cleaned and replaced regularly, the cost in the management of the MBR system accounts for 23.58% of the total O&M costs; among them, the cost of replacing the membrane accounts for 12.35%, and the cleaning cost accounts for 11.23%. This is followed by the repair cost of the HRG (accounting for 16.53%). The above maintenance costs account for 82.82% of the O&M costs of the HRG.

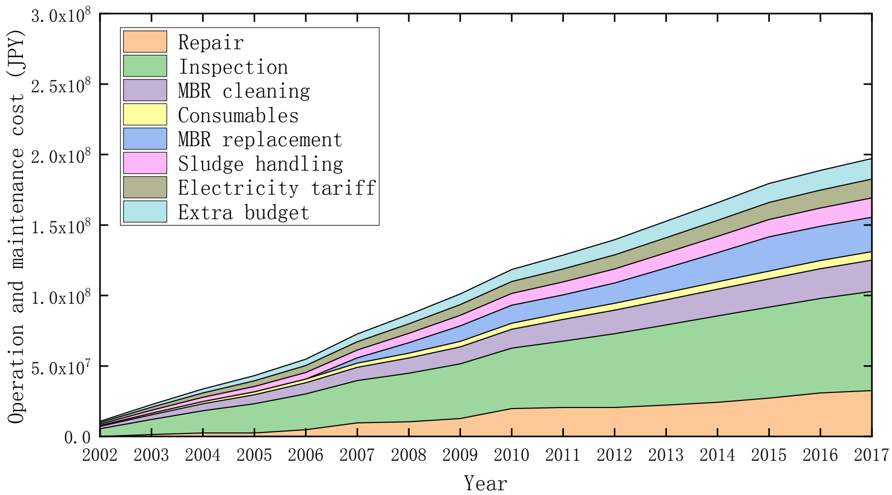

Fig 4-7 Cumulative O&M costs of the HRG from 2002 to 2017

In order to determine the overall economic benefits of the HRG in every year of the 15-year life cycle, the cumulative life cycle cost, cumulative life cycle benefit, and cumulative NPV of the HRG are shown in Fig 4-8. Unfortunately, no economic benefits were obtained by the HRG on the campus over the 15-year life cycle (NPV is −174,285,093 JPY). A trend of continuous decline was shown in the NPV, indicating that in addition to the initial investment cost, the O&M costs of the HRG is higher than the direct benefit of the system for water conservation. In addition to the O&M costs mentioned above, the excess graywater discharged as sewage water also cut the direct benefits of the HRG (Fig 4-3).

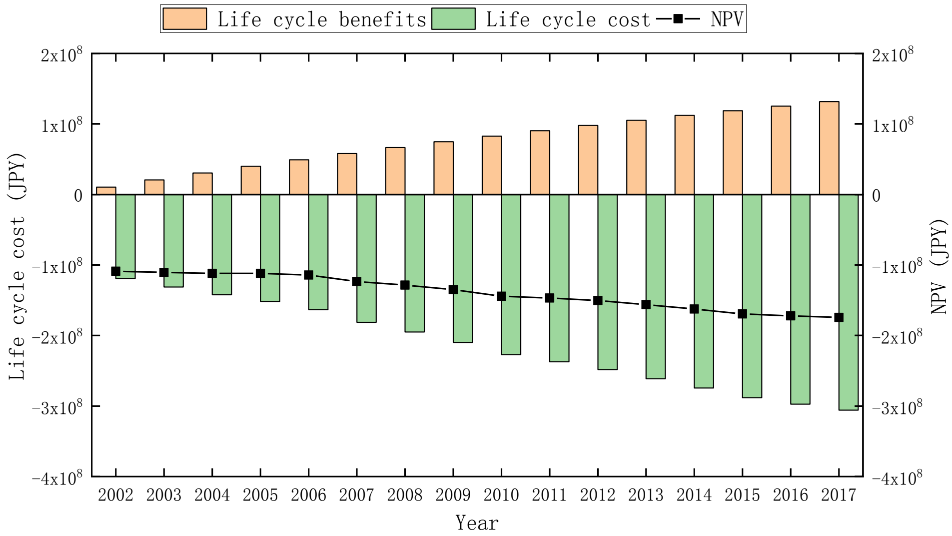

Fig 4-8 Economic benefits of the HRG over 15-year life cycle

(2) Economic optimization analysis

The cumulative NPV of the HRG under optimization Scenarios 1 to 3 are shown in Fig 4-9, Fig 4-10 Fig 4-11, respectively.

In Scenario 1, only when the non-potable water tariff was set at 300 JPY/m^3 does the NPV of the HRG exhibit an upward trend; the HRG could not recover the costs to achieve an overall economic benefit during the 15-year life cycle. However, because the upper limit of the water tariff is 325 JPY/m^3 (Table 4-1), and the water tariff model is a step-up mode, it can be considered that the installation of the HRG in Scenario 1 does not show economic advantages. Therefore, only setting non-potable water tariff is unfeasible to improve the economic feasibility of HRGs in public buildings

In Scenario 2, the NPV assuming all the non-potable water is consumed exhibits an upward trend because the excess graywater was not discharged into the sewer. This optimization can reduce the drainage tariffs. When the non-potable water tariff was set as 0 JPY/m^3, the NPV of the HRG increased from −100,080,742 JPY to −64,517,439 JPY in 15 years. Predictably, economic returns could be obtained by extending the service time of the HRG. When the non-potable water tariff was set as 200 JPY/m^3, the economic benefits of the HRG can be achieved within the life cycle.

In Scenario 3, all the rainwater and graywater yielded by the HRG were used and not free for users. Compared with Scenario 2, the payback period of all the non-potable water consumed is shortened. For example, the HRG can achieve an economic return within 11 years by setting the non-potable water tariff as 200 JPY/m^3; however, it cannot obtain an economic return of 15 years under the same non-potable water tariff as in Scenario 2.

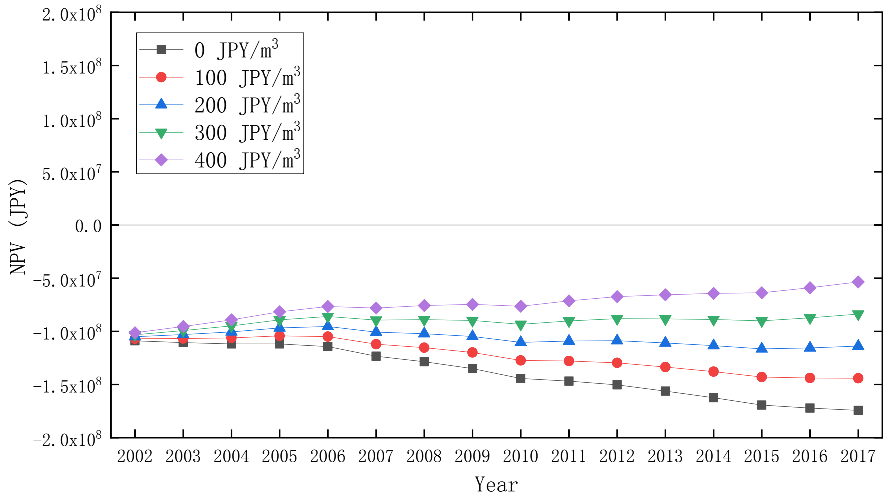

Fig 4-9 The optimized NPV of the HRG under the Scenarios 1 in the campus

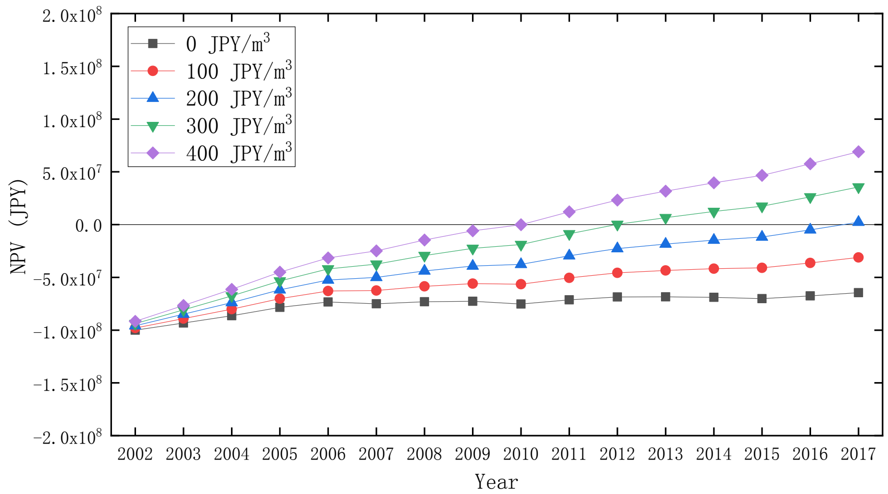

Fig 4-10 The optimized NPV of the HRG under the Scenarios 2 in the campus

The cumulative NPV of the HRG under different water tariff scenarios is shown in Fig 4-12. The cumulative NPV exhibits a downward trend before the water tariff increases to 160%, and the NPV remains stable when the water tariff increases to 180% (NPV from −103,364,749 JPY to −105,624,711 JPY) in the 15-year life cycle. This indicates that when the water tariff increases to approximately twice the current price, 586 JPY/m^3, the benefits of using the HRG to save water can offset the high O&M costs. An upward trend of the cumulative NPV continues with an increase in the water tariff, but the economic benefit of the HRG is still not achieved within the 15-year life cycle. Interestingly, when the water tariff increases to 300%, approximately 880 JPY/m^3, the HRG can almost recover the investment and O&M costs within its service life (NPV is −2,641,364 JPY).

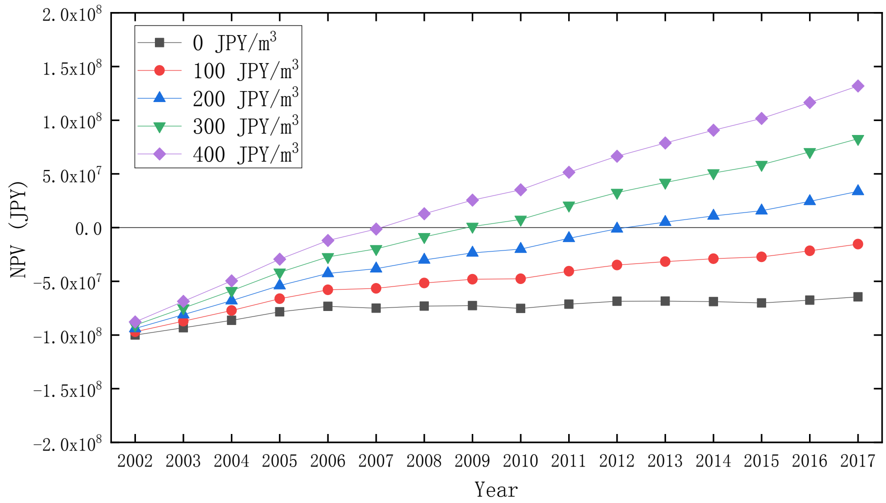

Fig 4-11 The optimized NPV of the HRG under the Scenarios 3 in the campus

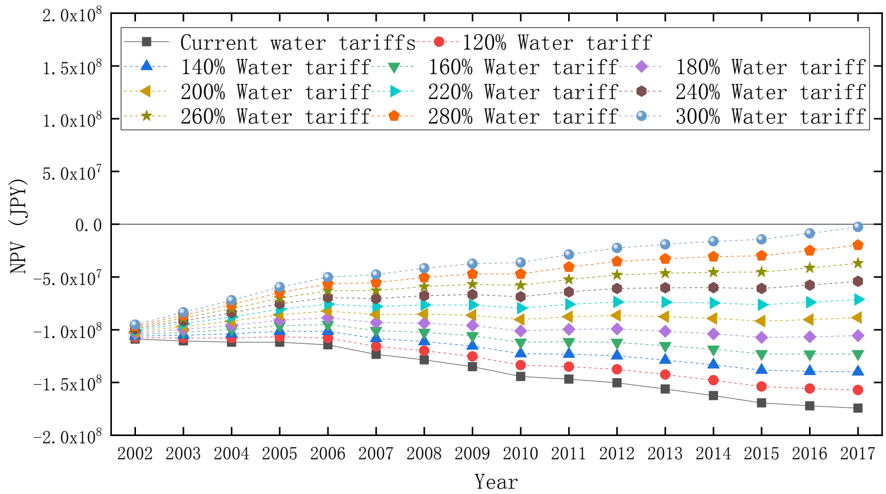

Fig 4-12 The NPV of the HRG under the different water tariffs in the campus

Considering the potential benefits of water-saving equipment for a building is an effective method to improve the economic feasibility of the HRG. For example, Morales-Pinzón, Rieradevall [47] and Lani, Syafiuddin [48] added future changes in water tariffs into the potential benefits of rainwater harvesting systems and found that the systems had financial feasibility, which was negative in the current situation. Amos, Rahman [42] proposed that the convenience to the city brought by the reuse of rainwater can be quantified as a hedonic price to obtain economic benefits of installing building water-saving systems. Severis, Silva [49] reported that reducing the discount rate can increase the economic benefits of rainwater harvesting systems. In this chapter, the economic unfeasibility of the HRG is caused by high maintenance costs and the waste of excess graywater. The excess graywater of the HRG can be directly discharged into the river or used to recharge groundwater. Additionally, the service range can be expanded by selling the non-potable water locally, which is more practical in remote areas or water-scarce areas. Simultaneously, the economic optimization results indicated that if excess rainwater and graywater can qualify for subsidies from the government because of the additional environmental benefits or if users are charged water tariffs, investments into the HRG will be more attractive. However, in order to recover the investment and O&M costs of HRG within 15 years, the water tariff should be increased by three times compared with the current scenario, which shows that the economic feasibility of the HRG is positive in regions or countries with high water tariffs. However, because the doubling the water tariff is just set off the O&M costs of the HRG, compared with increasing the water tariff, reducing maintenance costs is one of the most effective means of improving the economic benefits of the HRG.

4.4.5 Literature comparison

In order to explore the feasibility of installing an HRG in public buildings in Japan, this section compares the results obtained with previous literature. The comparison results are listed in Table 4-8.

It can be seen from Table 4-8 that public buildings have more water end-uses and water consumption scales. These annual water demands of the public building are 1−3 orders of magnitude higher than the previous cases of single family and commercial buildings, and three times higher than that of multi-story residential buildings in Brazil. Although the total water demand in public buildings is significantly lower than that in residential areas, the proportion of the non-potable water demand of the total water demand in public buildings is higher than the latter, which can lead to better water-saving efficiency of the HRG in public buildings. Therefore, the HRG in public buildings can improve water-saving efficiency and feasibility by at least 10%, excluding the single family case in Malaysia and the tourism building case in the United States. In these cases, the higher water-saving efficiency is caused by larger roof areas and lower non-potable water consumption, where an RWH can meet the water demand.

Due to the lower investment, wetlands are more inclined to apply the HRG as graywater treatment units. However, wetlands require high electricity consumption, which consumes 7.8−12.27 kWh to treat 1 m^3 of graywater. The lower electricity consumption demonstrated in the Brazilian single-family housing case is caused by the idealized calculation of the wetland system. In contrast, an MBR can greatly reduce the electricity consumption of an HRG. For example, the electricity consumption of an HRG for residential areas with CAS and MBR is 0.005 kWh/m^3 in Mexico; and the electricity consumption of an MBR-based HRG in this chapter is 1.16 kWh/m^3 for graywater, including the pretreatment consumption of sludge, which can promote the environmental significance of the HRG. However, the economic feasibility of the HRG is not shown in any configuration, which has become one of the critical factors hindering the popularization of the HRG. However, the HRG has huge economic potential in public buildings, such as the return to municipal pipelines or groundwater replenishment.

Table 4-8 Comparison of the major conclusions with other literatures

Study area	Building type	Water end-use	Water demand	Treatment method	Electricity consumption	Water-saving efficiency	Payback period	Cite
Japan	Campus	Toilet, cooling, irrigation, renewable energy facility non-potable water tanks	32,844 m^3/year	FM filter, MBR	39,291 kWh/year 0.35 kWh/m^3 rainwater 1.16 kWh/m^3 reclaimed water	57.44%	None [a]	This paper
Brazil	Residential building	Toilet, laundry, irrigation, car washing	11,142.72 m^3/year	First flushing, wetland	Energy consumption reduced by 36.1%	41.9%	—[b]	[31]
Malaysia	Single family	Toilet, irrigation	427 m^3/year	MMF [c]	1,460.34 kWh/year 3.42 kWh/m^3	83.37%	None	[33]
Malaysia	Commercial building	Toilet, irrigation	2,266 m^3/year	MMF [c]	7,944.64 kWh/year 6.34 kWh/m^3	31.99%	None	[33]
Australia	Residential areas (3,455 households)	Toilet	481,730.65 m^3/year	Recycle water treatment plant	—[b]	26.53%	—[b]	[50]
Brazil	Residential building	Toilet, laundry tap and outdoor tap	136.80 m^3/year	Wetland	347.13 kWh/year 7.8 kWh/m^3	32.5%	—[b]	[51]
Malaysia	Government office building	Toilet, bathroom, cooling towers, irrigation	55,752 m^3/year	MMF [c]	—[b]	24.4%-25.1%	—[b]	[32]
The United States	Tourism building	Toilet	836.47 m^3/year	Wetland	6,776.00 kWh/year 12.27 kWh/m^3	66%	—[b]	[36]

Continued from Table 4-8

Study area	Building type	Water end-use	Water demand	Treatment method	Electricity consumption	Water-saving efficiency	Payback period	Cite
Mexico	Residential area (6,916 residents)	Toilet, laundry room, irrigation	538,376 m^3/year	CAS[d], MBR	119.19 kWh/year 0.0005 kWh/m^3	42.42%	64,562,52 0JPY/year	[26]
Brazil	Single family	Toilet	210.16 m^3/year	First flushing, wetland	1.00 kWh/year 0.01 kWh/m^3	36.4%	More than 37 years	[17]
Brazil	Single family	Toilet	88.70 m^3/year	First flushing, wetland	1.00 kWh/year 0.03 kWh/m^3	33.8%	More than 250 years	[17]

Note: [a] It is no payback period of the HRG in the current scenario;

[b] Presented that the item is not found in the paper;

[c] MMF: Multi-media filter

[d] CAS: Conventional Activated Sludge

Overall, compared with other building types, an HRG in public buildings is a water reuse system with high water saving, low electricity consumption, and a low payback rate. Stakeholders, especially in regions with high water tariffs, should consider the huge environmental benefits of the HRG to subsidize or set non-potable water tariffs to promote the development and application of HRGs in public buildings.

4.5 Summary

In order to evaluate the feasibility of hybrid rainwater-graywater systems in public buildings in Japan, this chapter investigated an on-site decentralized hybrid rainwater-graywater system on a campus. The water-saving performance, operational electricity consumption, and economic benefits of the HRG were analyzed. The conclusions are as follows:

Compared with residential and commercial buildings, HRGs in public buildings are efficient water-saving equipment: 57.44% of potable water can be conserved on the campus, with a supply reliability of 83.29% during the year. Compared with other HRG configurations, MBR-based HRGs in public buildings are efficient electricity-saving equipment: 22.05% of electricity consumption can be saved by the MBR-based HRG during the year. However, an HRG in public buildings is economically unfeasible: the high maintenance costs of the HRG, especially the inspection costs, which account for 35.66% of the O&M costs, are not returned by the direct benefit of water conservation, and the economic benefits of the HRG are not achieved within a 15-year life cycle. In addition, the waste of excess graywater is also a significant reason for the weakening of the economic benefits of HRG.

HRGs in public buildings have great economic potential. Reasonable reuse of the excess graywater or setting a non-potable water tariff of at least 200 JPY/m^3 can enable the use of HRGs in public buildings to achieve economic benefits within a 15-year life cycle. Simultaneously, it is feasible to promote HRGs in public buildings in the region where the water tariff is higher than 880 JPY/m^3. However, compared with increasing the local water tariff, reducing the maintenance costs is the key to improving the economic feasibility of the HRG.

In summary, after considering the economical optimization scenarios of HRGs, installing HRGs in public buildings in Japan is a viable option and can prioritize the promotion of HRG in public buildings to realize its feasibility earlier. Future research should focus on exploring the economic potential of HRGs to increase the investment attractiveness, which is one of the obstacles to expanding the usage of HRGs, and the optimization of maintenance costs and reasonable graywater utilization of the HRG in a specific area to promote the popularization and utilization of HRG.

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Chapter 5

DIMENSIONLESS PARAMETER METHOD FOR GENERAL EVALUATION OF HRGS IN BUILDINGS

Contents

5.1 Content

In order to avoid wasting the excess rainwater and reclaimed water of HRGs, proper implementation of optimally scaled decentralized water reuse systems is especially important. This requires systematic evaluation and optimization for each system in buildings. However, the performance of the decentralized water reuse systems that are widely implemented for the conservation of building water is affected by various characteristics, such as the location and type of building. Generalized methods to evaluate and compare different system configurations under various scenarios are currently lacking. Previously devised methods have focused on specific parameters describing buildings and are therefore not suitable for regionalized application. This chapter proposes a dimensionless parameter method for the evaluation of three decentralized systems in buildings with stable and seasonal daily non-potable water demands: rainwater harvesting systems (RWHs), graywater recycling systems (GWRs), and hybrid rainwater-graywater systems (HRGs). Japan was selected as a case study to illustrate the feasibility of this method. The results indicate that the favorable precipitation patterns in Japan support the use of RWHs rather than GWRs for conserving water, especially in buildings with seasonal daily non-potable water demands. Upgrading the existing systems to HRGs when RWHs and GWRs cannot meet the demand can increase the maximum water-saving efficiency by 40%. Thus, the method can effectively determine the optimum scenarios and configurations of RWHs, GWRs, and HRGs and provide policy guidance for the regional implementation of decentralized water reuse systems.

5.2 Introduction

Water scarcity has been increasing worldwide owing to the rapid rise in population and global warming. According to predictions from the World Water Assessment Programme (UNESCO WWAP, 2012) [1], 47% of the global population will experience water scarcity by 2030. The collection of rainwater and graywater in buildings for on-site reuse has been recommended as an efficient water conservation measure in some countries to alleviate the municipal demand for potable water. These alternative water sources are prioritized for non-potable uses, such as industrial manufacturing [2] and toilets [3]. Rainwater, which is a fairly clean alternative water source, has been reused as potable water in some poor and remote regions [4]. Rainwater and graywater can be collected, treated, and redistributed using decentralized water reuse systems that can be tailored to match the specified water demands of a building and thus conserve large amounts of fresh water [5]. Therefore, the performance of these systems needs to be evaluated for use in each individual building before installation. The gradual implementation of decentralized water reuse systems means that new evaluation methods are required that can match the rapid promotion of decentralized systems because the current methods are limited to specific scenarios alone. A generalized method for evaluating and designing decentralized water reuse systems on a regional level is therefore essential for the popularization of these systems.

A general evaluation method should not only be available for a particular country or region but also needs to be applicable to various measures used in decentralized water reuse systems.

Rainwater harvesting systems (RWHs) [6], graywater recycling systems (GWRs) [7], and hybrid rainwater-graywater systems (HRGs) [8] are three typical decentralized water reuse systems that have been widely installed to conserve building water in Malaysia, Brazil, Africa, and China [9-12]. The water-saving efficiency and economic benefits of these systems can be enhanced by installing them in accordance with the environmental and demand characteristics of a building. Since RWHs are climate-sensitive, the feasibility of RWHs is limited by precipitation patterns and environmental conditions [13]. Previous studies have indicated that RWHs are superior in humid and hilly regions to warm desert and flat regions because of improved water-saving efficiency and economic benefits [14, 15]. The use of GWRs is not highly affected by the natural environment [16]. However, the implementation of GWRs is hindered by the need for expensive investment due to water quality requirements [17]. GWRs can be made economically feasible through concise configuration, wherein low-quality effluents can be re-used [18]. For high-standard effluent requirements, GWRs must be equipped with sophisticated configurations such as membrane reactors, UV disinfection devices, and septic tanks, which will extend the payback period of GWRs [19]. The implementation of GWRs can avoid collecting the dark graywater from toilets such that a more concise treatment unit for treating light graywater with low pollution (e.g., graywater produced by washbasins) can be installed to conserve water. HRGs are essential for achieving net-zero water in buildings. HRGs can simultaneously supply rainwater and graywater, thereby conserving water and markedly reducing the amount of wastewater that is discharged from a building [20]. However, the outstanding environmental benefits of implementing HRGs are generally offset by the high investment required to install such systems, especially in buildings where satisfactory water-saving effects can be achieved by using RWHs or GWRs [21]. HRGs are therefore only likely to be installed in buildings where the use of RWHs or GWRs cannot save sufficient amounts of water.

Furthermore, the feasibility of RWHs, GWRs, and HRGs differs according to building category. de Gois, Rios [22] reported that the economic feasibility of using RWHs in commercial buildings within Brazil is greater than that of GWRs, whereas Ghisi and Ferreira [23] revealed that GWRs are more feasible in residential buildings in Brazil. However, the opposite conclusion was proposed by Leong, Chong [24] for buildings in Malaysia. The authors indicated that more water can be conserved by using RWHs than GWRs in residential buildings, whereas markedly more water can be conserved by using GWRs in commercial buildings. The authors also proposed that HRGs should be implemented in commercial buildings because the required water conservation can almost entirely be met by installing RWHs in residential buildings [9]. Evaluating decentralized water reuse systems in different building categories is unsuitable for region-level evaluation because common evaluation models such as the linear programming model [25], life cycle assessment [26], and the water balance model [27, 28] require detailed data to describe each individual building. As a result, it is impossible to represent the characteristics of each building category via selected case studies, and the conclusions from an evaluation cannot be applied universally in buildings that are of a different scale but in the same category. For example, RWH is suitable for public buildings with smaller areas of the roof assigned to water-capture in Brazil, whereas the use of RWH in public buildings that have larger areas allocated to capturing rainwater is economically unfeasible [29].

The dimensionless model was proposed by Schiller and Latham [30] based on the water balance model to evaluate RWHs regionally. The model categorizes buildings by the demand fraction, which is the ratio of water demand to rainfall harvested, instead of building category, thereby avoiding the need to collect data about each individual building for regional-level evaluation [31]. The performance of RWHs for buildings in the same category can be determined by the relationship between the demand and storage fractions (the ratio of water tank size to the rainfall harvested). Of these, the water-saving efficiency and rainwater spillage rate of RWHs are most affected by the demand fraction, and the retention time of rainwater is most affected by the storage fraction [32]. Various optimization models that are based on the dimensionless model have subsequently been widely used to evaluate RWHs at the regional level. Campisano and Modica [33] optimized the storage fraction by adding the ratio of dry days to rainy days throughout the year to evaluate RWHs in Sicily. The authors concluded that the ability to model the performance of RWHs is increased by optimizing the storage fraction and pointed out that the feasibility of using RWHs decreases as the rainwater availability decreases. Mun and Han [34] removed the precipitation parameter in the storage fraction to evaluate RWHs in Seoul and indicated that the optimal fraction of RWHs in Seoul is 0.03–0.08. This development of this fraction allows the performance of RWHs to be compared in regions with different levels of precipitation [35], and was denoted the "Rainwater Accumulation Potential (RAP)" by Imteaz, Ahsan [36]. The authors recommended that the optimal RAP of RWHs in Melbourne range from 0.8–0.9. However, the limitations of the current dimensionless model and its optimized model are limited to evaluating RWHs, with only RWHs assumed to be implemented in buildings over the entire region, and the feasibility of using GWRs and HRGs is ignored. The obtained results only discuss the optimal implementation scenarios of RWHs, thus hindering the promotion of other decentralized water reuse systems.

To develop a generalized method that is suitable for evaluating and designing RWHs, GWRs, and HRGs in different buildings on a regional level, a dimensionless parameter method was generated that uses four dimensionless parameters to determine the optimal scenarios for using RWHs, GWRs, and HRGs in buildings: the rainwater demand fraction, graywater demand fraction, storage fraction, and treatment fraction. Furthermore, the feasibility of using RWHs, GWRs, and HRGs in buildings with seasonal daily non-potable water demand was discussed to ensure that the method is not limited to specific scenarios in which the daily non-potable water demand of a building remains stable throughout the year. Finally, the dimensionless parameter method was used to obtain design curves for RWHs, GWRs, and HRGs in the buildings studied in Japan. The proposed method can comprehensively and easily evaluate different decentralized water reuse systems for use in buildings and provide new ideas for a generalized design method that can produce decentralized systems at a regional level.

5.3 Methodology

5.3.1 System description

(1) Rainwater harvesting systems

Fig 5-1 is a flow diagram illustrating the use of RWHs, GWRs, and HRGs for non-potable water reuse in buildings.

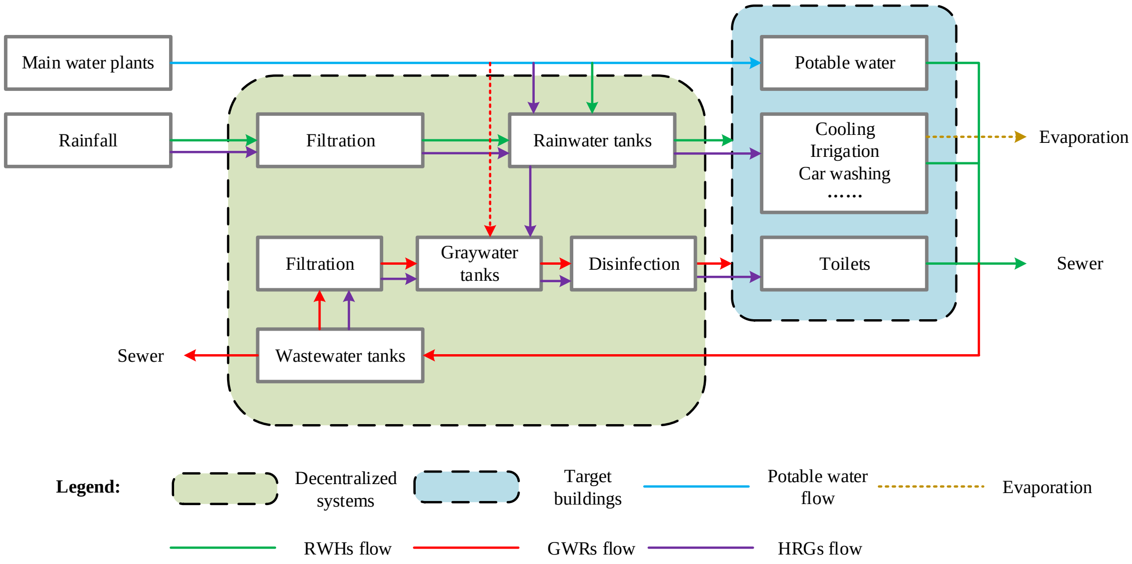

Fig 5-1 Lay out of RWHs, GWRs, and HRGs

As shown by the green line in Fig 5-1, rainfall harvested from capture on the roofs of buildings is filtered and stored in rainwater tanks for use as non-potable water. First flushing or suspended filtration devices are used to remove suspended solids from the rainwater [14]. Supplementation from the main water supply is essential when using RWHs to avoid the problem of insufficient rainfall. The rainwater retention time can be monthly or seasonal without worrying about water quality, ensuring that the water supply of RWHs can be maintained during the dry monsoon period. The wastewater generated when using RWHs is directly discharged into the sewer, and excess rainwater is spilled into the storm drain or into the sewers from the rainwater tanks.

(2) Graywater recycling systems

The red line in Fig 5-1 illustrates the layout of GWRs. The wastewater generated in buildings is collected as graywater and transferred into storage tanks where the volume and flow rate can be adjusted prior to treatment. The treated graywater is then stored in graywater tanks and supplied to buildings after disinfection. The filtration devices used in GWRs are combined differently for primary, secondary, and tertiary treatments, which depend on the quality requirements of the influent and effluent. Supplementation with water from the main supply is less necessary in GWRs than in RWHs because of the stable input of wastewater. Excess wastewater and graywater must be discharged daily into the sewer because retaining graywater for more than 24 hours can lead to bacterial proliferation [37]. The water-saving efficiency of GWRs can be insufficient in some scenarios because the wastewater that is generated by some activities, such as cooling and irrigation, evaporates after use and cannot be collected again.

(3) Hybrid rainwater-graywater systems

HRGs integrate RWHs with GWRs to achieve increased water conservation in buildings. The configuration of HRGs varies, and it includes the use of rainwater and graywater either separately or in combination [8]. The flow diagram describing HRGs in Fig 5-1 refers to the general configuration of HRGs described by Leong, Chong [24] and Chen, Gao [38]. The graywater subsystem of an HRG preferentially collects light wastewater, such as that from washbasins, to provide non-potable water for use in toilets, reducing the complexity of the graywater treatment process. Low-quality wastewater from toilets and kitchens is discharged into the sewer as dark wastewater. The remaining non-potable water demands of a building are supplied by the rainwater subsystem of HRGs, especially water that is used in activities that include the evaporation of large quantities of water. The rainwater tanks are directly supplemented with the main water supply, and water is added into the graywater tanks from the rainwater tanks through a one-way plumbing system to avoid insufficient water supplies.

5.3.2 Design method development

The non-potable water-saving efficiency, which is defined by the proportion of the non-potable water demanded in buildings that is outputted from the systems, is proposed to obtain the design curves of RWHs, GWRs, and HRGs (W, %) [39].

$$W_R = \frac{\sum_{t=1}^{n} Y_{Rt}}{\sum_{t=1}^{n} D_{Rt}} \tag{5-1}$$

$$W_G = \frac{\sum_{t=1}^{n} Y_{Gt}}{\sum_{t=1}^{n} D_{Gt}} \tag{5-2}$$

$$W_H = \frac{\sum_{t=1}^{n} Y_{Rt} + \sum_{t=1}^{n} Y_{Gt}}{\sum_{t=1}^{n} D_{Ht}} \tag{5-3}$$

where W_R, W_G, and W_H are the non-potable water-saving efficiencies of RWHs, GWRs, and HRGs, respectively; Y_R and Y_G are the non-potable water outputs of RWHs and GWRs, respectively (m^3); and D_R, D_G, and D_H are the non-potable water demands using RWHs, GWRs, and HRGs, respectively (m^3).

The rainwater overflow rate is the proportion of the harvested rainwater that is overflowed (S_r, %), which reveals the potential of RWHs to improve the efficiency of non-potable water-saving. The rate at which graywater overflows is the proportion of the treated wastewater that is overflowed, which can affect the economic potential of GWRs and HRGs (S_e, %) [38].

$$S_r = \frac{\sum_{t=1}^{n} SP_{rt}}{\sum_{t=1}^{n} Q_{Rt}} \tag{5-4}$$

$$S_r = \frac{\sum_{t=1}^{n} SP_{rt}}{\sum_{t=1}^{n} Q_{Rt}} \tag{5-5}$$

where SP_r is the rainwater overflowed from rainwater tanks (m^3), SP_e is the graywater overflowed from graywater tanks (m^3), and D_T is the volume of water treated in a GWR (m^3). Notably, D_T is associated with both the water demand of wastewater tanks and the water flowing into the graywater tanks.

5.3.3 Dimensionless parameters

The factors affecting the W_R of RWHs mainly include the non-potable water demand of buildings (D), the rainfall capture area of building (A), precipitation (H), and the size of the rainwater tank (V_r), whereas the factors affecting the W_G of GWRs mainly include the non-potable water demand of a building (D), the volume of wastewater generated in a building (Q_G), and the volume of graywater treated (D_T). Converting these independent variables into dimensionless parameters can simplify calculating the influence that the independent variables have on the system by changing the values of the parameters. The demand fraction *D/AH* and storage fraction V_r/AH have been used to design RWHs [30, 33, 40]. In this study, four dimensionless parameters were tailored based on the demand and storage fractions to qualify the performance of RWHs, GWRs, and HRGs.

$$d_r = \frac{D}{Q_R} = \frac{D}{\varphi AH/1000} \tag{5-6}$$

$$d_g = \frac{D}{Q_G} \tag{5-7}$$

$$s = \frac{V_r}{Q_R} = \frac{V_r}{\varphi AH/1000} \tag{5-8}$$

$$g = \frac{D_T}{Q_G} \tag{5-9}$$

where d_r is the rainwater demand fraction (dimensionless), d_g is the graywater demand fraction (dimensionless), s is the rainwater storage fraction (dimensionless), and g is the graywater treatment fraction (dimensionless). d_r and d_g are used to describe the non-potable water demand characteristics of a building, and s and g are used to determine the optimum configuration of RWHs and GWRs, respectively. Design curves can be obtained for of RWHs under different scenarios from the relationship between W_R and s under different values of d_r, whereas design curves for GWRs under different scenarios can be obtained from the relationship between W_G and g under different values of d_g. Design curves for HRGs under different scenarios can be obtained from the relationship between W_H and s under different d_r values and specific d_g values. Therefore, the optimal scale of RWHs, GWRs, and HRGs can be determined simultaneously from these design curves.

5.3.4 Data sources and initial assumptions

(1) Study area and precipitation data

Japan was selected as a case study to obtain design curves for RWHs, GWRs, and HRGs using the dimensionless parameter method. Japan is a rainy country with an annual precipitation of 1718 mm. The precipitation in cities that are subjected to the highest rainfall can reach seven times that of those with the lowest precipitation.

Fig 5-2 shows the precipitation distribution in Japan from 2001 to 2020. According to the Köppen-Gieger classification, Japan comprises four climate zones (Fig 5-3) and the average annual temperature ranges from 12 °C–19 °C.

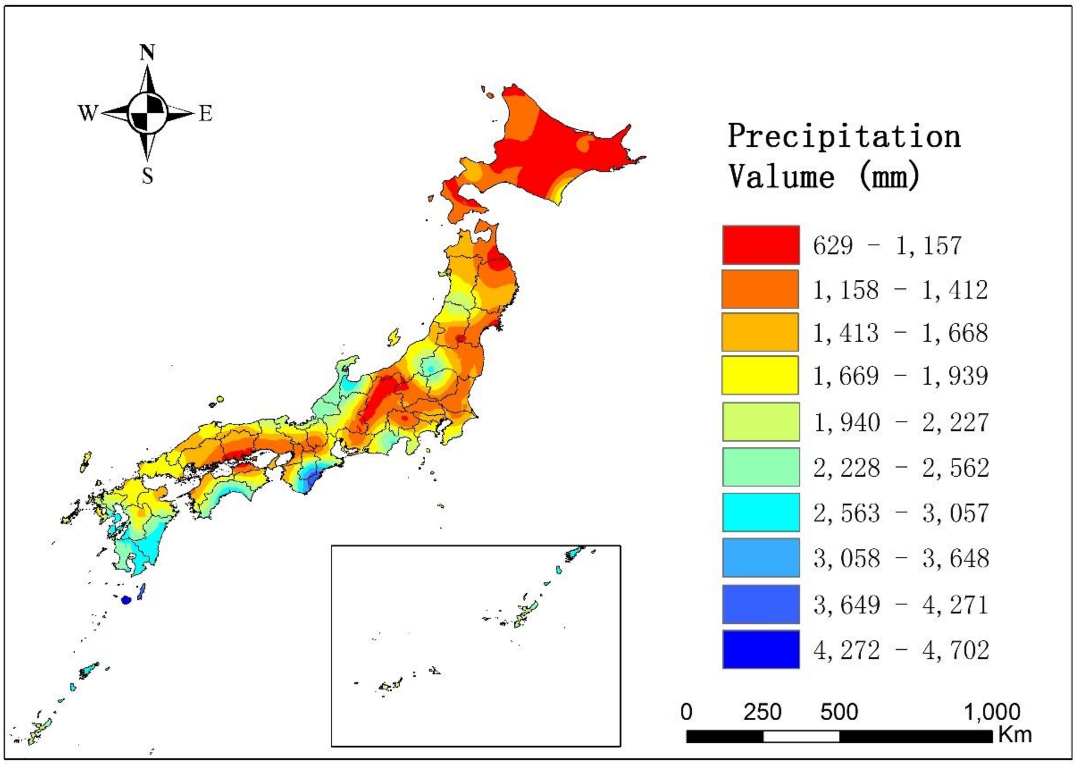

Fig 5-2 Precipitation distribution in Japan from 2001 to 2020

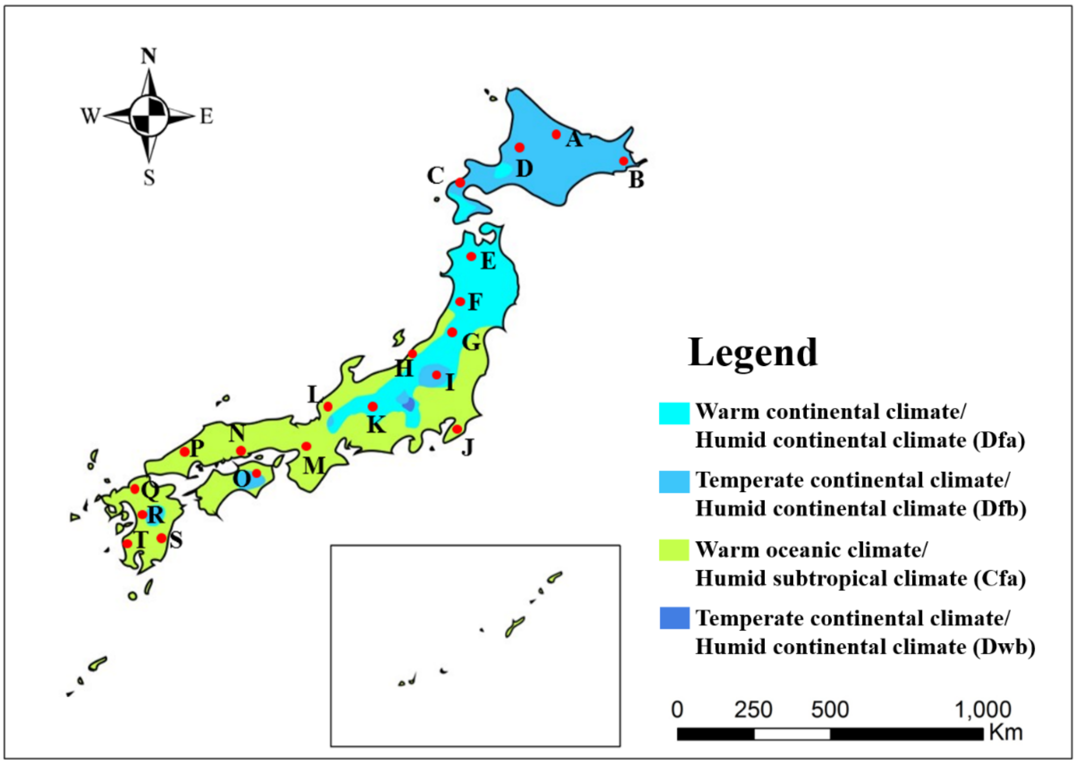

Fig 5-3 The Köppen-Gieger classification of Japan

The precipitation and temperature in Japan show a unimodal trend throughout the year, with the wet monsoon period concentrated from June to September, and the highest temperature observed in August. The average precipitation and average temperature in Japan are shown in Fig 5-4.

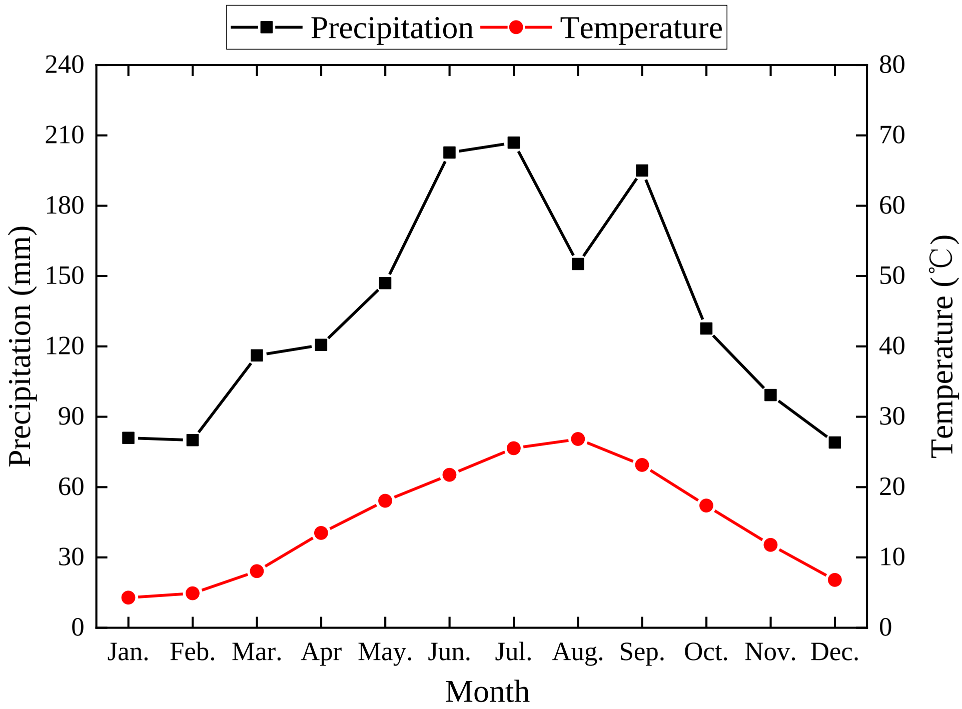

Fig 5-4 Average precipitation and temperature in Japan

A sufficiently long precipitation resolution is required by an integrated model to simulate the performance of RWHs precisely. Previous studies have indicated that 10- and 15-year daily precipitation can achieve results similar to those of 30-year daily precipitation [41, 42] and that data covering daily precipitation for at least 20 years can obtain similar results to hourly precipitation over 50 years [43, 44]. Considering the simulation accuracy and availability of precipitation data, 20-year precipitation was therefore selected for the simulation. In this study, the precipitation distribution and climate classification map were used to source 20 cities that could include all the different precipitation characteristics of Japan. Data describing the daily precipitation over 20 years, from 2001 to 2020, were obtained for the 20 cities studied from the Japan Meteorological Agency [45]. The detailed information on these cities is provided in Table 5-1.

Table 5-1 Detailed information describing the 20 cities studied

City	Latitude	Longitude	Altitude (m)	Average annual precipitation from 2001 to 2020 (mm)	Climate classification
Monbetsu	N 44°20.7′	E 143°21.3′	15.8	853.95	Dfb

Continued from Table 5-1

City	Latitude	Longitude	Altitude (m)	Average annual precipitation from 2001 to 2020 (mm)	Climate classification
Nemuro	N 43°19.8′	E 145°35.1′	25.2	1046.71	Dfb
Kutchan	N 42°50.4′	E 140°45.4′	176.1	1545.29	Dfb
Asahikawa	N 43°45.4′	E 142°22.3′	119.8	1116.29	Dfb
Aomori	N 40°49.3′	E 140°46.1′	2.8	1410.07	Dfa
Akita	N 39°43.0′	E 140°05.9′	6.3	1725.00	Dfa
Yamagata	N 38°15.3′	E 140°20.7′	152.5	1227.24	Dfa
Niigata	N 37°53.6′	E 139°01.1′	4.1	1823.86	Cfa
Nikko	N 36°44.3′	E 139°30.0′	1291.9	2271.10	Dfb
Katsuura	N 35°09.9′	E 140°18.7′	11.9	2051.14	Cfa
Matsumoto	N 36°14.8′	E 137°58.2′	610	1059.50	Cfa
Fukui	N 36°03.3′	E 136°13.3′	8.8	2330.21	Cfa
Osaka	N 34°40.9′	E 135°31.1′	23	1332.95	Cfa
Okayama	N 34°41.1′	E 133°55.5′	5.3	1140.05	Cfa
Tokushima	N 34°04.0′	E 134°34.4′	1.6	1690.57	Dfb
Hamada	N 34°53.8′	E 132°04.2′	19	1624.52	Cfa
Fukuoka	N 33°34.9′	E 130°22.5′	2.5	1672.02	Cfa
Kumamoto	N 32°48.8′	E 130°42.4′	37.7	1986.91	Dfb
Miyazaki	N 31°56.3′	E 131°24.8′	9.2	2690.83	Cfa
Kagoshima	N 31°33.3′	E 130°32.8′	3.9	2415.05	Cfa

(2) Initial assumptions of the simulation

The size of the wastewater tank and graywater tank used in GWRs have less effect on non-potable water-saving efficiency because these tanks are not used for long-term storage. Because graywater may be used as emergency water for disasters in some buildings, the wastewater tank and graywater tank sizes were set to 1.5-flod the maximum daily water demand in this study, which is larger than the recommendations made by Liu, Butler [37]. Furthermore, all wastewater generated from buildings was considered to flow into the wastewater tanks to simplify the calculation.

A treatment fraction of 1 indicates that all wastewater is treated in GWRs. Therefore, a treatment fraction ranging from 0 to 1 was assumed to simulate the design curves for GWRs. A storage fraction between 0 and 1 was used for simulating the design curves for RWHs, based on recommendations made by Schiller and Latham [30] and Palla, Gnecco [40]. The rainwater demand fraction was assumed to be between 0.1 and 10 to simulate the different non-potable water demand scenarios in buildings because a rainwater demand fraction > 10 can render the RWHs inefficient [35]. The graywater demand fraction was also assumed to fall between 0.1 and 10 when determining the design curves for GWRs.

To obtain the design curves for HRGs, the percentage of dark wastewater that is generated by toilets from a building should be determined. This was assumed to be 28% in the present study, in accordance with a report from the Ministry of Land, Infrastructure, Transport and Tourism in Japan (2016) [46]. GWRs are not recommended when the graywater treatment fraction is greater than 0.72 because the cost of treating the dark wastewater increases to ensure sufficient supply. The water demanded for flushing toilets as a percentage of the total non-potable water demand of a building (P, %) can be determined as follows:

$$P = \frac{28\% \times Q_G}{D} = \frac{28\%}{g} \tag{5-10}$$

The non-potable water demand of buildings may be stable throughout the year or change seasonally because of various activities, such as irrigation [47, 48] and air-conditioning [49]. Therefore, the design curves of RWHs, GWRs, and HRGs in buildings with stable daily non-potable water demand and seasonal daily non-potable water demand were examined in this study. According to a report by the Ministry of the Environment in Japan (2009), there is a linear relationship between the potable water distribution volume of main water plants and the outdoor temperature in Japan, with a coefficient of 4 [50]. Therefore, a simple linear relationship according to the coefficient was designed to calculate the seasonal daily non-potable water demands of buildings as follows:

$$\frac{y - \bar{y}}{\bar{y}} = 4 \times \frac{x - \bar{x}}{\bar{x}} \tag{5-11}$$

where y is the seasonal daily non-potable water demand (m^3), $\bar{y}$ is the stable daily non-potable water demand (m^3), x is the daily outdoor temperature (°C), and $\bar{x}$ is the average outdoor temperature (°C). Notably, this fraction of the increasing water demand is considered a result of the increase in temperature and is expected to evaporate after the water is used. The graywater generated from buildings was therefore assumed to be consistent with the stable daily non-potable water demand.

5.4 Results

5.4.1 Performance of RWHs

Design curves for RWHs in buildings with stable daily non-potable water demand and seasonal daily non-potable water demand are shown in Fig 5-5. As shown in Fig 5-5 (a), three trends can be seen in the design curves for RWHs: a marked increasing trend, slight increasing trend, and steady trend. Taking the design curve of d_r=1 as an example, W_R increased from 52.25% to 93.67% as a result of increasing the storage fraction from 0.01 to 0.3, whereas the W_R only increased by 2.47% (96.14%) as a result of a subsequent increase to 0.7. The W_R then remained stable as the storage fraction was further increased, indicating that the maximum non-potable water-saving efficiency was achieved at this point. The maximum W_R of RWHs was also observed to decrease as the rainwater demand fraction increased. The maximum W_R of RWHs can reach almost 100% when the d_r of buildings is less than 0.7 and is reduced to 96.21%, a decrease of 3.79%, in buildings for which d_r=1. However, as the d_r of a building continues to increase from 1 to 3, the maximum W_R of RWHs markedly reduces from 96.21% to 33.31%. Subsequently, the maximum W_R of RWHs decreases gradually from 33.31% to 9.99% when the d_r of a building increase from 3 to 10. This indicates that harvesting rainwater to conserve water in buildings with stable daily non-potable water demand buildings that have a $d_r > 1$ in Japan cannot meet the non-potable water demand.

Comparing Fig 5-5 (a) with Fig 5-5 (b) suggests that it is feasible to use RWHs to meet the seasonal daily non-potable water demand of a building. The design curves for RWHs in buildings with stable and seasonal daily non-potable water demands were similar. For example, the maximum WR of RWHs in buildings with stable daily non-potable water demand was 99.60% when the dr of the buildings was 0.7 and the s of RWHs was 0.5, whereas the maximum WR of RWHs in buildings with seasonal daily non-potable water demand is 99.76% at the same dr and s. The similar design curves of RWHs in Fig 5-5 (a) and Fig 5-5 (b) are a result of the consistency of the wet monsoon period and the period of higher outdoor temperatures in Japan (Fig 5-4). The higher rainfall during this period can match the increasing non-potable water demand that is affected by higher temperatures. Therefore, the use of RWHs can feasibly meet the seasonal daily non-potable water demand of buildings in Japan.

Fig 5-6 shows the rainwater overflow rate when using RWHs in buildings with both stable daily and seasonal daily non-potable water demands. The rate at which rainwater is overflowed in RWHs in buildings with d_r=1 is > 0 when the design curve reaches the water-saving threshold, which suggests that additional rainwater can be harvested by the RWHs. When the W_R of the RWHs is unachievable in these buildings, measures such as expanding the area of the capture roof and the use of additional rainwater tanks can be used to harvest more rainfall, increasing the W_R. However, the rate at which rainwater overflow occurs when using RWHs in buildings with a d_r greater than 1 is 0 when the design curve reaches the maximum W_R, indicating that the non-potable water demand of these buildings cannot be met using rainfall only. This explains why the maximum W_R of RWHs in the design curves decreases sharply from d_r=1 (Fig 5-5)

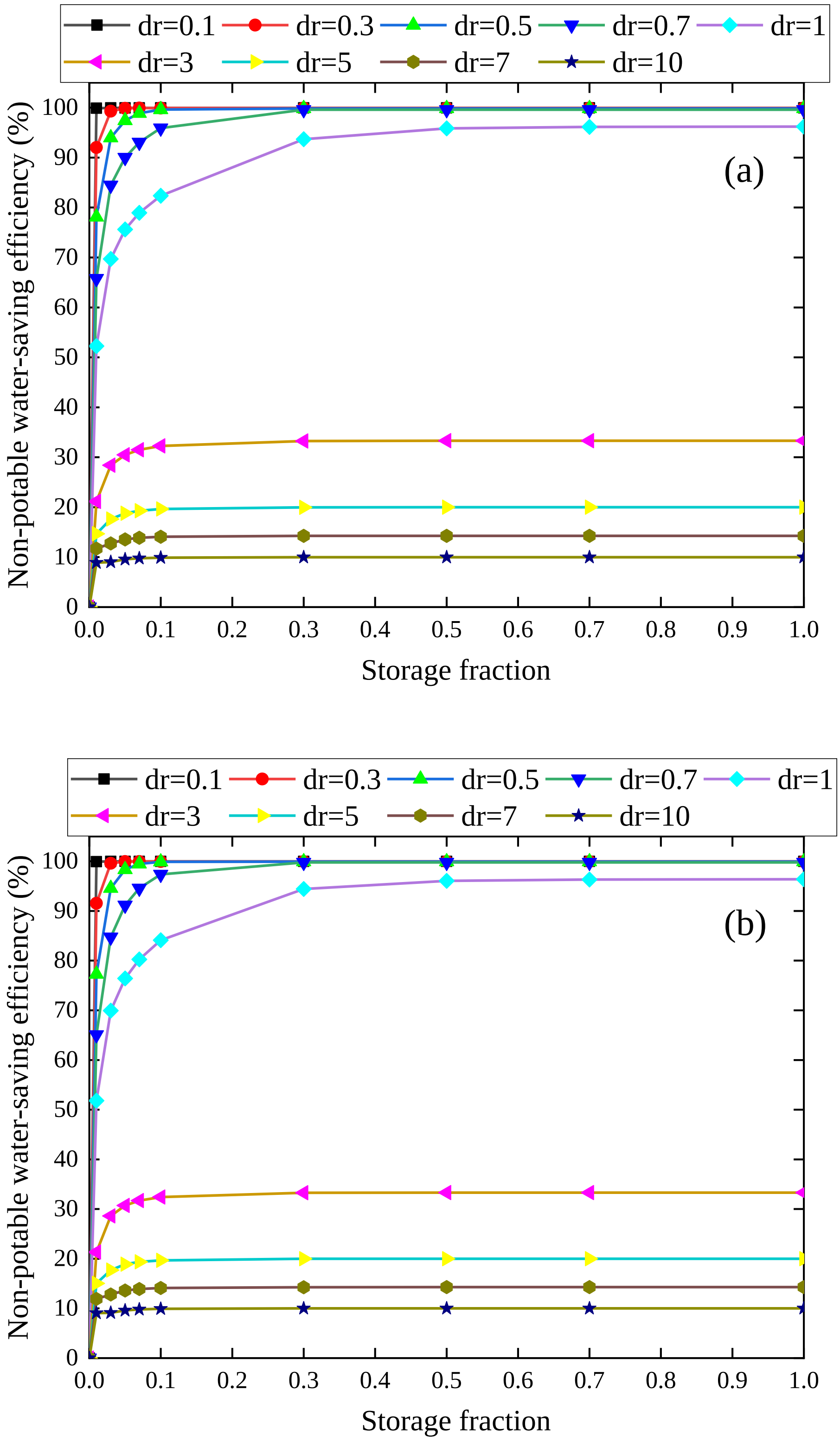

Fig 5-5 Design curves for RWHs in Japanese buildings
((a) stable daily non-potable water demand scenario; (b) seasonal daily non-potable water demand scenario)

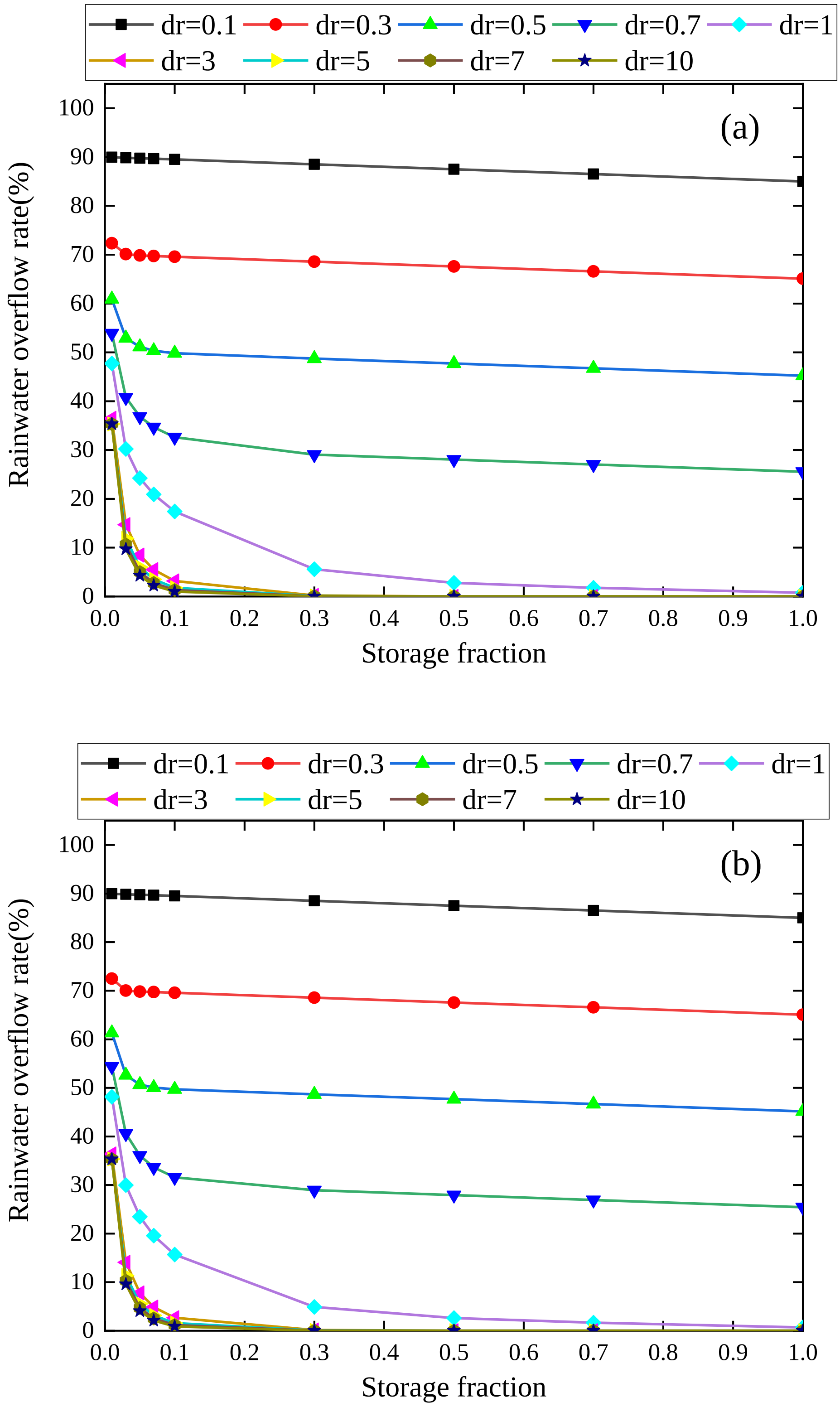

Fig 5-6 Rainwater overflow rate of RWHs in Japanese buildings

((a) stable daily non-potable water demand scenario; (b) seasonal daily non-potable water demand scenario)

5.4.2 Performance of GWRs

The design curves for GWRs in buildings with stable daily non-potable water demand and seasonal daily non-potable water demand are shown in Fig 5-7. Compared with Fig 5-5, two trends are visible in the design curves for GWRs in buildings with stable daily non-potable demand: a marked increasing trend and a steady trend. The maximum W_G of GWRs in buildings with $d_g < 1$ can reach 100%, and GWRs are not able to achieve sufficient W_G in buildings with $d_g > 1$. For example, the maximum W_G of GWRs in buildings with d_g=3 was only 33.34%. The reason for the two trends in the design curves for GWRs is that the wastewater generated from buildings is continuous and steady in terms of water conservation and tanks that contain graywater will be emptied in time to avoid storing graywater over long periods. The relationship between W_G and t in a GWR is therefore almost linear before the maximum W_G is achieved in this system. Considering the maximum W_G of GWRs, installing GWRs in Japanese buildings with stable daily non-potable water demand buildings and $d_g < 1$ is feasible. However, the greater the value of d_g, the greater the proportion of wastewater that needs to be treated to achieve the maximum W_G. All wastewater must be treated to achieve the maximum W_G in buildings where d_g =1, including both light and dark wastewater. This suggests that a more sophisticated treatment process is required to bring the water quality of the effluent up to standards, which is uneconomical in decentralized water reuse systems. Therefore, the implementation of GWRs can only be recommended for buildings with smaller values of d_g. The maximum d_g is 0.72 in Japan because the percentage of dark wastewater generated from toilets is 28% of the total.

The design curves for GWRs show the same three trends as RWHs in buildings with seasonal non-potable water demands, and the maximum W_G will decrease at the same treatment fraction of GWRs in comparison with scenarios that include stable non-potable water demand. The results indicate that the treatment fraction needs to be increased in buildings with seasonal daily non-potable water demand to achieve 100% W_G. The treatment fraction of GWRs for achieving 100% W_G in buildings with seasonal daily non-potable water demands that have d_g=0.7 is 1, whereas the value in the buildings with stable daily non-potable water demand where d_g=0.7 is 0.7. In addition, the treatment fraction of GWRs increases from 0.6 to 0.7 in buildings with d_g=0.7, and the W_G can be increased from 85.71% to 100% under stable daily non-potable water demand, whereas that under seasonal daily non-potable water demand can only be increased from 83.36% to 92.55%. The W_G of GWRs will decrease under the seasonal daily non-potable water demand scenario because of the demand for unstable non-potable water. Greater amounts of wastewater therefore need to be treated to improve the W_G, but the water-saving benefits brought by increasing the treatment capacity of GWRs have gradually decreased. This makes the implementation of GWRs in buildings with seasonal daily non-potable water demand lower than that in buildings with stable non-potable water demand.

The graywater overflow rate of GWRs is shown in Fig 5-8. The maximum W_G of GWRs in buildings with seasonal non-potable water demand requires that more graywater is overflowed. For example, the maximum W_G and graywater overflow rate at the maximum W_G of GWRs in buildings with d_g=0.7 is 100% and 0 under stable daily non-potable water demand, respectively, whereas these values are 92.55% and 7.49% under the seasonal daily non-potable water demand scenario, respectively. Furthermore, the graywater tanks used for GWRs in buildings with the seasonal daily non-potable water demand must be larger to store the treated wastewater. The optimal graywater tank size for GWRs in buildings with seasonal daily non-potable water demand where d_g=0.7 is 2.88 m^3, whereas that in buildings with stable daily non-potable water demand where d_g=0.7 is 3.59 m^3.

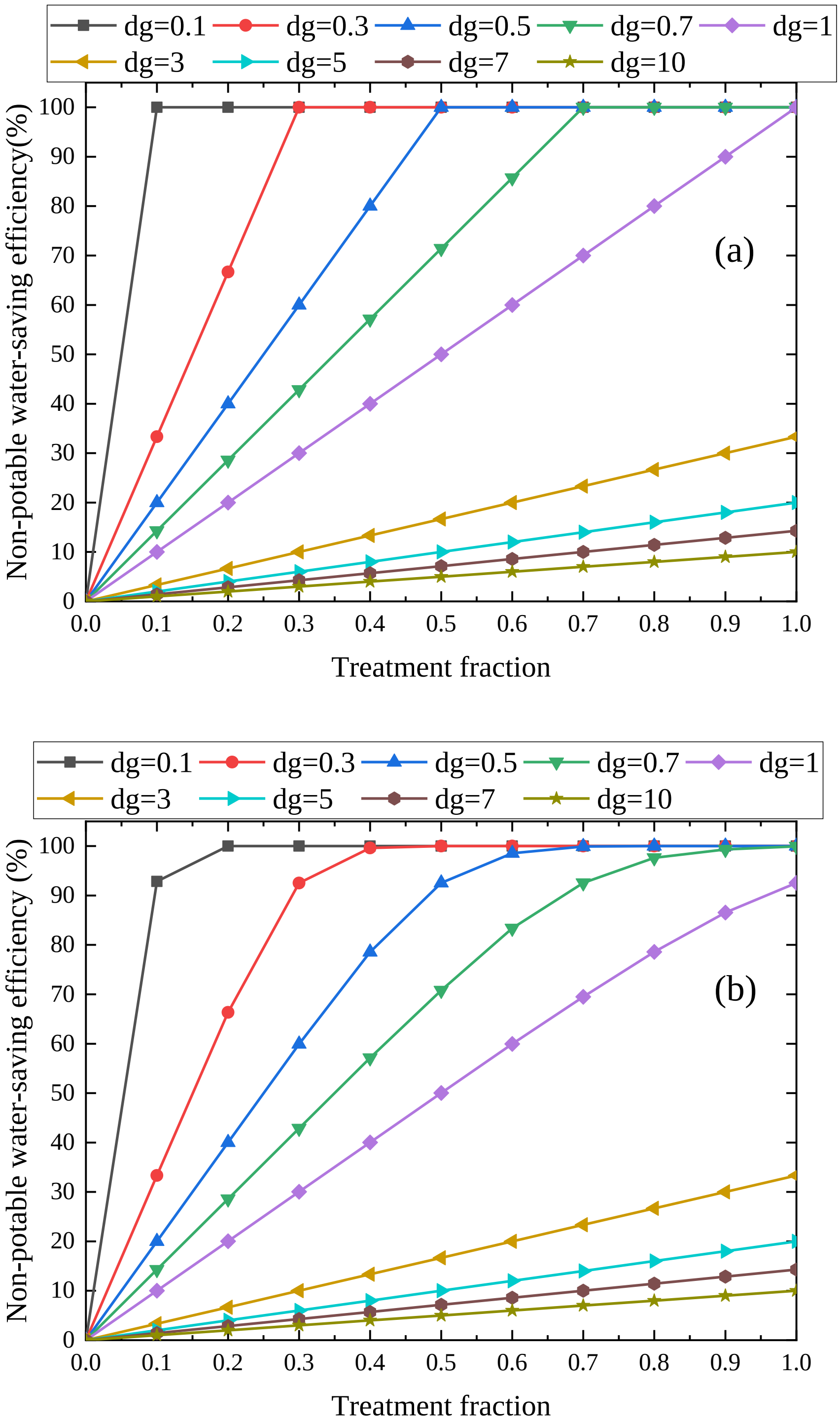

Fig 5-7 Design curves for GWRs in Japanese buildings
((a) stable daily non-potable water demand scenario; (b) seasonal daily non-potable water demand scenario)

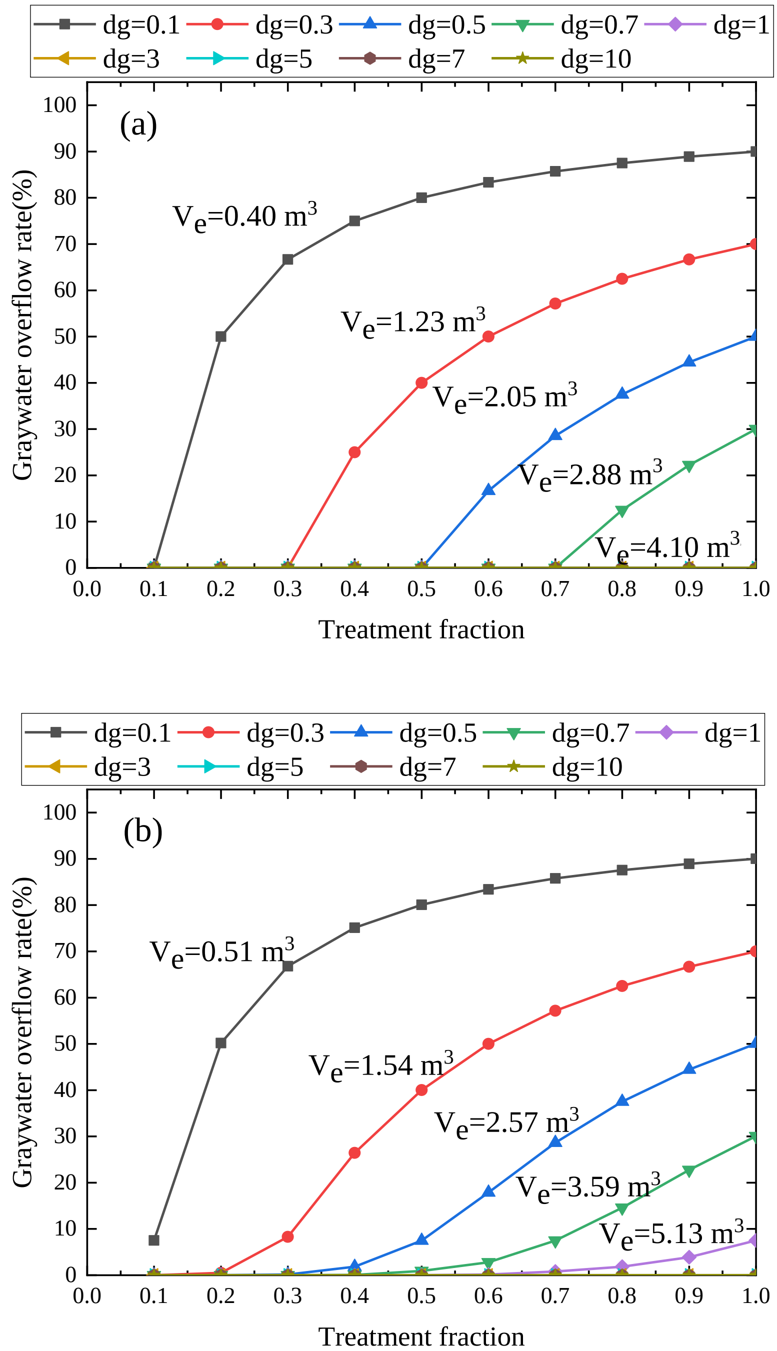

Fig 5-8 Rate at which graywater is overflowed from GWRs in Japanese buildings
((a) stable daily non-potable water demand scenario; (b) seasonal daily non-potable water demand scenario)

5.4.2 Performance of HRGs

As shown in Fig 5-5 and Fig 5-7, buildings in Japan with a d_r greater than 1 and a d_g greater than 0.72 cannot use RWHs or GWRs to conserve water, respectively, meaning that HRGs could potentially be implemented in these buildings. The design curves for HRGs in buildings with

d_g=0.75 and a d_r > 1 are shown in Fig 5-9.

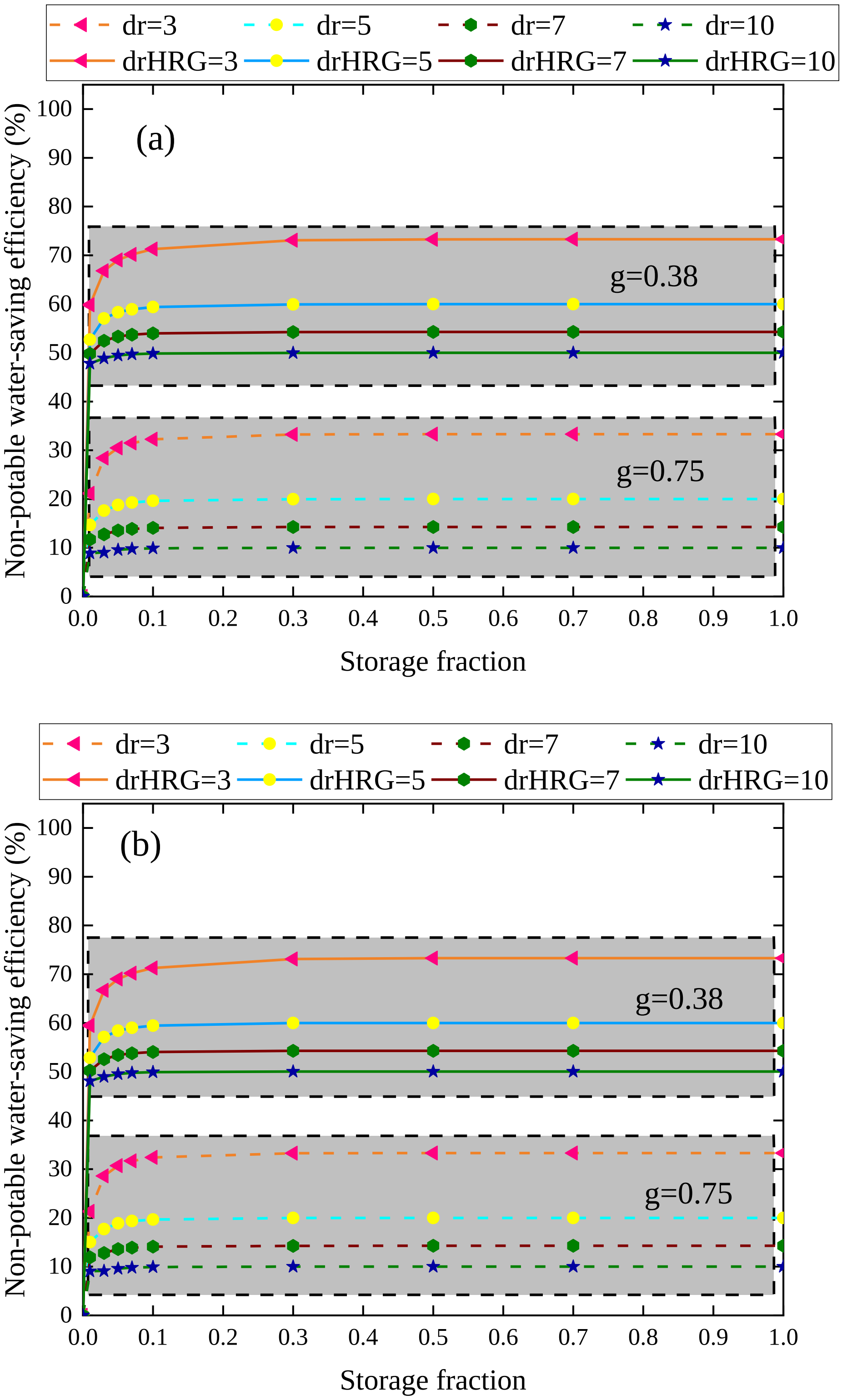

Fig 5-9 Design curves for HRGs in Japanese buildings
((a) stable daily non-potable water demand scenario; (b) seasonal daily non-potable water demand scenario; d_rHRG: the design curves for HRGs)

Approximately 40% of the maximum non-potable water-saving efficiency can be increased by upgrading the RWHs and GWRs to HRGs in these buildings. The maximum non-potable water-saving efficiency of RWHs and GWRs in buildings with d_r=3 and d_g=0.75 is 33.31% (s=0.5) and 100% (the dark wastewater needs to be treated), respectively, whereas the maximum W_H of HRGs in the same buildings can reach by 73.27% (s=0.5), if only 38% of the total wastewater is treated (g=0.38). Furthermore, the maximum W_H of HRGs in buildings with seasonal daily non-potable water demands can also reach by 73.30% (s=0.5 and g=0.38), which indicates that HRGs can adapt to dynamic water demand scenarios, and therefore, they can be used in such scenarios in Japan.

The graywater demand of buildings that install HRGs will decrease as d_g increases under the same d_r (Table 5-2). The proportion of rainwater demand and graywater demand to the total non-potable water demand of buildings with d_r=3 and d_g=0.75 are 62% and 38%, respectively, whereas the proportions in buildings with d_r=3 and d_g=3 are 91% and 9%, respectively. The greater rainwater demand in buildings that have installed HRGs will cause the design curves for HRGs to gradually approach the design curves for RWHs. For example, the maximum W_R in buildings with d_r=3 and d_g=10 using RWHs is 10%. If an HRG is generated by updating an existing RWH in these buildings, only 4% of the non-potable water demand will be graywater. The major alternative water in these buildings is still rainwater, and the non-potable water-saving efficiency does not increase significantly, which is uneconomical in complex HRGs.

Table 5-2 Rainwater and graywater demand of buildings with HRGs installed under different values of d_g

d_r	d_g	Toilet wastewater generated	Other wastewater generated (rainfall)	Rainwater demand	Graywater demand
3	0.75	28%	72%	62%	38%
3	1	28%	72%	72%	28%
3	3	28%	72%	91%	9%
3	5	28%	72%	94.4%	5.6%
3	10	28%	72%	96%	4%

5.5 Discussion

The implementation of RWHs, GWRs, and HRGs in the buildings of Japan can be determined by the design curves of these systems. The design curves show the relationship between the non-potable water-saving efficiency, demand fraction, storage fraction, and treatment fraction. The non-potable water-saving efficiency is not only a critical index for evaluating decentralized water reuse systems, but also reflects the economic potential of the systems because the direct economic benefit of the decentralized water reuse systems is in the saving of water tariffs. The rainwater demand fraction and graywater demand fraction are used to classify buildings with different water demand scenarios. The rainwater tank is a critical component of

RWHs, and significantly affects the non-potable water-saving efficiency and economic benefits of RWHs [51]. The rainwater tank sizes for RWHs in buildings with different rainwater demand fractions can be selected based on the relationship between the maximum W_R and the storage fraction. Increasing the storage fraction to achieve 100% of W_R should be optimal for RWHs, but the benefits of expanding the storage fraction to the maximum W_R will decrease. For example, the storage fraction of RWHs in buildings with d_r=1 is increased from 0.7 to 1, whereas the W_R is only increased by 0.07%. Campos Cardoso, Cavalcante Blanco [29] reported that the W_R of RWHs increases by less than 1% when expanding the rainwater tank sizes to the next level and is considered uneconomical. However, this standard should not be fixed throughout Japan. An appropriate rainwater tank for RWHs should be selected when the increasing cost of additional rainwater tanks is lower than the water tariff savings. The range of the optimal storage fraction of RWHs should be in the second trend of the design curves for RWHs (Fig 5-5) because the water tariffs and investment costs of RWHs will vary with location.

Buildings with stable daily non-potable water demands such as single-family residential buildings, especially those in the south of Japan that have a $d_r < 1$, are suitable for RWHs because of the 100% W_R. These types of buildings have larger roof areas allocated to the capture of rainfall and precipitation in comparison to the lower water demands of the few householders, and the lower rainwater demand fraction can allow a greater W_R to be achieved via the implementation of RWHs [52]. The similar design curves for RWHs in buildings with stable daily non-potable water demands and seasonal daily non-potable water demands in Japan (Fig 5-5 (a) and Fig 5-5 (b)) indicate that RWHs can also adapt to the seasonal daily non-potable water demand of other buildings in Japan, such as commercial buildings, which have larger non-potable water demands in summer because of cooling by air conditioning and a lower d_r because of the larger roof areas allocated to rainfall capture. However, the feasibility of using RWHs in buildings with seasonal non-potable water demand may be greatly affected by regions with bimodal rainfall patterns, such as Ecuador [35]. Furthermore, according to Fig 5-6, buildings where d_r=1 can expand the area of a roof that is allocated to rainfall capture to decrease the rainwater demand fraction and improve the W_R, whereas buildings with a d_r greater than 1 can reduce the non-potable water use to improve the W_R.

Compared with RWHs, the performance of GWRs rises steadily before reaching the maximum W_G (Fig 5-7), and the optimal treatment fraction of GWRs should be equal to d_g. However, the maximum W_G of GWRs in buildings with d_g = 1 is less economical than those buildings with a lower d_g because filtration devices greatly affect the economic feasibility of using GWRs [17]. Therefore, the maximum d_g of buildings in which GWRs are installed in Japan should be 0.72. Buildings with larger d_g values, such as those used for industrial manufacturing, which has a larger non-potable water demand for cooling and less wastewater because of the large amount of water evaporation, must recycle dark wastewater to meet the high non-potable water demands. In contrast, a building with d_g=0.3 may only need to collect the light wastewater that is generated by washbasins to meet all the non-potable water demands of the building. One representative of this type of building is the multi-story residential buildings. Compared with the large number of residents, the smaller area allocated for rainwater capture may make it unfeasible to use RWHs in multi-storied buildings, whereas the higher proportion of potable water consumption means that GWRs should be widely used in such buildings [23].

The use of GWRs in buildings with seasonal daily non-potable water demand in Japan is unfeasible. Although increasing the daily filtration volume of the treatment unit (treatment fraction) of GWRs can make the design curves reach the maximum W_G, the water-saving benefits of increasing the treatment capacity of GWRs gradually decrease (Fig 5-7 (b)). Meanwhile, the use of GWRs in buildings with seasonal daily non-potable water demands will lead to more overflowed graywater during periods of low non-potable water demand. Without proper measures to deal with excess treated graywater, the water will be discharged into the sewer. However, in Japan, payment via drainage tariffs is required to discharge sewage. Excess graywater that is discharged is not only wasted, but also increases the secondary costs of disposal, which seriously weaken the economic benefits of GWRs [38]. In contrast, the oversized graywater tanks used for GWRs in buildings with seasonal daily water demands (Fig 5-8) may increase the retention time of treated graywater during periods of low water demand, leading to the proliferation of bacteria [37].

Installing HRGs in buildings where RWHs and GWRs cannot achieve high non-potable water efficiency is feasible. Buildings in which $d_r = 1$ and $d_g = 0.75$ can improve the efficiency in saving non-potable water by 40% by using HRGs for water conservation, which can provide an efficiency that is more than double that of RWHs and GWRs. This high return can offset, to a certain extent, the disadvantage of the high investment cost associated with the installation of complex HRGs. Furthermore, upgrading GWRs to HRGs in this type of building can reduce the volume of wastewater that must be treated and avoid the need to use dark wastewater in buildings. HRGs has strong adaptability to seasonal daily non-potable water demand in Japan because the graywater used in HRGs is only supplied to toilets and other non-potable water demands are supplied by rainwater, although this method of water supply does not particularly affect the scale of rainwater tank sizes used in HRGs compared to those used in RWHs. The use of HRGs to supply water also means that buildings with a $d_g > 1$, which are unsuitable for the use of HRGs in Japan because a larger d_g will result in a smaller proportion of graywater demanded, and the non-potable water-saving efficiency of HRGs will not be much higher than that of RWHs. Graywater supplied by HRGs is only used for toilet flushing to ensure the proper compromise of graywater quality requirements. It is also optional to meet higher non-potable water demands in buildings by using graywater, but this requires higher water quality requirements; for example, the use of graywater for irrigation may cause permanent changes in the soil quality [7].

Based on the design curves for RWHs, GWRs, and HRGs in Japan obtained by the dimensionless parameter method, the optimal implementation scenarios of decentralized water reuse systems in Japan can be determined (Fig 5-10 and Fig 5-11). Four types of buildings with stable daily non-potable water demand and three types of buildings in Japan with seasonal daily non-potable water demand were divided according to d_r and d_g. Under the stable daily water demand scenarios, the higher non-potable water-saving efficiency of RWHs and GWRs can be achieved in buildings with a d_r between 0 and 1 and a d_g between 0 and 0.72. However, rainwater is a cleaner alternative water source in comparison with graywater, the use of RWHs is therefore preferable in these buildings, and RWHs can better adapt to seasonal changes in the daily non-potable water demand of a building. RWHs can be used in buildings with a d_r between 0 and 1 and a d_g between 0.72 and 10, and GWRs can be implemented in buildings with a d_r between 1 and 10 and a d_g between 0 and 0.72. HRGs are preferable in buildings with a d_r between 1 and 10 and a d_g between 0.72 and 1.

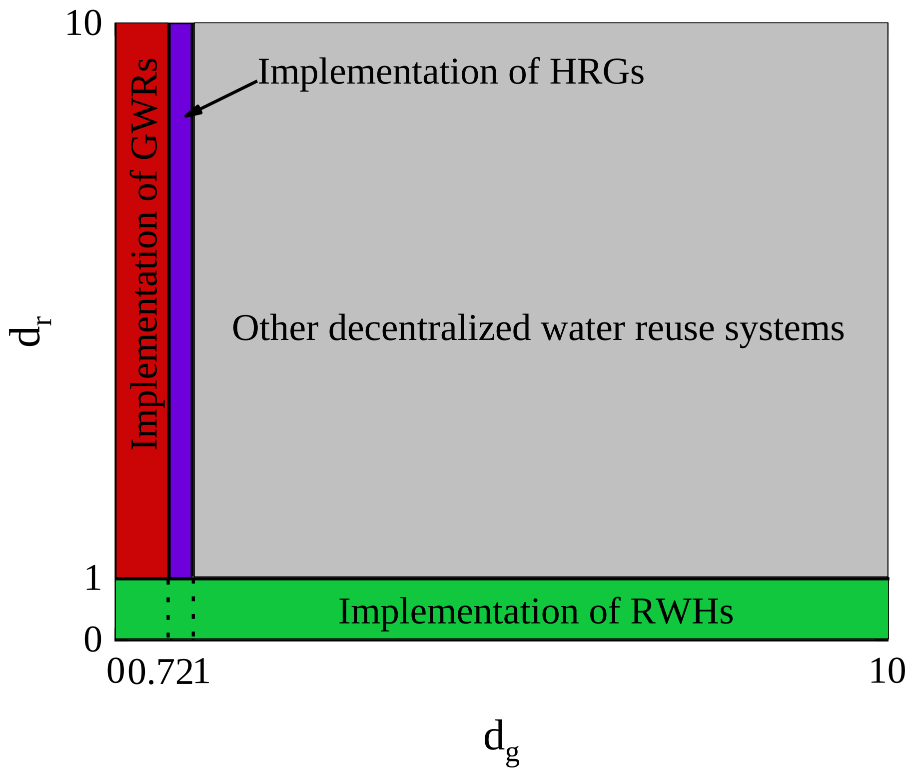

Fig 5-10 Implementation scenarios of decentralized water reuse systems in Japan (stable daily non-potable water demand scenario)

Under seasonal daily water demand scenarios, GWRs will no longer be used. RWHs can be used in buildings with a d_r between 0 and 1 and a d_g between 0 and 10, and HRGs are preferable in buildings with a d_r between 1 and 10 and a d_g between 0 and 1 (Fig 5-11). RWHs, GWRs, and HRGs are not recommended in buildings where d_r and d_g are simultaneously > 1 neither in stable demand scenarios nor seasonal demand scenarios. Adding other alternative water sources or changing the configuration of HRGs, such as mixing the graywater with rainwater to increase the supply, can be considered for this type of building.

The dimensionless parameter method can effectively help stakeholders evaluate, design, and optimize decentralized water reuse systems at a regional level in Japan without the requirement for collecting detailed data about each building in a region. Some buildings, such as large commercial buildings and small single-family houses, have the same demand fractions because of their specific building characteristics and the same design curve can therefore be used to design a suitable decentralized water reuse system for both types of building. Therefore, the use of the dimensionless parameter method can greatly accelerate the promotion of decentralized water reuse systems. For buildings in Japan with decentralized water reuse systems, the existing system can be evaluated and optimized according to the design curves (Fig 5-5, Fig 5-7, and Fig 5-9) based on the rainwater and graywater demand fractions of a building, to achieve the optimal non-potable water-saving efficiency. For buildings in Japan that have not installed decentralized water reuse systems or are newly built, stakeholders can determine the rainwater and graywater demand fractions of a building to select the appropriate water reuse system from RWHs, GWRs, and

HRGs according to Fig 5-10 and Fig 5-11, and implement the optimal decentralized water reuse systems based on the corresponding design curves. To extend the dimensionless parameter method to other regions, the local rainfall pattern and the water consumption characteristics of buildings should first be determined, and the design curves for RWHs, GWRs, and HRGs can be drawn according to the rainwater and graywater demand fractions of buildings. Finally, local implementation scenario diagram can be obtained based on the expected non-potable water-saving effect from the design curves, as shown in Fig 5-10 and Fig 5-11 in Japan.

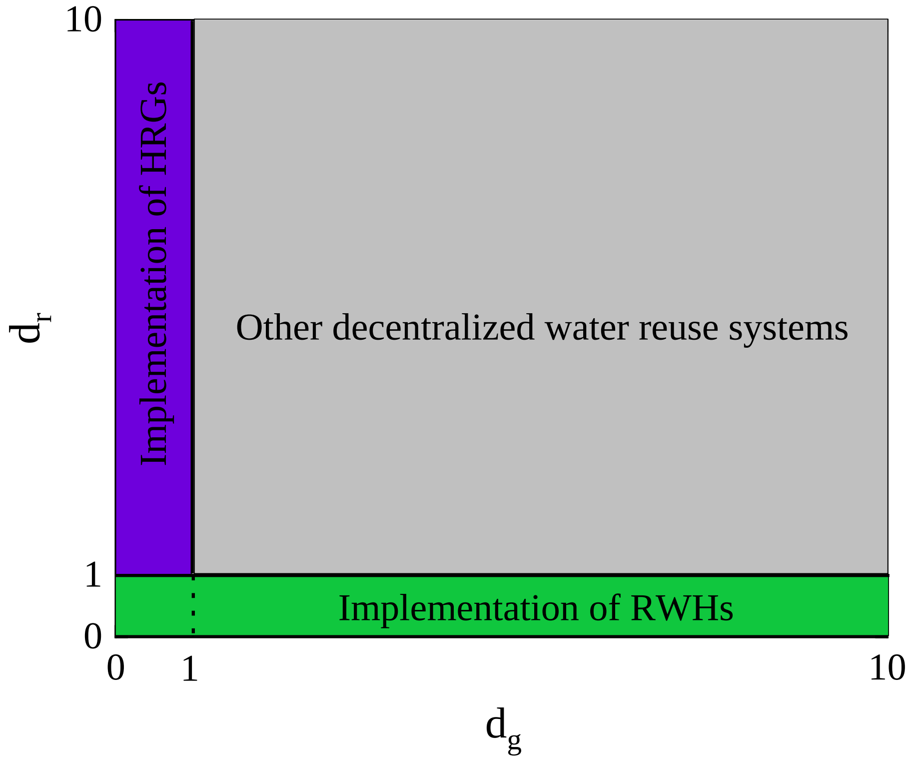

Fig 5-11 Implementation scenarios of decentralized water reuse systems in Japan (seasonal daily non-potable water demand scenario)

The dimensionless parameter method also can be used to design the optimal decentralized water reuse systems in the University of Kitakyushu. According to the induction from Chapter 2 and Chapter 3, the basic parameters of the campus are listed in Table 5-3. As shown in Table 5-3, according to the equation (5-6), equation (5-7), equation (5-8), and equation (5-9), the d_r of the campus can be calculated, which is approximately 1.79. Similarly, the d_g of the campus is approximately 0.82. The percentage of dark wastewater that is generated by toilets on the campus is approximately 30% according to the equation (5-9). However, because the water demand pattern of the campus is seasonal daily non-potable water demand scenario, the optimal decentralized water reuse systems of the campus are HRGs instead of GWRs. Therefore, the design curves of the optimal decentralized water reuse systems on the campus can be determined in Fig 5-12.

Table 5-3 The basic parameters of the University of Kitakyushu

Parameter	value
Precipitation	1672.02 mm
Capture areas	10,632 m^2
Wastewater generation	31,164 m^3/year
Rainwater water demand	15,615 m^3/year
Graywater demand	9,822 m^3/year
Non-potable water demand	25,437 m^3/year
Existing rainwater tank of the HRG	1000 m^3
Existing graywater treatment capacity	84 m^3/d
Water demand pattern	Seasonal daily non-potable water demand scenario

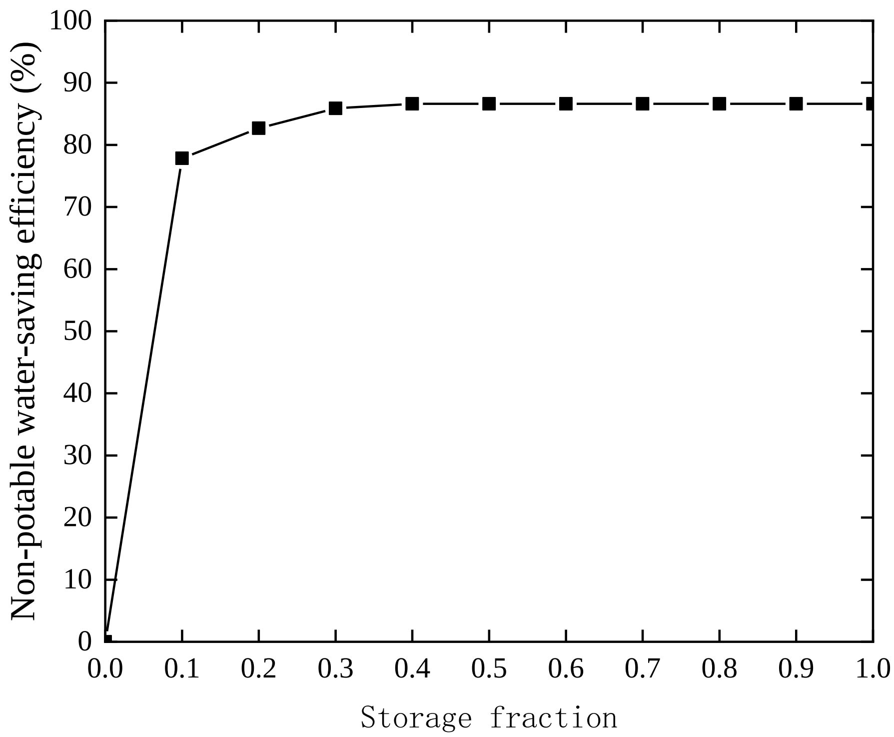

Fig 5-12 The design curves of the optimal decentralized water reuse systems on the campus obtained from the dimensionless parameter method

As shown in Fig 5-12, the optimal s of the campus is approximately 0.2 to 0.3 and the optimal g of the campus is 0.3. Therefore, according to the equation (5-8), the optimal rainwater tank of the HRG on the campus can be calculated, which is approximately 4,500 m^3. In addition, according to equation (5-9), the HRG can treat 30% of the total wastewater generated from the campus, approximately 27 m^3/d, to meet the graywater demand. The treatment capacity of the graywater subsystem in the HRG can be determined according to the optimal g, which can treat wastewater approximately 27 m^3 in a day.

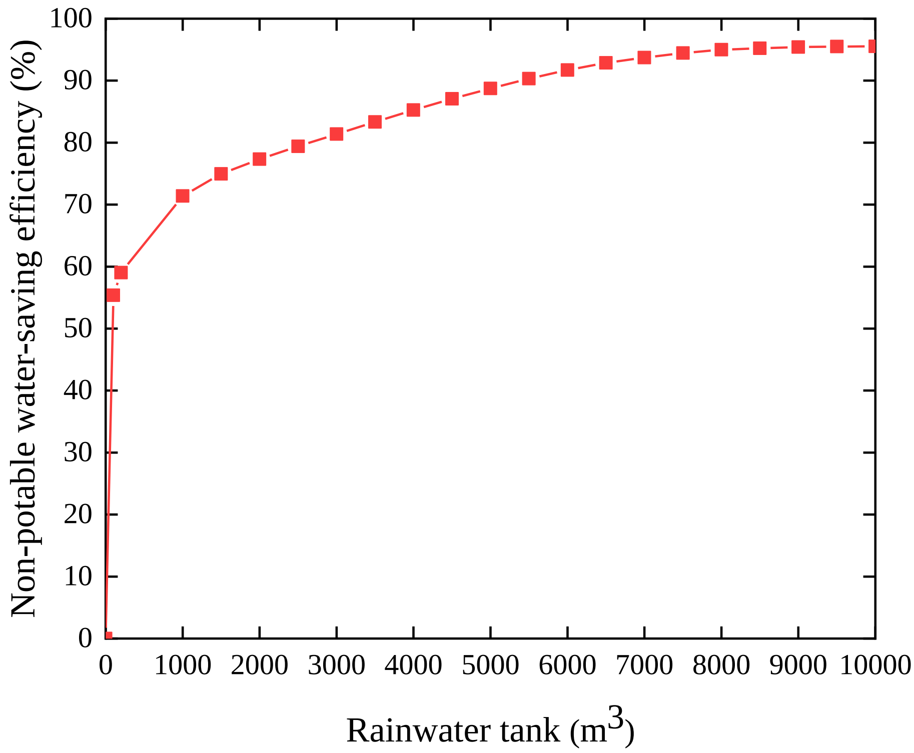

Fig 5-13 The design curves of the optimal decentralized water reuse systems on the campus obtained from the simulation model

Fig 5-13 shows the design curves of the optimal decentralized water reuse systems on the campus, HRGs, obtained from the simulation model mentioned in chapter 3. The total non-potable water demand of the campus is approximately 25,437 m^3 throughout the year including 15,615 m^3 of rainwater demand and 9,822 m^3 of graywater demand. As shown in Fig 5-13, the non-potable water-saving efficiency of the HRG increases by less than 2%, from 87.70% to 88.74%, when increasing the size of the rainwater tank in the HRG from 4500 m^3 to 5000 m^3. In other words, the HRG cannot conserve 500 m^3 year of potable water, which approximately 424.75 m^3 throughout the year, by continuing to increase 500 m^3 of the rainwater tank size after the rainwater tank reaches 4,500 m^3. Therefore, the optimal rainwater tank of the HRG on the campus obtained from the simulation model of HRGs is consistent with the result obtained from the dimensionless parameter method. In addition, the optimal treatment capacity of the HRG can be determined from the simulation model that 24 m^3/d of treatment capacity can meet the 9,822 m^3 of non-potable water demand throughout the year, which is consistent with the results obtained from the dimensionless parameter method that the treatment capacity of the HRG can be designed as 27 m^3/d. Therefore, this also verifies that the design curves obtained from dimensionless in Japan are accurate.

The difference between the optimal HRG scale obtained from the simulation model and the dimensionless parameter method is caused by the initial assumptions of the simulation. The initial assumption of the season daily non-potable water demand scenario is that there is a linear relationship between the potable water distribution volume of main water plants and the outdoor temperature in Japan, with a coefficient of 4. This coefficient is quoted from a report by the Ministry of the Environment in Japan (2009) and can be used as a reference. However, the actual water demand of a building cannot vary strictly with the outdoor temperature. The total water demands of the campus and the outdoor temperature of Kitakyushu throughout the year are shown in Fig 5-14.

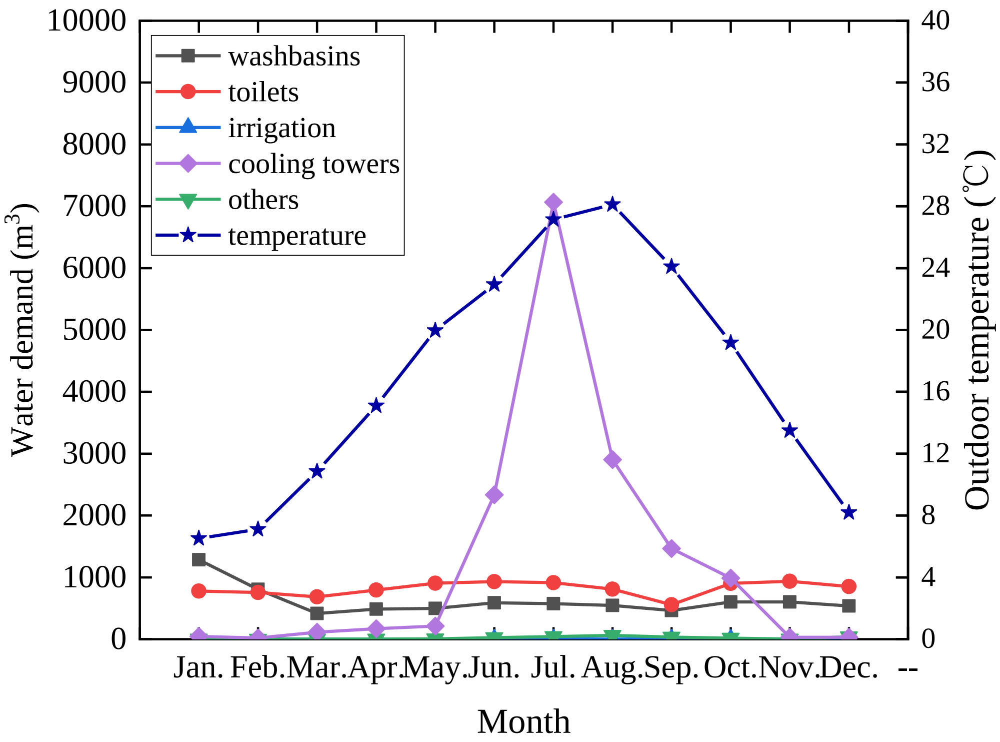

Fig 5-14 The water demands of the campus and the outdoor temperature of Kitakyushu throughout the year

According to Fig 5-14, the water demand of the University of Kitakyushu is extremely high in July because the air conditioning cooling towers work frequently from June to August. Therefore, the initial assumption of this study of the seasonal daily non-potable water demand scenario will underestimate the water demand of buildings in July and August and overestimate the water demand of buildings in March, April, May, September, October, and November when obtaining the design curves for the University of Kitakyushu. However, this initial assumption is also feasible to define the seasonal daily water demand of buildings because the report of Ministry of the Environment in Japan is an average of a lot of statistical data and the result will be consistent with water demands in most buildings in Japan.

The limitation of this study is that it only considers the reuse of rainwater and graywater for water conservation in buildings and ignores other alternative water sources, such as air conditioning condensate and desalination. Such alternative water sources may have more favorable application potential than rainwater and graywater in some regions [16, 53]. Furthermore, seasonal daily water demand is assumed to be related to outdoor temperature in this study, which may affect the extension of this method to other regions when discussing the feasibility of decentralized water reuse systems in buildings with seasonal daily non-potable water demand.

5.6 Summary

This chapter proposed a dimensionless parameter method to evaluate three decentralized water reuse systems in buildings at a regional level and obtained universal design curves for these systems in buildings with stable and seasonal daily non-potable water demand in Japan. The conclusions are as follows:

Four dimensionless parameters were designed in this study to evaluate decentralized water reuse systems: the rainwater demand fraction (d_r), graywater demand fraction (d_g), storage fraction (s), and treatment fraction (t). The modeling results indicate that d_r and d_g affect the feasibility of using RWHs, GWRs, and HRGs in buildings, and the storage fraction (s) and treatment fraction (g) affect the optimal configuration of RWHs, GWRs, and HRGs to achieve the maximum non-potable water-saving efficiency.

According to the design curves for RWHs, GWRs, and HRGs in Japan, favorable precipitation patterns will better support the priority use of RWHs and HRGs for building water conservation, not only in buildings with stable daily non-potable water demands but also in buildings with seasonal daily non-potable water demands. GWRs are only recommended for installation in buildings with stable daily non-potable water demands where the d_r is between 1 and 10 and d_g lies between 0 and 0.72, because GWRs cannot cope with changes in the demands for non-potable water that may be required in buildings.

The optimal configuration of RWHs in Japan is recommended to be selected using the second trend observed in the design curves for RWHs according to local water tariffs, whereas the optimal configuration of GWRs should be referred to the d_g of a building. The implementation of HRGs can greatly improve the non-potable water-saving efficiency of a particular building by reducing the costs of graywater treatment and using cleaner rainwater, although the size of the rainwater tanks used in HRGs do not evidently require changing in comparison with RWHs.

Our findings not only extend the generalized method of evaluating decentralized water reuse systems to GWRs and HRGs, but also extend the background of such evaluations from buildings with stable daily non-potable water-saving demands to those with seasonal daily non-potable water-saving demands. The results obtained in this study can help stakeholders combine local water tariffs and system costs to easily select the optimal decentralized water reuse systems under different scenarios. Future research should focus on other alternative water sources, diverse precipitation patterns, and changes in the water demand to further explore the generalized methods for use with decentralized water reuse systems to other regions.

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Chapter 6

ECONOMICAL OPTIMIZATION METHOD FOR IMPROVING THE ECONOMIC BENEFITS OF HRGS

Contents

6.1 Content

The economic unfeasibility of HRGs has hindered their implementation and methods to improve the economic benefits of HRGs have rarely been explored. To explore the economic potential of HRGs, this chapter proposes a comprehensive economic analysis based on the cooperative game theory to explore the economic potential of HRGs. The economic feasibility of the HRG was then analyzed based on the life cycle cost model. Then, considering that the implementation of the HRG weakened the profit of the main water plants, the cooperative feasibility and driving factors between the HRG and main water plants were explored in terms of mutual benefits based on the cooperative game theory. The results highlight that the construction costs significantly reduce the economic benefits of HRGs. HRGs have more substantial economic benefits in cooperative games than in non-cooperation. In addition, the subsidy of the government for HRGs makes it easier to drive the success of the cooperation. This chapter not only provides a new idea for improving the economic feasibility of HRGs but also provides policy orientations to the government to promote decentralized water reuse systems.

6.2 Introduction

The operation phase of buildings consumes large amounts of fresh water worldwide [1]. Some consumers in buildings do not require high-quality fresh water, such as toilets [2] and air conditioning cooling systems [3, 4]. These water demands in a building can be considered non-potable water demands and can be supplied by the on-site reuse of rainwater and graywater to conserve water. However, the on-site reuse of rainwater is unreliable in some regions owing to the irregular and insufficient rainwater that may not match the non-potable water demand in buildings [5, 6]. Similarly, recycling graywater in buildings with the seasonal water demand, such as for air conditioning cooling towers, has not attracted stakeholders [7]. Oh, Leong [8] indicated that graywater should not be reused for irrigation for maintaining soil quality. Hybrid rainwater-graywater systems (HRGs) are among the decentralized water reuse systems that can replace main water plants to simultaneously reuse rainwater and graywater on-site, in order to supply non-potable water to buildings [9]. HRGs circumvent the limitations of separately installing rainwater harvesting systems (RWHs) and graywater recycling systems (GWRs) through the hybrid water supply method and have profound implementation potential in buildings to conserve water.

HRGs can significantly enhance the water-saving efficiency of buildings [10]. Ghisi and Ferreira [11] found that the potable water-saving efficiency of simultaneously reusing rainwater and graywater in a multi-story residential building can be improved from 14.7%–34.8% to 36.7%–42.0% in comparison to separately reusing rainwater and graywater. The increasing potable water-saving efficiency can even reach 32.3% in commercial buildings by conversing the existing systems to HRGs [12]. Sapkota, Arora [13] proposed that HRGs are not only the most efficient systems for conserving water but also reduce wastewater and stormwater flows and contaminant loads, thereby reducing the cost of municipal systems. In addition, HRGs exhibit superior environmental performance in terms of curbing global warming, reducing water toxicity, and improving atmospheric quality [14]. Leong, Balan [15] carried out a life-cycle assessment among HRGs, RWHs, and GWRs in Malaysia. The authors determined that HRGs are the optimal systems in commercial buildings in Malaysia because they have the highest potable water-saving efficiency and the lowest environmental impact scores in comparison to RWHs and GWRs, as assessed by seven factors such as global warming potential, freshwater aquatic ecotoxicity potential, eutrophication potential, etc. HRGs have become the optimal water reuse systems in residential buildings in Brazil as they can help save 41.9% of potable water, 40.0% of domestic sewage, and 36.1% of total energy consumption [16].

However, environmentally friendly HRGs are accompanied by high investment and operation costs, which are difficult to amortize by the direct economic benefits of implementing HRGs [17]. The economic unfeasibility of HRGs has been demonstrated in the majority of previous studies. Rygaard, Godskesen [18] determined that HRGs are significantly more expensive than main water plants for conserving water in industrial harbor areas in Denmark. Furthermore, HRGs have no investment attractiveness in residential buildings in Brazil because the payback period for implementing HRGs is more than 17 years [19]. Similarly, Zang, Kumar [20] investigated the economic benefit of an HRG on a campus with student accommodation in India, and found that the payback period of the HRG is over 250 years if there are no economic optimization plans. Although the life cycle cost of HRGs can be reduced by installing more concise treatment facilities to purify water, the environmental benefits will also be reduced, particularly with regard to energy consumption [21]. HRGs with more economically constructed wetlands, which are optional for low-income houses, have the most embodied energy of all water-saving measures, whereas HRGs with relatively expensive membrane bioreactors (MBRs) can significantly reduce the total energy consumption [22-24]. Economic feasibility is one of the most essential factors for promoting HRGs because developers or residents, but not the government, invest on decentralized water reuse systems. Therefore, only economic benefits and financial support drive stakeholders to be willing to implement such systems in buildings to conserve water [25]. However, economic optimization strategies for uneconomical HRGs have rarely been explored. Previous studies on the economic optimization of decentralized water reuse systems in buildings have concentrated on increasing the local water tariff [26], seeking the virtual benefit of hedonic prices [27], comparing the economic feasibility of systems in different regions [28], and introducing a non-potable water tariff [29]. For example, the economic benefits of RWH in single-family buildings in Spain can be obtained when the local water tariffs reach to 555 JPY/m^3 [30]. In addition, Morales-Pinzon, Luruena [31] found that large-scale RWHs are only economically feasible in Spanish regions where the water tariff is higher than 139 JPY/m^3. Similarly, Friedler and Hadari [23] found that GWR could not achieve economic benefits in buildings under five floors in Israel. The results obtained from these economic optimization methods are limited to summarizing the advantages and water tariff scenarios for the implementation of decentralized water reuse systems. However, they are unsuitable for generally promoting the optimization of the economic benefits of HRGs, because when HRGs are implemented in a given building, the generation of rainwater and graywater has been determined, and the local water tariff will not change unreasonably in the short term. The operation of HRGs in regions that have less expectations of soaring water tariffs and subsidies may be stopped owing to negative economic benefits. Therefore, an economic optimization method that can be commonly used to improve the economic benefits of HRGs is essential for extending their life cycle and increasing their investment attractiveness, which can promote the implementation of decentralized water reuse systems in buildings.

A cooperative game is a game consisting of players in the form of alliances and cooperation. The results obtained by cooperative games increase the profits of all players or at least one player without being harmful to other players and ultimately increase the overall profits of alliances through cost allocation, complementing existing planning models, and changing the current operating models [32]. Cooperative games reveal the impact of the incentives of independent decision-makers and the agreement among players on the optimal profit of the alliance and have been widely used to improve the economic benefits of newly introduce renewable energy systems [33, 34]. In the last decade, the cooperative game theory has been expanded to various fields such as the optimization of the costs of air pollution governance [35] and the development of strategies of spatial planning [36]. Cooperative game theory has great potential for coping with the economic unfeasibility of decentralized water reuse systems. An independently running decentralized water reuse system without any financial subsidies has high water-saving cost [37], whereas the profit of the main water plants is weakened because the implementation of such systems reduces the load of water supply and indirectly increases the cost of water production. The mutually beneficial cooperation between decentralized water reuse systems and the main water plants may eliminate the adverse effects of non-cooperation and improve both economic benefits. However, the cooperative feasibility between decentralized water reuse systems and main water plants is still a largely underexplored domain, which underestimates the economic potential of such systems.

The aim of this chapter was to explore the economic potential of HRGs. To this end, we proposed a comprehensive economic analysis based on cooperative game theory. Our case study was a campus in Japan with an HRG tailored to achieve maximum water-saving efficiency. The economic benefits of the HRG were then evaluated based on the life cycle cost model. Finally, we compared the economic performance of the HRG by itself and in conjunction with the main water plants. Based on our findings, we suggested an optimal strategy to achieve an economically beneficial HRG. The results of this study can provide a new orientation for stakeholders to improve the economic benefits of HRGs and make such systems more economically attractive for water conservation in buildings.

6.3 Methodology

6.3.1 Life cycle cost model

The life cycle of the HRG on campus was assumed to be 15 years, as the corresponding plumbing system of the HRG was considered to have a 15-year life cycle [31]. In addition, the life cycle cost assessment of the HRG on campus excluded the cost of potable water demand for washbasins because such cost can be attributed to the total cost of the campus and is not affected by implementing the HRG. The net present value (NPV) was used to determine the profitability of HRGs by presenting the overall monetary value of the benefits and costs over the life cycle:

$$NPV = \sum_{n=1}^{15} \frac{B_{(HRG)total} - C_{(HRG)operation}}{(1+i)^n} - C_{(HRG)initial} \tag{1}$$

where n is the number of years; $B_{(HRG)total}$ is the overall benefit of HRGs in a year (JPY); $C_{(HRG)operation}$ represents the operation and maintenance costs of HRGs in a year (JPY); $C_{(HRG)initial}$ is the initial investment cost of HRGs (JPY); i is the discount rate (%), which is 3.5% in this chapter [38].

The benefit-cost rate (BCR) was used to evaluate the investment attractiveness of HRGs through the relative value between benefits and costs instead of the absolute value of cash flows. If BCR >1, then the HRG has economic benefits and is a sound investment. Otherwise, it is not recommended to invest on an HRG. The payback period of the HRG can be determined by the number of years when the BCR is greater than 1.

$$BCR = \frac{\sum_{n=1}^{15} \frac{B_{(HRG)total}}{(1+i)^n}}{\sum_{n=1}^{15} \frac{C_{(HRG)operation}}{(1+i)^n} + C_{(HRG)initial}} \quad (2)$$

The direct benefits of HRGs include saving water tariffs by conserving water and saving draining tariffs by reducing domestic sewage owing to the recycling of graywater. $B_{(HRG)total}$ can be expressed as follows:

$$B_{(HRG)total} = \sum_t Y_t \times T_W + \sum_t F_t \times T_d \quad (3)$$

where Y_t is the water output from the systems (m^3), T_W is the water tariff (JPY/m^3), F_t is the reduction in wastewater flow (m^3), and T_d is the draining tariff (JPY/m^3).

The initial investment, operation, and maintenance costs of the HRG are calculated as follows:

$$C_{(HRG)initial} = C_{(HRG)tank} + C_{(HRG)treatment} + C_{(HRG)plumbing} + C_{(HRG)labor} \quad (4)$$
$$C_{(HRG)operation} = C_{(HRG)MBR} + C_{(HRG)disinfection} + C_{(HRG)exam} + C_{(HRG)sludge} + C_{(HRG)energy} + C_{(HRG)extra} \quad (5)$$

where $C_{(HRG)tank}$ is the cost of water tanks (JPY); $C_{(HRG)treatment}$ is the cost of treatment devices (JPY); $C_{(HRG)plumbing}$ is the cost of the corresponding plumbing and pump systems (JPY); $C_{(HRG)labor}$ is the labor cost during the construction phase (JPY); C_{MBR} is the maintenance cost of MRB (JPY), which requires annual cleaning and replacement; $C_{(HRG)disinfection}$ is the cost of water disinfection (JPY); $C_{(HRG)exam}$ represents the routine annual examination and maintenance costs of HRGs (JPY); $C_{(HRG)sludge}$ is the cost of sludge disposal (JPY); $C_{(HRG)energy}$ is the electricity cost of HRGs (JPY);$C_{(HRG)extra}$ represents extra costs incurring from, e.g., the replacement of system accessories (JPY).

According to the current policy for decentralized water reuse systems in buildings in Japan, the Japanese government has mandated the implementation of rainwater or graywater in new buildings to conserve water. In addition, the government is willing to encourage users or stakeholders to install decentralized water reuse systems in buildings and actively provide up to 50% construction subsidies for such systems to promote the development of an environmentally friendly society. However, the government does not permit the potable water demands of buildings to be fulfilled using alternative water sources, such as rainwater and graywater. 7,407 m^3 of water on campus must be supplied by potable water from the main water plants. In addition, some decentralized water reuse systems cannot meet all non-potable water demands owing to the limited availability of alternative water sources. Therefore, the government must build or expand the main water plants to provide high-quality potable water in new buildings. The government also provides corresponding construction subsidies and annual subsidies for the building or expansion of the main water plants because such public facilities have a long investment cycle, high investment costs, and a wide range of benefits.

Therefore, in the non-cooperative scenario, the main water plants must expand the production scale of potable water to supply water to the newly built campus over the next 15 years. The profits of the main water plants are expressed as follows:

$$P_{(main)no} = \sum_{n=1}^{15} \frac{M \times T_W \times (1-\varepsilon) + M \times A - C_{(main)operation}}{(1+i)^n} - C_{(main)initial} \times (1 - G_{(main)}) \quad (6)$$

where $P_{(main)no}$ represents the profits of the main water plants in the non-cooperative scenario (JPY); M is the scale of the main water plants (m^3); ε is the self-use rate of the main water plants (%); A represents the annual subsidies of the government for the main water plants in the non-cooperative scenario (JPY/m^3); $C_{(main)operation}$ is the annual operation cost of the main water plants (JPY); $C_{(main)initial}$ is the initial investment cost of the main water plants (JPY); $G_{(main)}$ is the government subsidy rate for the expansion of main water plants (%).

The government will provide 50% of the construction subsidy for the HRG on the campus in the non-cooperative scenario, and the profits obtained by HRGs in a 15-year life cycle can be expressed as:

$$P_{(HRG)no} = \sum_{n=1}^{15} \frac{B_{(HRG)total} - C_{(HRG)operation}}{(1+i)^n} - C_{(HRG)initial} \times (1 - G_{(HRG)}) \quad (7)$$

where $P_{(HRG)no}$ represents the profit of the HRG in non-cooperative scenarios (JPY) and $G_{(HRG)}$ is the government subsidy rate for HRGs (%).

6.3.2 Cooperative game theory

In the non-cooperative scenario, the economic unfeasibility of HRGs has become a vital factor hindering the development of such systems. After receiving high government subsidies, it is difficult to further improve the economic benefits of HRGs from the limited public resources. On the other hand, the implementation of HRGs will reduce the profitability of the main water plants by reducing potable water demands. Therefore, HRGs can cooperate with the main water plants and form alliances with special payment mechanisms for mutual benefits. The ultimate goal of the cooperation is to improve the economic benefits and investment attractiveness of HRGs without hindering the profitability of other systems (e.g., the main water plants). Cooperative game theory was used to analyze the feasibility and driving factors of this cooperation. Two players, the HRG and the main water plants, were considered in this study. In cooperative games, the two players within an alliance are no longer independent individuals. To make the alliance profitable, the HRG can negotiate with the main water plants to appropriately increase the water tariffs (bargaining tariffs, BT) within the service areas of the HRG in exchange for the investment of the main water plants. The main water plants can also claim a higher BT by increasing the investment in the HRG (investment rate, IR). In addition, to avoid harming their own benefits, the main water plants have limited the upper limit of IR, whereas the HRG has limited the upper limit of BT. Therefore, BT and IR constitute the negotiating factors for a cooperative game between the two players. The two players can fairly participate in the cooperation by changing the BT and IR to make the alliance profitable and allocate profits based on their contribution to the alliance.

The government has played an essential role in external incentives to maintain a stable cooperative game between the HRG and the main water plants. As a macro-controller, the government does not participate directly in the negotiation of the cooperation. However, the government can influence the cooperative feasibility by regulating subsidy policies for the HRG and the main water plants. When the campus was built and the HRG was planned to be implemented on the campus, the government provided subsidies for the HRG and the expansion of the main water plants to conserve water on the premise of ensuring sufficient water supply for the campus. The government can adjust the subsidy policy in a cooperative game between the HRG and the main water plants. The government can increase the annual subsidy of the main water plants according to the proportion of the investment from the main water plants in the HRG to encourage the main water plants to cooperate with the HRG. On the other hand, the government can reduce the subsidy support for the HRG according to the proportion of investment that the latter accepts from the main water plants to ensure that the HRG can participate in the cooperation stably. In addition, the reduction of subsidies for the HRG not only reduces the annual expenditure for the government to implement decentralized water reuse systems in buildings, but also reduces the excessive intervention of the government in the private investment in the HRG. Therefore, the establishment of different subsidy scenarios by the government will affect the willingness of the HRG and the main water plants to cooperate, as well as the BT and IR within the alliance. Fig 6-1 shows the relationship between the HRG and the main water plants in the cooperative game and the relationship between the government and the alliance.

In the cooperative game, the main water plants invested in the construction cost of the HRG and received bargaining tariffs from the latter and an additional subsidy from the government. The profits of the main water plants in the cooperative game can be expressed as follows:

$$P_{(main)co} = \sum_{n=1}^{15} \frac{M\times(BT+T_W)\times(1-\varepsilon)+M\times(A+V)-C_{(main)operation}}{(1+i)^n} - C_{(main)initial}\times\left(1-G_{(main)}\right) - C_{(HRG)initial}\times IR \tag{8}$$

where $P_{(main)co}$ is the profit of the main water plants in the cooperative game (JPY), BT is the bargaining tariff (JPY/m^3), V is the value-added subsidy of the government for the main water plants (JPY/m^3), and IR is the investment rate of the main water plants for the HRG (%).

$$P_{(HRG)co} = \sum_{n=1}^{15} \frac{B_{(HRG)total}+\sum_t Y_t\times BT-\sum_t D_{Wt}\times BT-C_{(HRG)operation}}{(1+i)^n} - C_{(HRG)initial}\times(1-G_{(HRG)}+G_{(HRG)re}-IR) \tag{9}$$

where $P_{(HRG)co}$ is the profit of the HRG in the cooperative game (JPY), D_W is the potable water demand of the campus (m^3), and $G_{(HRG)re}$ is the reduced subsidy of the government when the HRG accepts the subsidy of the main water plants (%).

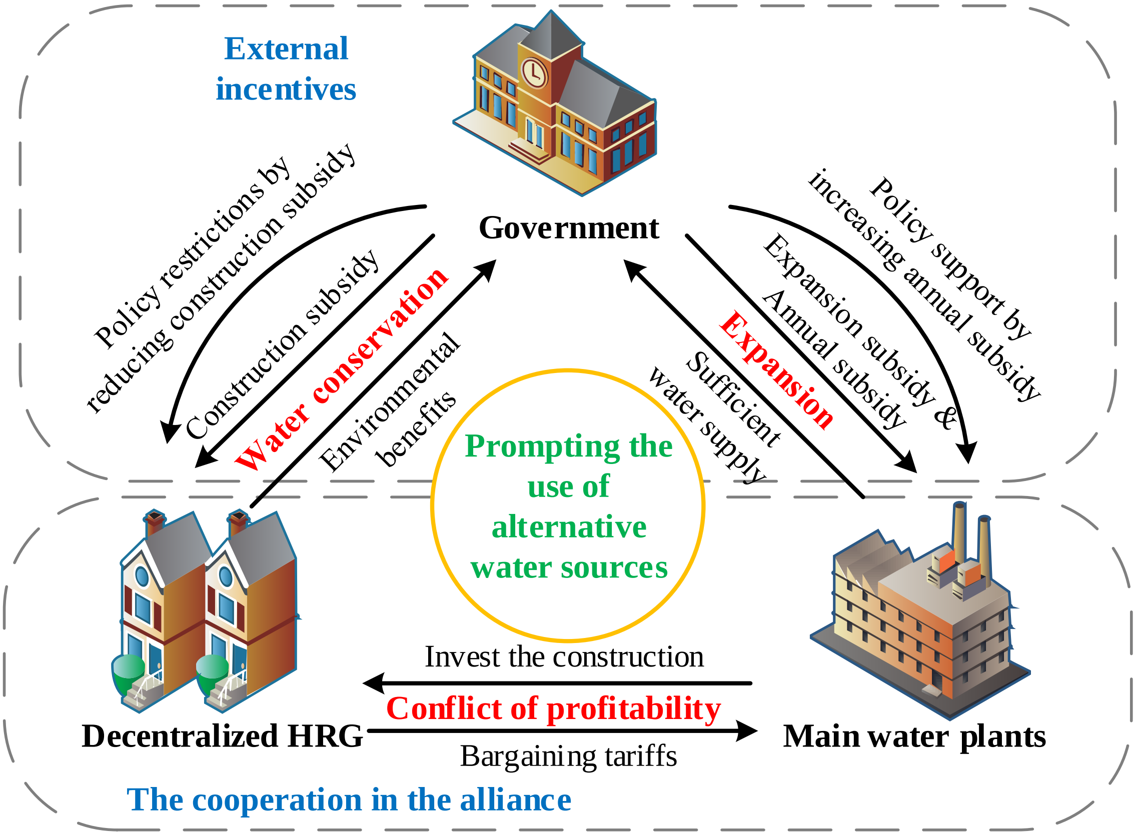


Fig 6-1 Relationship between the government, the HRG, and the main water plants in the cooperative game

The overall profit of the alliance is P (JPY):

$$P = P_{(HRG)co} + P_{(main)co} \tag{10}$$

To allocate the overall profit of the alliance to each player fairly, the Shapley value was used in this chapter, which allocated the profit according to the contribution of each player when joining the alliance. The Shapely value method can be expressed as follows:

$$P_j' = \sum_{K \in Z} \frac{[(|K|-1)!(z-|K|)!]}{z!} \times [v(K) - v(K_j/[j])] \tag{11}$$

where P'_j is the allocated profit of the player j (JPY), $P'_{(HRG)co}$ and $P'_{(HRG)co}$ are considered in this study, which represent the allocated profit of the HRG and the main water plants, respectively; Z is the permutation of the alliance; K is any subset of Z; z is the number of members in alliance Z; $|K|$ is the number of members in subset K; $v(K)$ is the overall profit of the subset K (JPY); $v(K_j/[j])$ is the overall profit of subset K excluding player j (JPY).

The government can affect the cooperation by adjusting the subsidy policy. Such effects can be quantified as follows:

$$GVS = 100\% \times \frac{V}{A} \tag{12}$$

$$GSR = 100\% \times \frac{G_{(HRG)re}}{G_{(HRG)}} \tag{13}$$

where *GVS* is the government value-added subsidy rate (%), which refers to the proportion of the government incentive for the main water plants, and *GSR* is the government subsidy reduction rate (%), which refers to the ratio that the government can reduce the subsidy to the HRG based on the investment from the main water plants that the HRG receives in the cooperation. GVS and GSR represent the macro-control of the government to the main water plants and the HRG in the cooperative game, respectively. The government can encourage the main water plants to invest in the HRG by increasing GVS, whereas the government can reduce subsidies for the HRG by increasing GSR.

Therefore, the result of the cooperation between the HRG and the main water plants varies with the change in GVS and GSR. In addition, in a specific subsidy policy (a certain GVS and GSR of the government), the two players can form various forms of cooperation by negotiating the BT and IR. The total number of negotiation plans in the specific GVS and GSR can be determined as *U*. Among *U*, a feasible cooperation can be determined by simultaneously satisfying Equations (14) and (15):

$$P'_{(HRG)co} > P_{(HRG)no} \& P'_{(main)co} > P_{(main)no} \tag{14}$$

$$P > P_{(HRG)no} + P_{(main)no} \tag{15}$$

The total number of the feasible cooperation can be determined as u.

Therefore, the cooperative feasibility rate between the HRG and the main water plants under a specific GVS and GSR can be calculated as follows:

$$Cooperative\ feasibility\ rate = 100\% \times \frac{u}{U} \tag{16}$$

The impact of the four parameters (*BT*, *IR*, *GVS*, and *GSR*) on the cooperative feasibility between the main water plants and the HRG is discussed in the next section.

6.3.3 Data source

Twenty-year daily precipitation data of Kitakyushu City were selected from the Japan Meteorological Agency (2020) [39] to determine the performance of the HRG, because precipitation data of such length can be comparable to the accuracy of the simulation by using 50-year precipitation data [40]. The study area is humid and rainy throughout the year, with an annual precipitation of approximately 1720 mm. The precipitation trend is unimodal, and the rainy season is concentrated from June to September, whereas other months have less precipitation (Fig 6-2).

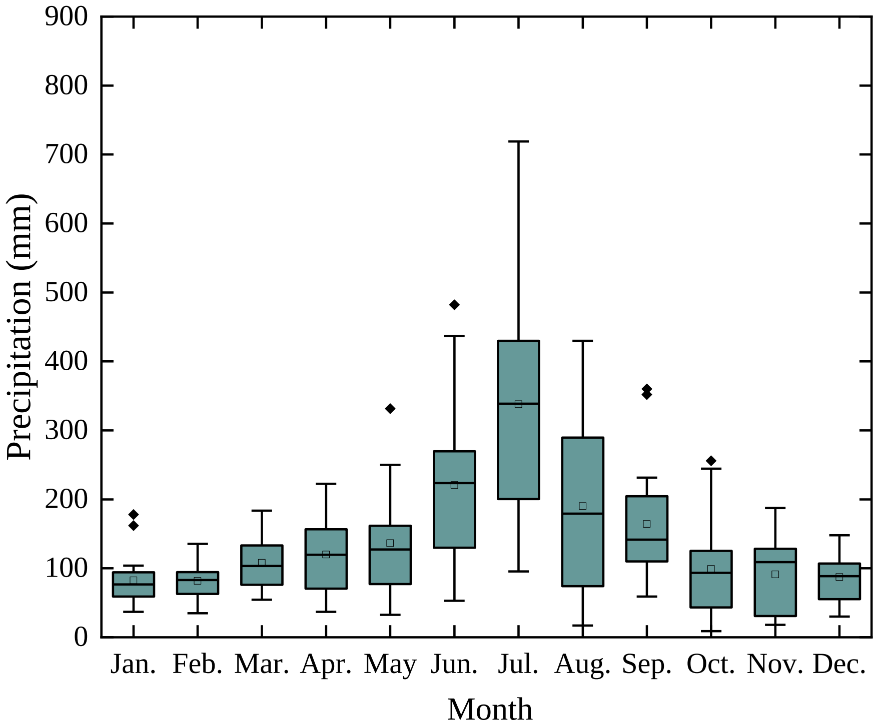


Fig 6-2 Annual precipitation of the study area

The rainfall capture areas on the campus were measured using Google Map. The electricity consumption of the HRG was reported by Chen, Gao [41]. The water consumption list of the campus and the initial investment cost of the HRG were determined by an on-site survey on the campus. The life cycle cost inventory of the HRG is shown in Table 6-1.

Table 6-1 Life cycle cost inventory of the HRG

Types	Costs
Plumbing and pump systems	84,970,960 JPY
Rainwater filter	700,000 JPY
Water tanks	9,009 JPY/m^3
Reverse osmosis membrane[a]	2,000,000 JPY
Cleaning of one membrane	225,000 JPY/year
Disinfection	500,000 JPY/year
Annual examination	5,925,000 JPY/year
Maintenance[b]	16.5% of life cycle cost
Sludge disposal	40 JPY/m^3
Extra cost	885,000 JPY/year

Note: [a] One membrane has a 5-year life cycle and 12 m^3/d flux;

[b] Citation from Chen, Gao [41]

The water tariffs and draining tariffs in the study area and the construction cost of the main water plants were obtained from the Kitakyushu City Water and Sewer Bureau (2020) [42] and are listed in Tables 6-2 and 6-3, respectively.

Table 6-2 Water tariffs and draining tariffs of the study area

Types	Price (JPY/ m^3)					
Water tariffs	Base	1–25 m^3	26–50 m^3	51–200 m^3	201–1,000 m^3	More than 1,000 m^3
	4,500 JPY	124	158	210	290	325
Draining tariffs	Unless than 20 m^3	21–50 m^3	51–100 m^3	101–400 m^3	401–20,000 m^3	More than 2,000 m^3
	1268 JPY	141	208	257	307	407

Table 6-3 Life cycle cost inventory of the main water plants

Types	Costs
Construction cost	1,038 JPY/m^3
Construction subsidy	50%
Water production cost	160 JPY/m^3
Annual operation cost	97 JPY/m^3
Annual subsidy	1 JPY/ m^3
Self-use rate	5%

6.4 Results

6.4.1 Water-saving efficiency

According to the on-site survey on the campus, the maximum daily non-potable water demand of the toilets was approximately 47 m^3. Therefore, four units of membranes were used by the HRG to treat wastewater. Fig 6-3 shows the design curves of the HRG on campus. Considering the additional environmental benefits of the HRG, 6,400 m^3 of rainwater tanks were selected as the optimal scale because less than 50 m^3 of potable water can be conserved when continuing to expand the rainwater tank by 100 m^3 (the water-saving efficiency and the non-potable water-saving efficiency increased by less than 0.2%). Therefore, an HRG with 6,400 m^3 of rainwater tanks and four membrane units was determined as the optimal scale to evaluate the economic feasibility and potential on the campus. The water-saving efficiency and non-potable water-saving efficiency of the HRG were 71.8% and 92.7%, respectively. Therefore, the HRG can output approximately 23,570 m^3 of non-potable water, while the campus still requires approximately 9,274 m^3 of potable water from the main water plants throughout the year.

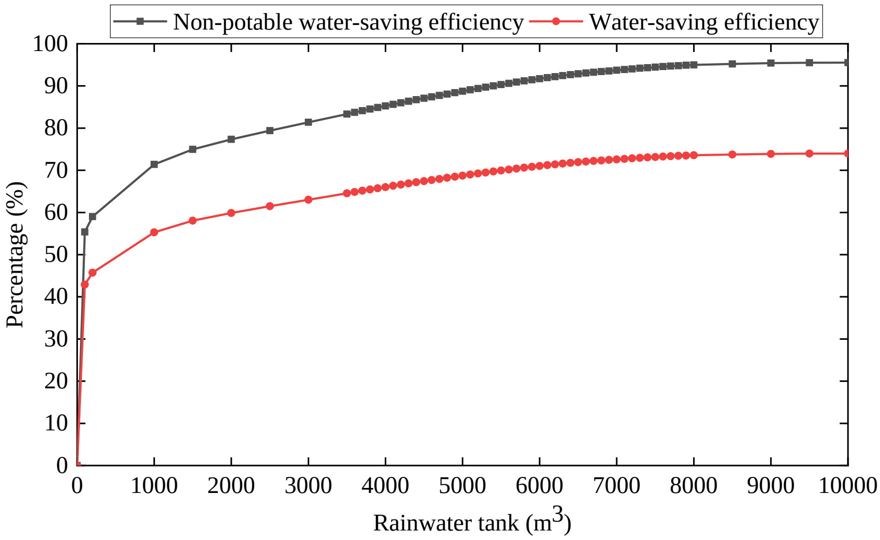


Fig 6-3 Design curves of the HRG

6.4.2 Economic benefit

The economic benefits of the HRG and main water plants in the non-cooperation scenario are shown in Fig 6-4. According to Fig 6-4, the HRG used on the campus was economically unfeasible in a 15-year life cycle with an NPV of -144,086,063 JPY. The lowest NPV of the HRG in the first year indicates that the initial investment cost was the major factor influencing the negative economic benefits. In addition, the initial investment cost cannot be recovered quickly by conserving water because of the high operation and maintenance costs of the HRG. A 50% construction subsidy from the government, the highest subsidy in Japan, was considered to salvage the HRG. The NPV of the HRG was enhanced to -64,375,400 JPY under the highest subsidy in 15 years, revealing that the economic unfeasibility of independently implementing the HRG was still a major obstacle to the promotion of such systems without other economic optimization.

The economic benefits of the main water plants were affected by implementing the HRG. Approximately 32,844 m^3 of potable water was required by the campus without conserving water by using the HRG, and the main water plants should be expanded to an appropriate scale to ensure a sufficient water supply. An additional income of 12,800,100 JPY in 15 years could be generate by the main water plants by selling water. However, approximately 9,274 m^3 of potable water was required by the campus in a year after implementing the HRG, because its water-saving efficiency was 71.8%. The high water-saving performance of the HRG weakened the economic benefits of the main water plants to -376,062 JPY over a 15-year life cycle.

To increase the investment attractiveness of the HRG, the government can adjust the construction subsidy for the HRG (Fig 6-5). The BCR of the HRG in a 15-year life cycle without any construction subsidies from the government was 0.5 and the payback period was more than 160 years, indicating that negative investment attractiveness appeared in the HRG. The investment potential of the HRG was still poor after receiving the current maximum 50% construction subsidy from the government, because the BCR was 0.7 and the payback period was more than 80 years. Continuing to increase the construction subsidy to 90%, the BCR of the HRG was close to 1, demonstrating that at least 90% of the construction subsidy was required to make the HRG attractive for investment.

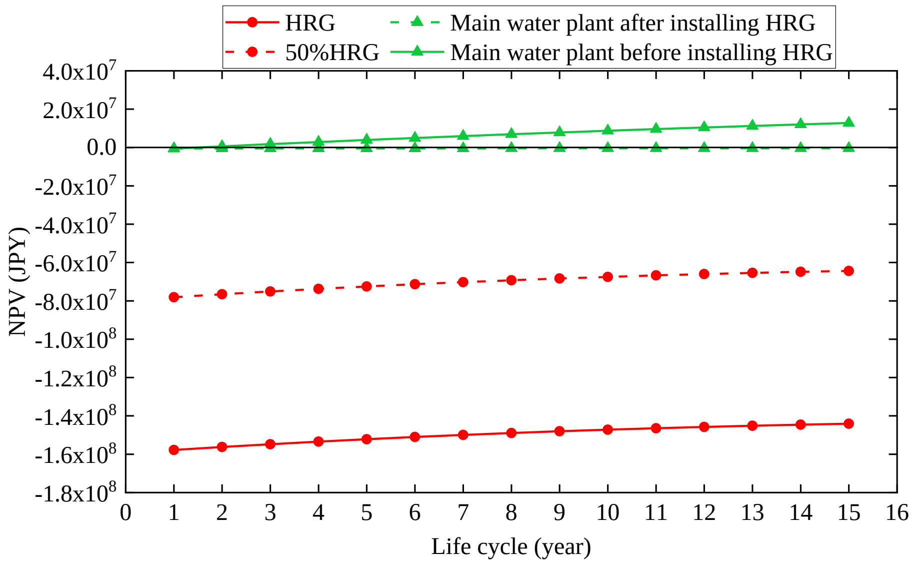


Fig 6-4 Economic benefits of the HRG and main water plants

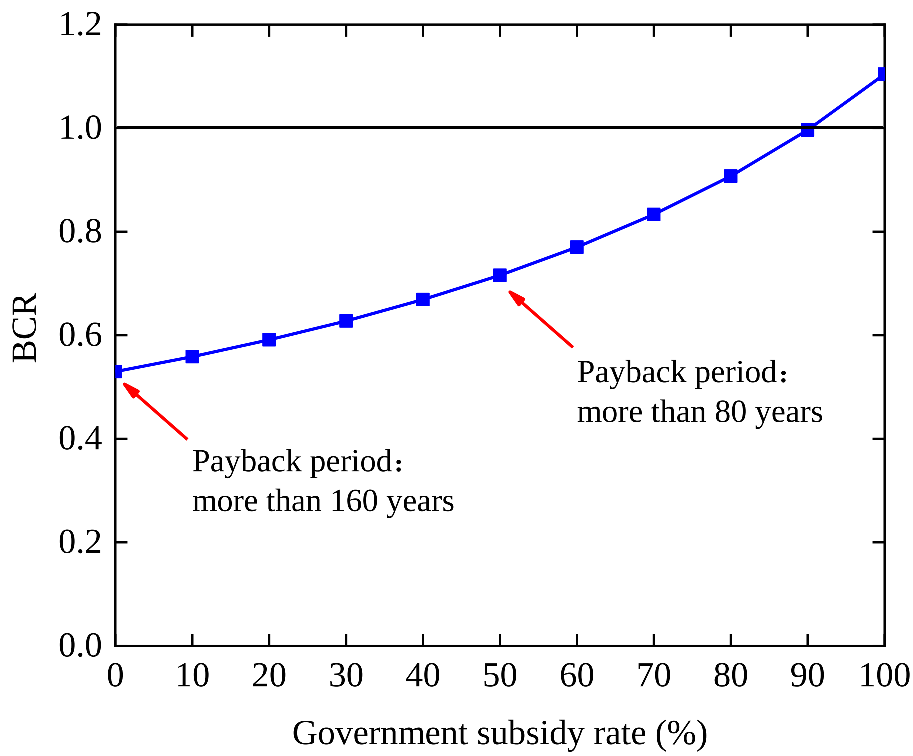


Fig 6-5 BCR of the HRG with different construction subsidies in 15 years

6.4.3 Economic potential

According to the vicious circle of economic benefits between the HRG and main water plants and while considering the fact that the government must subsidize almost all construction costs under the non-cooperative scenario to achieve the economic feasibility of the HRG, a huge cooperation potential between the HRG and main water plants has emerged to improve mutual benefits. The government can also adjust policies to actively support this cooperation because it can reduce annual expenditure by reducing subsidies to the HRG in the cooperation. The economic potential of the HRG in a cooperative game with the main water plants was evaluated in this section.

(1) Cooperation feasibility rate

The simulation of the cooperative game was based on the current subsidies of the government, in which the annual subsidy for main water plants was 1 JPY/m^3 and the construction subsidy for the HRG was 50%. Therefore, the external incentives of the government, which involved increasing the annual subsidy from 1 JPY/m^3 to 50 JPY/m^3 based on the amount of the investment rate from the main water plants to the HRG and the decrease of the construction subsidy from 50% to 0% based on the amount of the investment rate accepted by the HRG, were assumed to evaluate the cooperative feasibility between the HRG and main water plants. The relationship among the cooperation feasibility rate, the GSR and the GVS is shown in Fig.8. The cooperation between the HRG and the main water plants to improve mutual benefits was feasible, with a maximum cooperation feasibility rate of 57.9% and a minimum cooperation feasibility rate of 0.2%. Additionally, the cooperation feasibility rate increased from 53.9% to 57.9% when the financial subsidy of the government fully supported the HRG (CSR = 0), whereas the cooperation feasibility rate increased from 1.4% to 57.9% when the financial subsidy of the government fully supported the main water plants (GVS = 4,900%). This demonstrates that it was easier for the government to promote the success of the cooperation by subsidizing the HRG than by subsidizing the main water plants.

(2) Scenario analysis

As is shown in Fig 6-6, $G_{(HRG)re}$ varied from 0% to 50% at 1% intervals, and V varied from 0 JPY/m^3 to 49 JPY/m^3 at 1 JPY/m^3 intervals. According to Equations (12) and (13), the variation range of *GSR* decreased from 100% to 0% at a rate of 2%, and the variation range of *GVS* increased from 0% to 4,900% at a rate of 100%. Therefore, 2,550 subsidy policies of the government were obtained. Under each subsidy policy, the HRG and main water plants have to negotiate the BT and IR to cooperate and make the alliance profitable. Therefore, six typical scenarios were set to discuss the impacts of different negotiation and subsidy policies on the alliance's overall profit (Table 6-4). Scenario 1 was used to discuss the impacts of the different negotiations between the HRG and the main water plants on the alliance's overall profit under the specific subsidy policy. Scenario 2 was used to discuss the cooperation plan between the HRG and main water plants when the government only supported the HRG. Scenario 3 was used to discuss the cooperation plan between the two players when the government only supported the main water plants. Scenario 4 was used to explore the impact of changing the GSR on the recommended BT and IR of the alliance. Scenario 5 was used to explore the impact of changing the GVS on the recommended BT and IR of the alliance. Finally, scenario 6 was used to analyze the optimal BT and IR in the cooperation under the lowest cooperative feasibility rate.

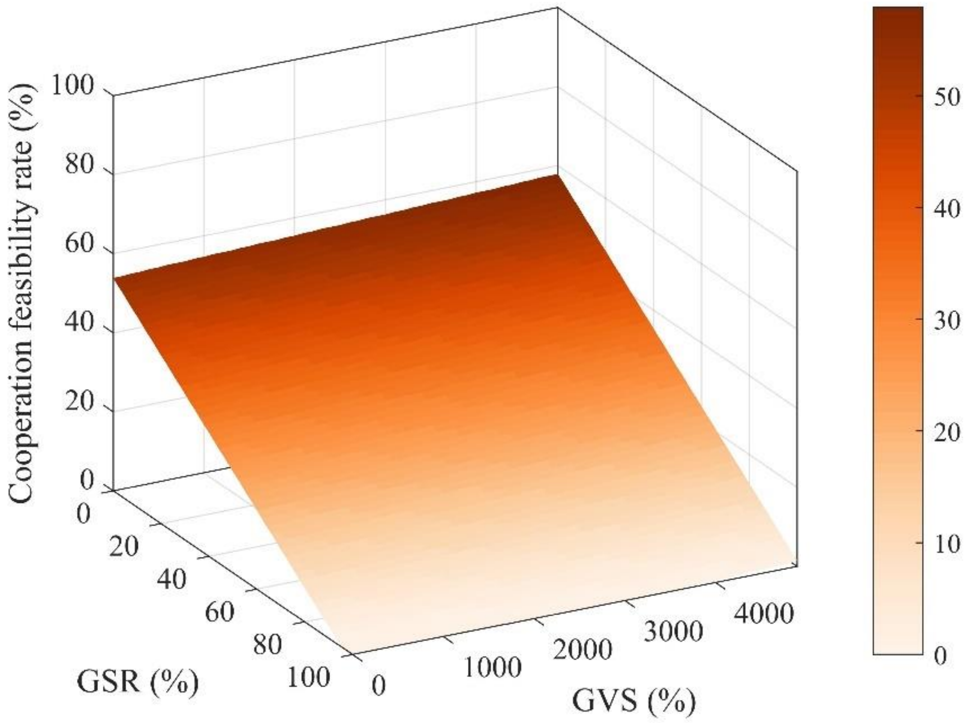


Fig 6-6 Cooperation feasibility rate between the HRG and main water plants

Table 6-4 Scenario settings

Scenarios	GSR (%)	GVS (%)	Cooperation feasibility rate (%)
1	50	2,500	27.8
2	0	0	53.9
3	100	4,900	1.4
4	22–78	2,500	11.8–43.5
5	50	1,100–3,900	26.6–28.7
6	98	2,100	0.2

The median value of the cooperation feasibility rate of scenario 1 as the representative scenario in that the government simultaneously subsidized the HRG and main water plants (Figs 6-7 and 6-8). The profit of the HRG increased with the increase of IR under the same BT, whereas the profit of the main water plants showed an opposite trend with IR. The profits of the HRG and main water plants increased with the increase of BT under the same IR. Therefore, HRG can contribute profits to the alliance with high IR and high BT (above the black line in Fig 6-7 (a)), whereas the main water plants can contribute profits to the alliance with low IR and BT (below the black line in Fig 6-7 (b)). The overall profit of the alliance increased with the increase of BT and was not affected by IR (Fig 6-8). The reason was that IR simultaneously became the expenditure of the main water plants and the profit of the HRG and offset each other in the overall profit of the alliance. Therefore, the overall profit of the alliance under different BT values mainly depended on the profit of water conservation by the HRG and the profit of selling water by the main water plants.

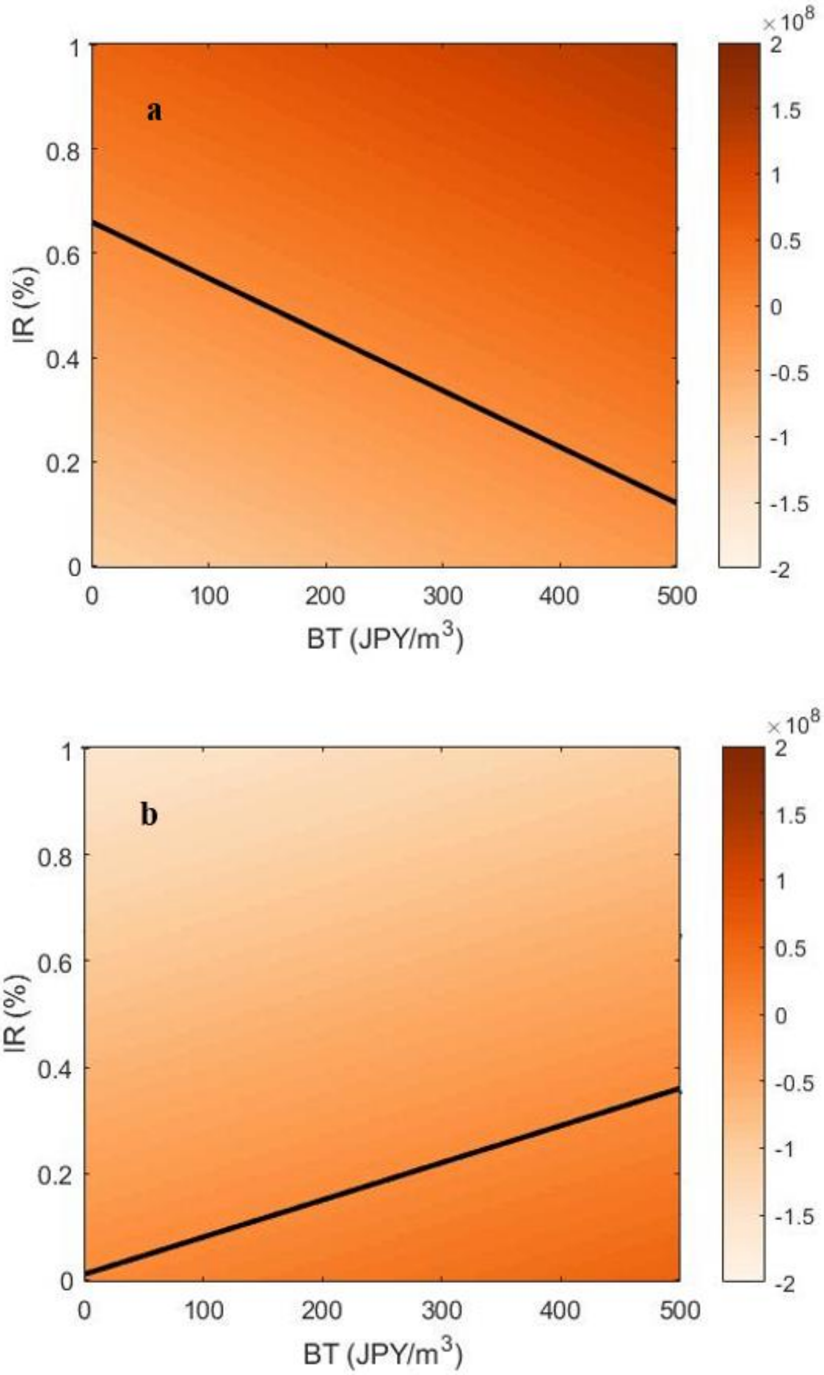


Fig 6-7 Profits of the HRG (a) and main water plants (b) of scenario 1

In scenario 1, the minimum BT that made the cooperation feasible was 362 JPY/m^3 (Fig 6-8). Under this BT, the HRG and the main water plants cannot simultaneously contribute profits to the alliance. The profit of the HRG appeared when IR was greater than 27%, whereas the profit of the main water plants appeared when IR was less than 27%. The alliance can rely only on a single player to obtain profits, whereas the other player allocates the overall profit of the alliance according to the Shapley value. Therefore, 27% of IR was recommended for the main water plants when the BT was negotiated at 362 JPY/m^3 to balance the initiative of both players, although the total profits of the alliance cannot be affected by IR. However, when the BT in scenario 1 was negotiated to 500 JPY/m^3, the HRG and main water plants could simultaneously obtain profits starting from under 12% to 36% of IR (Fig 6-8). Therefore, the two players can negotiate in a larger IR interval, which increases the chance of a successful cooperation.

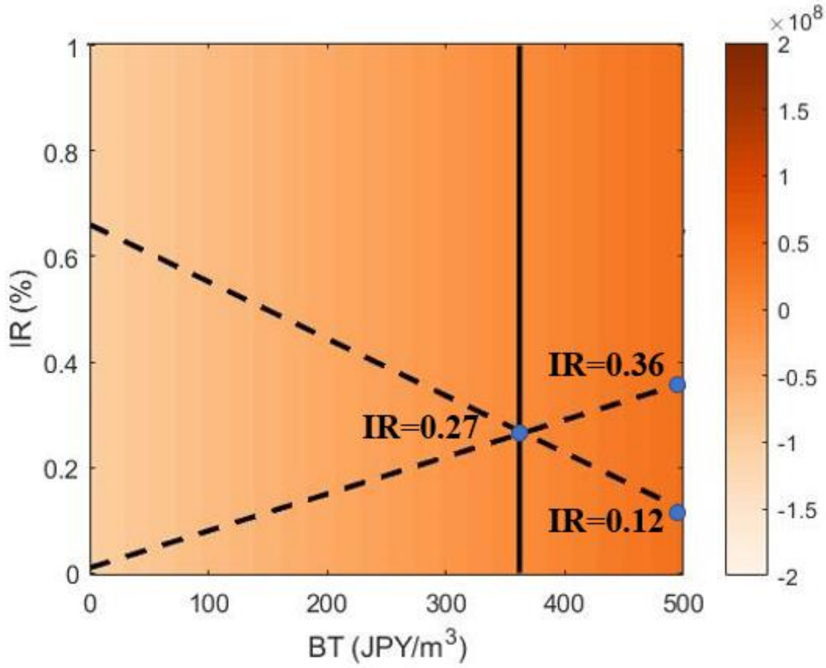


Fig 6-8 Profits of the alliance of scenario 1

On the other hand, when the cooperation run at the lowest BT, the recommended IR percentage (27%) also included the profit allocated between the two players. Fig 6-9 shows the allocated profit of the HRG and the main water plants in scenario 1. According to the distribution principle of the Shapley value, the player with greater marginal contribution to the cooperation (higher contribution to the alliance) will be allocated more profit. The allocated profits of the HRG and the main water plants significantly increased with an increase in BT. Under the same BT, the allocated profit of the HRG decreased slightly with an increase in IR, whereas the allocated profit of the main water plants exhibited the opposite trend. The ultimate goal of the cooperative game between the HRG and the main water plants is to realize the economic feasibility of the HRG without hindering the benefits of water plants. Therefore, keeping IR at a lower value (27% in scenario 1) helps the HRG to allocate more profits.

According to the analysis of scenario 1, when the BT of the alliance was large, not only would the total profits of the alliance be higher, but the range in which the HRG and main water plants could simultaneously contribute profits to the alliance would also increase, thereby facilitating the formation of the cooperation. Therefore, only the minimum profit of the alliance is discussed in the following scenarios to represent that under a specific government subsidy policy, a cooperation between the HRG and main water plants will be feasible with the lowest bargaining water tariffs and the optimal IR. BT and IR were determined as recommended in the scenario.

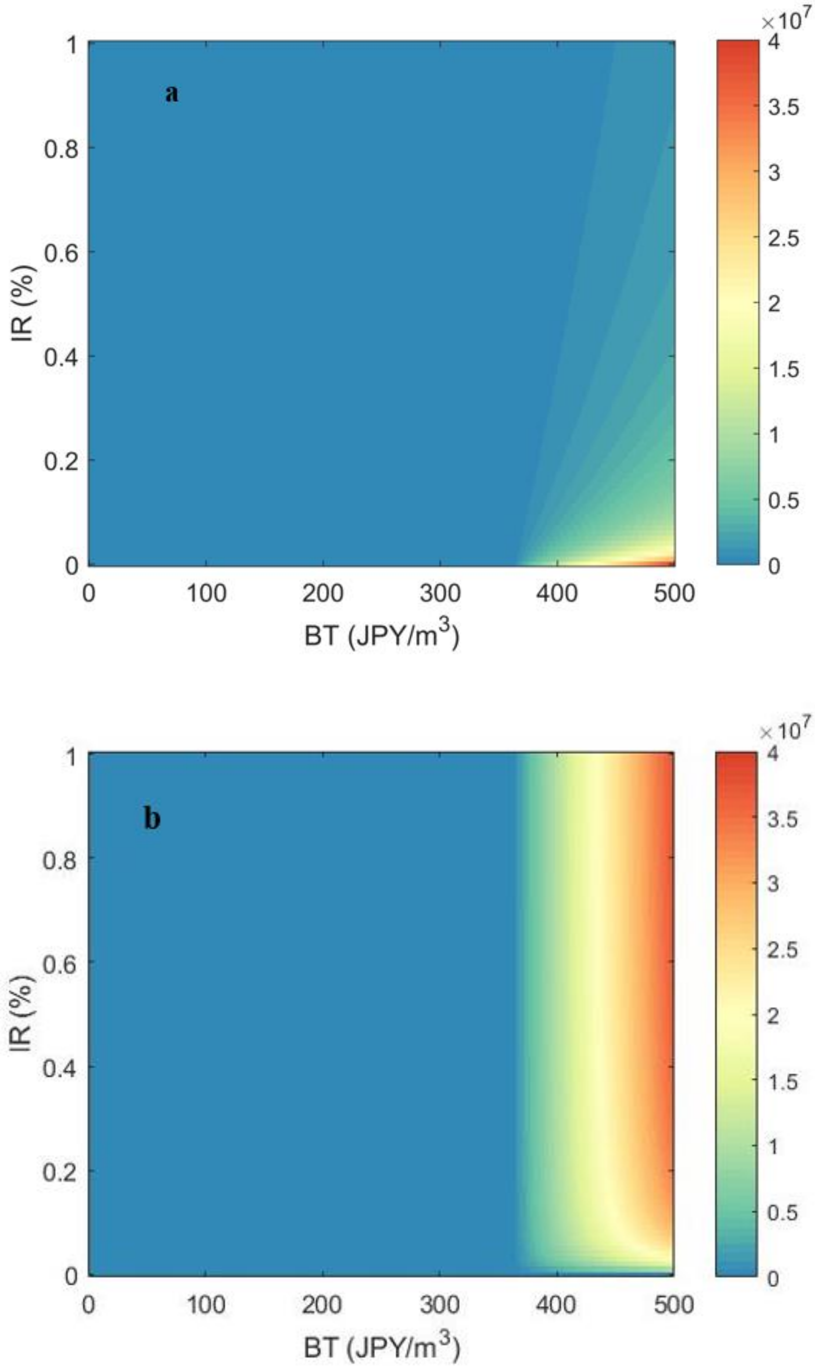


Fig 6-9 Allocated profits of the HRG (a) and main water plants (b) of scenario 1

The profits of the HRG, the main water plants, and alliances in scenario 2 are shown in Fig 6-10 and Fig 6-11. In scenario 2, a 50% government construction subsidy for the HRG and 1 JPY/m^3 annual government subsidy for the main water plants were not adjusted based on the negotiations of the two players. Scenario 2 was beneficial to the HRG, as it received double construction subsidies from both the government and main water plants, whereas the investment of the main water plants was not incentivized. The cooperation feasibility rate of scenario 2 was 53.9%, and the minimum profit of the alliance over 15 years was 153,176 JPY when the BT was 231 JPY/m^3 (Fig 6-11). In the BT, the HRG and main water plants could not simultaneously contribute profits and the dividing IR was 16%. Therefore, 16% was selected as the recommended IR in scenario 2. The cooperation plan was that the main water plants invested 16% of the construction cost for the HRG and negotiated 231 JPY/m^3 of BT with the HRG. The subsidies provided by the government maintained their current status.

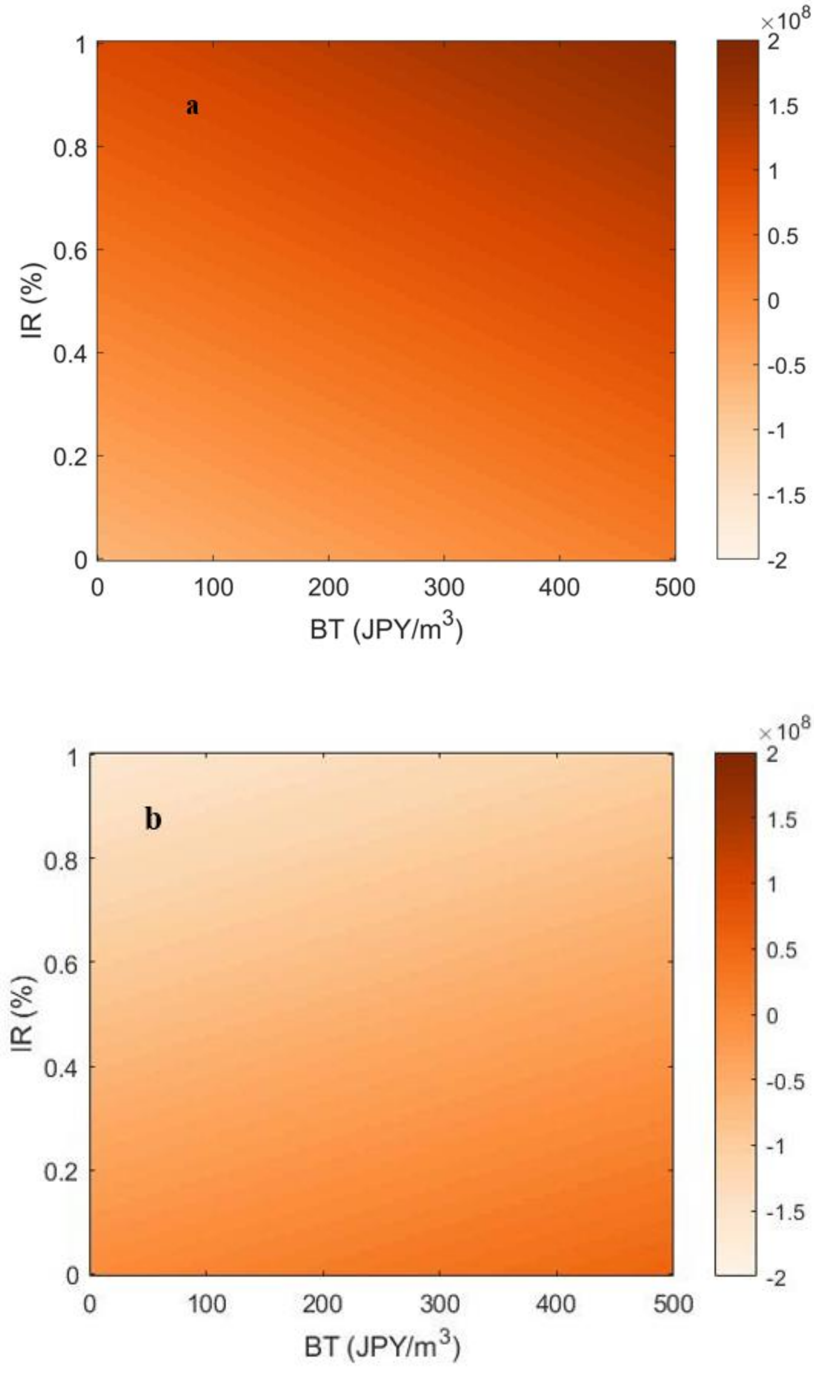


Fig 6-10 Profits of the HRG (a) and main water plants (b) in scenario 2

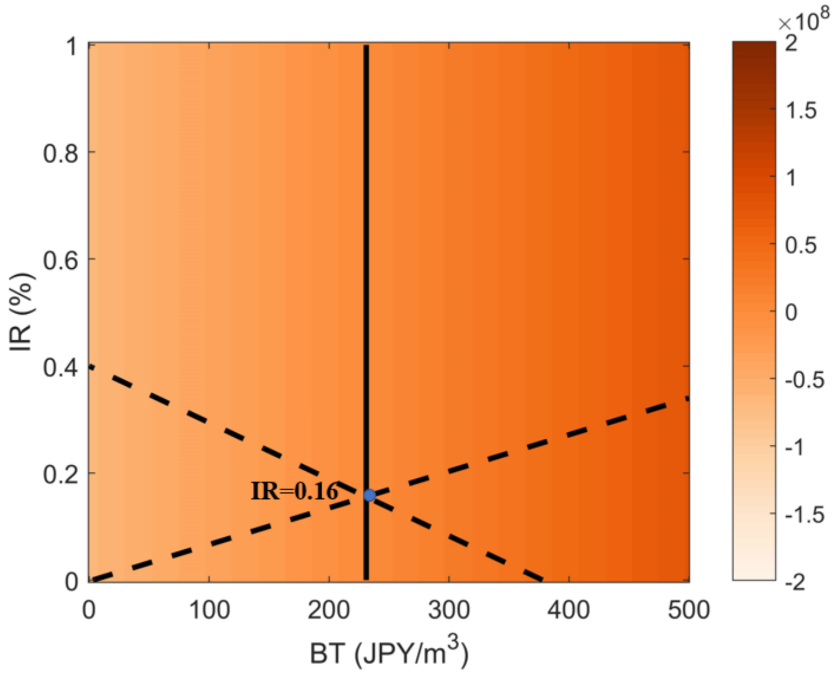
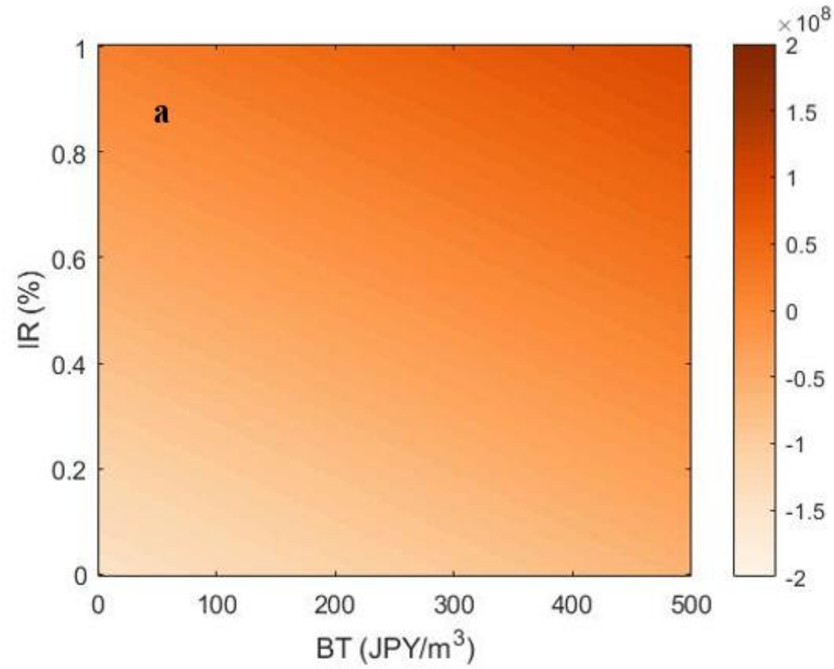


Fig 6-11 Profits of the alliance in scenario 2

Fig 6-12 and Fig 6-13 show the profits of the HRG, main water plants, and alliances in scenario 3. Scenario 3 showed that the government gave 49 JPY/m^3 of value-added subsidy to encourage the main water plants to invest on the HRG and reduced the construction subsidy to 0% to enforce the HRG to participate in the cooperation. Scenario 3 had 1.4% cooperation feasibility. The minimum profit of the alliance was 40,044 JPY in 15 years, when the BT reached 494 JPY/m^3.



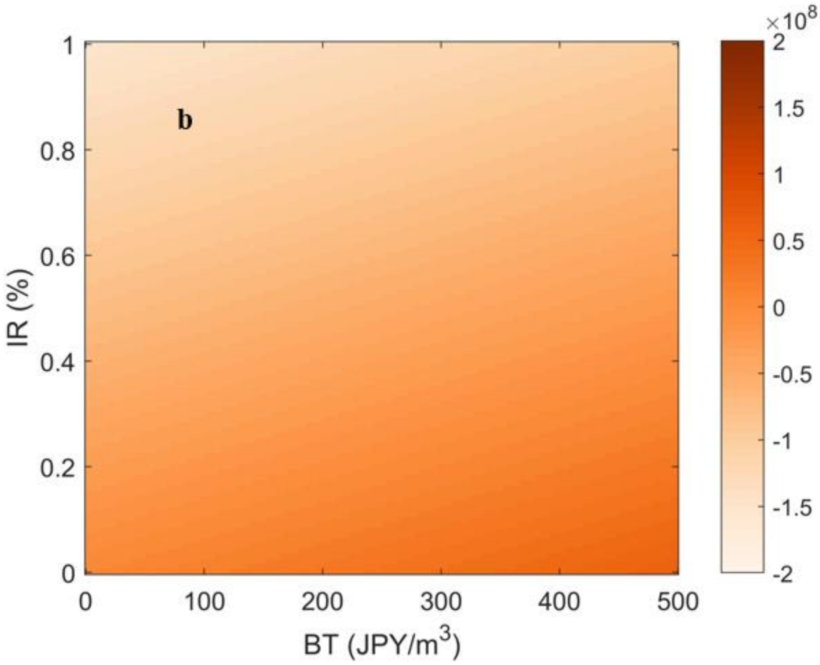


Fig 6-12 Profits of the HRG (a) and main water plants (b) in scenario 3

As is shown in Fig 6-12 (a) and (b), the main water plants and the HRG can contribute profits under a BT of 494 JPY/m^3 before and after 38% of IR, respectively. The cooperation plan of scenario 3 was that the main water plants invested 38% of the construction cost for the HRG and negotiated 494 JPY/m^3 of bargaining tariffs with the HRG. The subsidy of the government for the main water plants increased by 1.3 JPY/m^3 when the IR increased by 1%, whereas the subsidy of the government for the HRG decreased by 2% when the BT increased by 10 JPY/m^3.

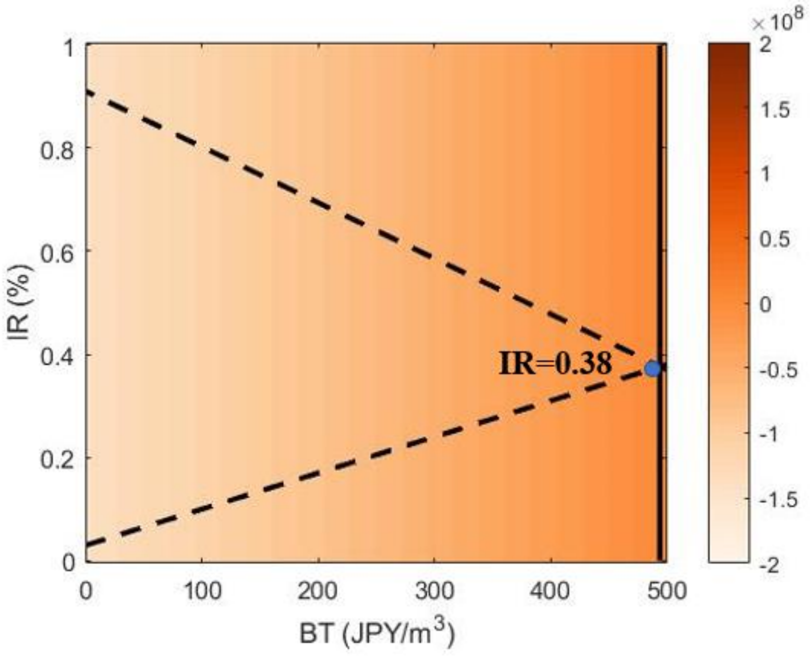


Fig 6-13 Profits of the alliance in scenario 3

The impacts of GSR and GVS on the recommended BT and IR were demonstrated by scenarios 4 and 5, respectively (Fig 6-14 and Fig 6-15).

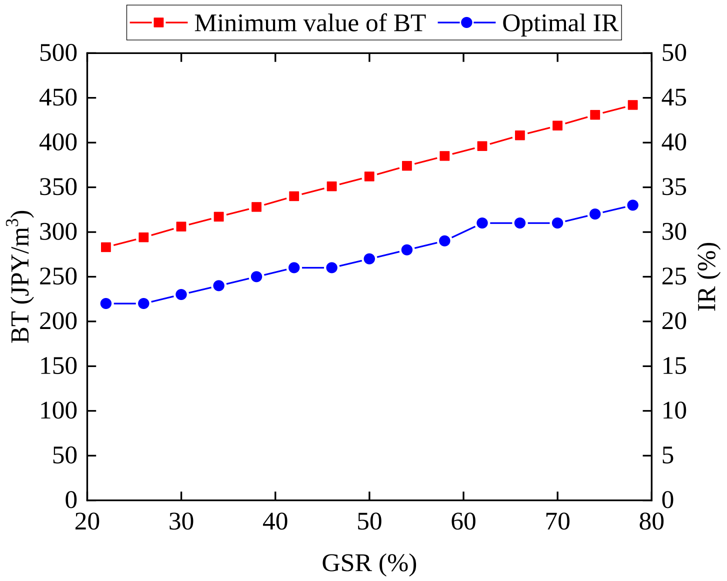


Fig 6-14 Effects of the external incentives on the recommended BT and IR in scenario 4

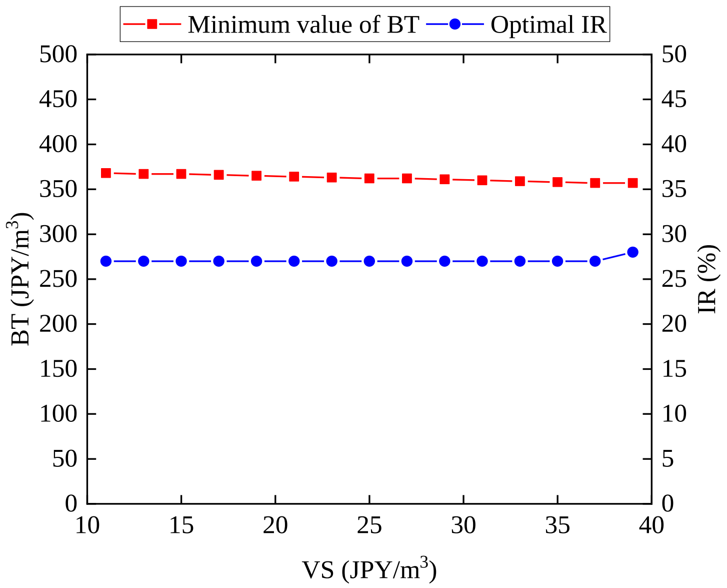
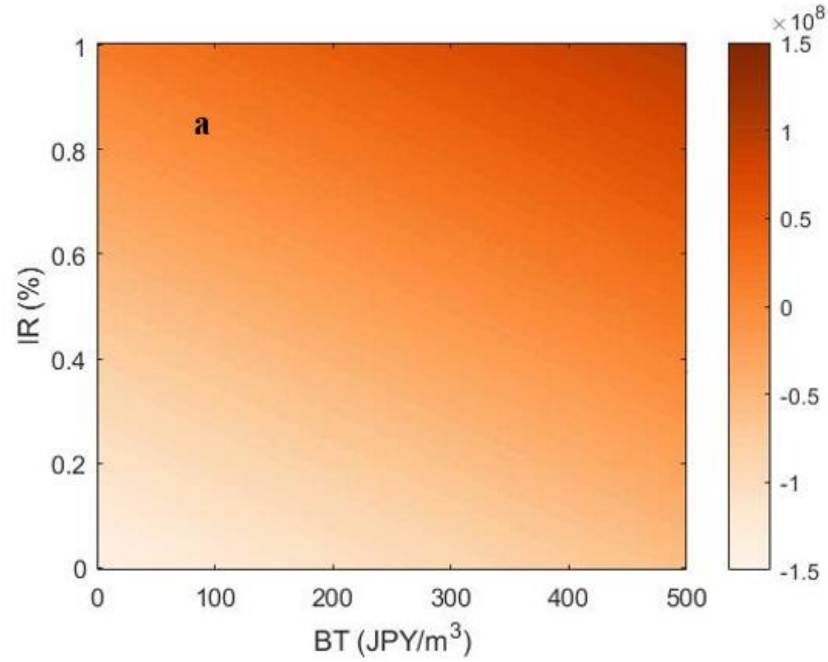


Fig 6-15 Effects of the external incentives on the recommended BT and IR in scenario 5

According to Fig 6-14 and Fig 6-15, the recommended BT and IR were more sensitive to GSR than to GVS. When the GSR decreased from 78% to 22%, the cooperation feasibility rate of scenario 4 increased from 11.8% to 43.5% and the minimum profit of the alliance increased from 136,467 JPY to 173,089 JPY in 15 years. In scenario 4, the recommended BT increased from 283 JPY/m^3 to 442 JPY/m^3 and the recommended IR increased from 22% to 33%, whereas the recommended BT was almost constant, ranging from 357 JPY/m^3 to 368 JPY/m^3. In scenario5, the recommended IR was 27%. Interestingly, the increase in the minimum profit of the alliance was higher in scenario 5 than in scenario 4 and range from 71,034 JPY to 238,552 JPY in a 15-year life cycle. This is because Fig 6-15 only depicts the change in the minimum profit of the alliance when the GVS increases, whereas according to the initial assumption, the prerequisite for the increase in GVS was the increase in IR. Therefore, Fig 6-15 demonstrates that GVS significantly affects the alliance's when IR is unchangeable.

Scenario 6 had the minimum rate of cooperation feasibility (Fig 6-16 and Fig 6-17).



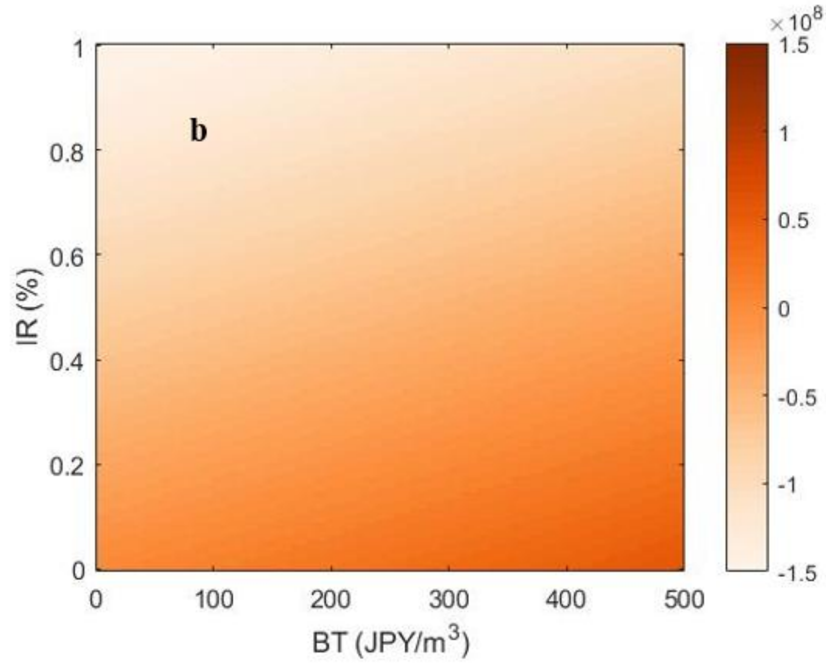


Fig 6-16 Profits of the HRG (a) and main water plants (b) in scenario 6

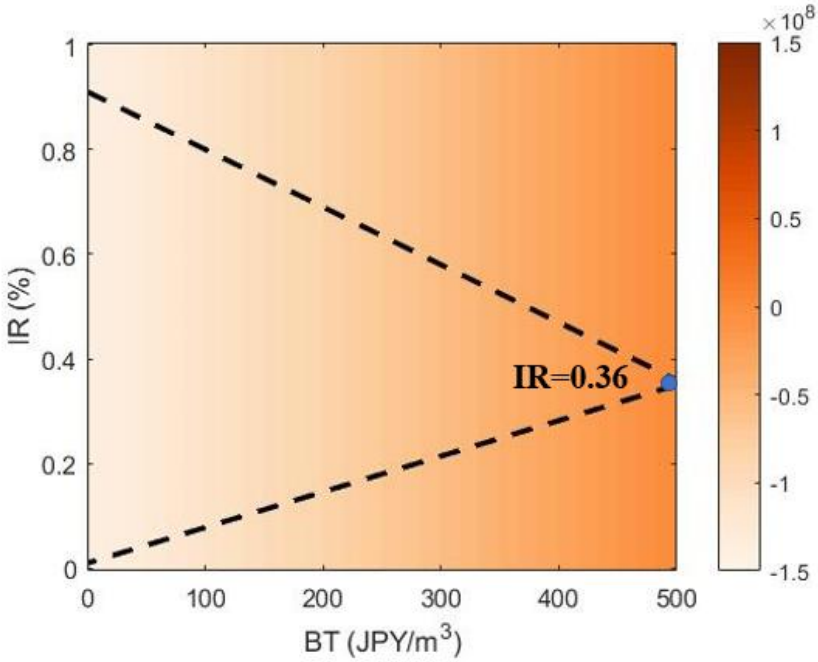


Fig 6-17 Profits of the alliance in scenario 6

The government reduced the subsidy to the HRG from 50% to 1% and increased the subsidy to the main water plants from 1 JPY/m^3 to 22 JPY/m^3 in scenario 6. With specific external incentives, the alliance could obtain a minimum profit of 61,880 JPY in 15 years if the BT increased to 500 JPY/m^3 (Fig 6-17). When IR was less than 36%, the alliance relied on HRG for profit, and the allocated profit of the main water plants was obtained by allocating the overall profits with the HRG (Fig 6-16 (a)); the alliance relied on the main water plants for profit when IR was greater than 36% (Fig 6-16 (b)). No cooperation simultaneously allowed both players to contribute to profit in scenario 6 because only the maximum BT could drive success in the cooperation. Therefore, the cooperation plan in scenario 6 was that the main water plants invested 36% of the construction cost for the HRG and negotiated 500 JPY/m^3 of bargaining tariff with the HRG. The subsidy of the government to the main water plants increased by 0.6 JPY/m^3 when IR increased by 1% and the subsidy of the government for the HRG decreased by 2 % when BT increased by 10 JPY/m^3.

A comprehensive evaluation was carried out by extending the results of scenario 1 to scenario 6 to all cooperation, as shown in Fig 6-6, to obtain the optimal strategy for the cooperative game between the HRG and the main water plants under the current subsidy policy. The evaluation results are listed in Table 6-5. The cooperation between the HRG and the main water plants can efficiently improve the economic feasibility of the HRG in a 15-year life cycle. In the current subsidy policy (Scenario 2), IR and BT are recommended as 16% and 231 JPY/m^3, respectively, for the main water plants and the HRG to form an alliance. As the cooperation strengthens, the government can gradually reduce the construction subsidies for the HRG. However, it is not recommended to reduce the subsidy for the HRG below 28% (GSR = 44%) because the feasibility of the cooperation at this time is less than 30%. With the reduction in the government subsidies, the HRG should negotiate with main water plants to gradually increase IR to 38% and increase BT to obtain higher profits for the alliance. Finally, the government can increase the annual subsidy to the main water plants according to the improvement in IR to encourage the main water plants to carry out stable cooperation with the HRG.

Table 6-5 Results of the cooperation between the HRG and main water plants

		HRGs	Main water plants
Non-cooperation	Profit	-64,375,400 JPY	-376,062 JPY
Cooperation	Cooperative feasibility	0.2–57.9%	
	Recommended IR	-	16–38%
	Recommended BT	211–500 JPY/m^3	-
	Profit	2,071–11,329,858 JPY	24,917–70,106,729 JPY

6.5 Discussion

The HRG on the campus was designed to meet all non-potable water demands (approximately 25,437 m^3) to maximize potable water conservation. However, the non-potable water-saving efficiency of the HRG was still not 100%, despite the collection of rainwater and graywater from all buildings on the campus (the maximum non-potable water-saving efficiency was 95.5%). Limited alternative water sources have resulted in at least 4.5% of non-potable water demands still being met by potable water from main water plants. In addition, the HRG requires larger rainwater tanks to store more rainwater for use during periods of high non-potable water demand, owing to the irregularity of precipitation, whereas the benefits of expanding the rainwater tanks of the HRG gradually diminish. According to the principle that expanding a certain volume of the rainwater tank cannot assist in the conservation of half the volume of potable water, the optimal rainwater tank size of the HRG was selected as 6,400 m^3 to maximally conserve potable water without excessive waste of resources. Therefore, the HRG can meet 92.7% of non-potable water demands (approximately 23,580 m^3) throughout the year, which accounts for 71.8% of all water demands on the campus.

An HRG on campus can achieve superior water-saving efficiency. However, the HRG is economically unfeasible, even under the highest incentive for construction subsidies from the government. To improve the economic benefits of HRGs, the government must subsidize almost all construction costs. In addition to the high construction cost, HRGs cannot provide a quick return of the initial investment cost by direct profits from water conservation, because of their high operation and maintenance costs [41]. The negative economic benefit of HRGs dictates that such systems can only be used in pilot programs and projects that rely on government support, such as "green building," and cannot be promoted by businesses and developers because of the higher cost of water conservation [43]. Therefore, evaluating the economic potential of HRGs is essential to increase their usability.

Implementing cooperative games on main water plants provides new opportunities to improve the economic benefits of HRGs. As shown in Fig.6, the HRG is economically unfeasible over a 15-year life cycle in the non-cooperative scenario, even when receiving government subsidies. In addition, the economic benefits of the main water plants will be significantly reduced when the campus implements the HRG to conserve water in comparison to the scenario in which the campus does not implement the HRG. Therefore, the main water plants actively participate in the cooperation, because the implementation of HRGs also affects the profit of the main water plants. The main water plants cannot balance the revenue and expenditure to maintain the labor and water production costs during the long-term use of HRGs because of the reduction in water supply. It is worth pointing out that this effect on the main water plants by implementing HRGs may not occur in the early stages of water conservation. However, when the water scarcity of a city gradually deteriorates, the government will successively introduce policies for water conservation, including switching from recommendations to mandating the implementation of decentralized water reuse systems in buildings to conserve water and alleviate the pressure on the main water plants. Furthermore, with the popularity of such systems and increasing awareness of water conservation, a large quantity of water in buildings can be replaced by rainwater and graywater instead of potable water from the main water plants, which ultimately damages the profits of main water plants [9]. This scenario is an inevitable consequence of the widespread use of alternative water sources in cities. For example, according to the report by Kitakyushu City Water and Sewer Bureau (2021) [42], the reuse of rainwater and graywater in Kitakyushu, Japan has achieved a certain scale since the implementation of the water saving policy in 1980, effectively reducing the consumption of potable water. The annual potable water supply from the main water plants decreased from approximately 120 million m^3 in 1990 to 98 million m^3 in 2019. Although the water tariffs in Kitakyushu rose twice in 2001 and 2019, the annual water sales revenue of the main water plants decreased from 18 billion JPY in 1990 to 14 billion JPY in 2019. Reduced profits have led to a lack of funds for the main water plants to maintain staff expenses, expand the municipal network, and maintain aging municipal systems. This part of the loss of main water plants is usually compensated by the Kitakyushu government in the form of increased annual subsidies. Therefore, when HRGs and the main water plants can achieve mutual benefits through cooperation, HRGs can attract investment by increasing profitability, which contributes to the large-scale implementations of such systems to conserve water. The profits of the main water plants can also be increased to maintain municipal facilities and other expenditures, without frequently raising water tariffs. The government can reduce financial subsidies for the implementation of HRGs and subsidies for the loss of the main water plants to reduce annual expenses. Therefore, the cooperation between HRGs and the main water plants to achieve mutual benefits may become a new trend in urban water-saving development.

Construction cost and water tariffs are two significant internal factors in cooperative games, as these factors ensure the greater economic feasibility and lower economic risks of decentralized water reuse systems [44]. Both players in the cooperative game can improve the profit of the alliance by adjusting the construction cost (IR) and water tariff (BT), and then fairly allocate the overall profit of the alliance based on the Shapley value to achieve mutual benefits. Successful cooperation can be considered as long as the alliance can obtain profit because both the HRGs and main water plants are uneconomical in the non-cooperative scenario. Improving the economic benefit of the main water plants aims to balance the cost of water production because the main water plants are non-profit organizations, whereas the higher economic benefit can drive the investment attractiveness of HRGs, which is beneficial for quickly promoting decentralized water reuse systems. Therefore, the main water plants can make some compromises while allocating the profit of the alliance to achieve sustainable development, which equally allocates the profit to the HRGs when the contribution of the main water plants in the alliance equals and exceeds that of HRGs.

Government support helps the adoption of decentralized water reuse systems and plays a vital role in cooperative games [45, 46]. The government can restrict superior players and encourage inferior players to cooperate to maintain fairness in the alliance. In the cooperative game between HRGs and main water plants, the latter invest in the construction costs of the former and then bargain water tariffs the former. A higher IR is beneficial for HRGs to obtain profit by reducing the construction cost, and regions with high water tariffs can promote the implementation of decentralized water reuse systems because such systems usually have a high water-saving efficiency [30]. Therefore, HRGs are more advantageous than the main water plants in a cooperative game. The government can subsidize the main water plants for encouragement (GVS) based on the increased IR and weaken the subsidy of HRGs to restrict oversized BT (GSR). Under the external incentives from the government, the cooperative game between HRGs and main water plants is feasible in Japan, with a maximum cooperation feasibility rate of 57.9%. In addition, the government's incentives for HRGs make it easier to promote the success of the cooperative game between the HRG and the main water plants.

The profit of the alliance increases with BT and is not affected by IR. However, IR, as a prerequisite for cooperation, affects investment willingness, and guides the BT value. In the specific BT, oversized and undersized IR will affect the profitability of the main water plants and HRGs during the cooperative game, respectively, and the actual profits of players rely on allocating the overall profit of the alliance, which weakens the initiative in the cooperation. As shown in scenario 1, the profitability of the alliance appears when BT reaches 362 JPY/m^3. In this BT, the minimum IR of 1% invested by main water plants results in a negative economic benefit of HRGs. The alliance relies only on the main water plants to obtain profit and then allocates the due benefits to the HRGs. However, the maximum IR of 100% is not optimal for main water plants because the allocated profits of main water plants are only slightly increased with the increase in IR in comparison to the higher investment cost for the HRG. According to Equation (4), the initial investment cost of the HRG was 159,421,416 JPY. Therefore, in the cooperation with 100% of IR and 362 JPY/m^3 of BT, the main water plants must invest 159,421,416 JPY of the construction cost for the HRG, but can only charge 50,357,820 JPY of additional water tariffs in 15 years as profits under this BT, which will make it impossible for the main water plants to contribute profits to the alliance. However, the allocated profits of the main water plants in 100% of IR can only increase from 13,271 JPY to 14,011 JPY in comparison to that in 27% of IR. This would place the main water plants in an unfair position in the cooperation. An intermediate value of IR should be selected to ensure that the HRGs and main water plants have sufficient enthusiasm in the cooperative game because both players cannot simultaneously make profits within the alliance, such as 27% in scenario 1. However, both players in the alliance can be simultaneously profitable with an increase in BT, which allows players to choose cooperative conditions more flexibly by adjusting BT and IR. For example, an alliance with high IR and low BT will greatly increase government subsidies to increase the overall profit, whereas alliances with low IR and high BT will make the overall profit of the alliance rely on internal profit instead of government subsidies. This provides a reference for formulating cooperative details within an alliance.

The overall profit of the alliance when the government provides sufficient support to HRGs will be approximately 3.8 times higher than full subsidies to main water plants, and more negotiation details are allowed in the alliance when the government supports HRGs. According to the determination of the optimal BT and IR in cooperative games, 38% of IR and 494 JPY/m^3 can result in the minimum profit of the alliance in scenario 3. A lower IR and a broader BT in scenario 2 result in more cooperative opportunities and a higher cooperation feasibility rate than in scenario 3. Therefore, the government can provide support for the construction cost of HRGs and facilitate a higher cooperation feasibility rate by adjusting the GSR and improving the household participation rate of decentralized water reuse systems, especially by accelerating water conservation in water-scarce regions [47]. In addition, the government subsidy for HRGs to improve the economic benefit in the cooperative game is also lower than that in the non-cooperation.

Changes in the government subsidies to HRGs can affect the feasibility rate of cooperation, whereas changes in GVS have a greater impact on the overall profit of cooperation. Although GVS should be changed with the IR, the government can adjust the subsidy for main water plants to greatly increase the minimum profit of the alliance under the circumstance that the investment of main water plants in HRGs remains unchanged. Therefore, the government can control the feasibility and economic attractiveness of the cooperation by actively regulating GSR and GVS, respectively, which enables the government to maintain a restrictive and facilitative role in the cooperative game and helps the latter develop more fairly. This provides a guide to the government in developing subsidy policies to promote decentralized water reuse systems in buildings.

The most unfavorable scenario of the cooperative game between the HRGs and main water plants is more economical than the non-cooperation. In the scenario of minimum cooperation feasibility rate, 500 JPY/m^3 of BT and 36% of IR can be negotiated to obtain profit. In this scenario, the overall subsidies of the government will be substantially reduced by decreasing GSR by 98% (approximately 63,768,566 JPY) and by increasing GVS by 2,100% (approximately 204,996 JPY annually). The BT in the alliance is approximately twice as high as the current water tariff to achieve the economic feasibility of HRGs and is more preferable than the increasing the local water tariff by three time in the non-cooperation [41]. In addition, directly raising the local water tariff is unsuitable for improving the economic benefit of decentralized water reuse systems because the water tariff is unpredictable in the future [27]. On the contrary, bargaining the tariff in an alliance can improve the mutual benefits of players without affecting the surrounding regions. Therefore, to promote the implementation of HRGs, the cooperative game should be given priority because of smaller regions of influence and quicker returns instead of giving HRGs a separate subsidy policy or raising local water tariffs.

In summary, the cooperation between the HRG and main water plants is feasible and can improve the economic feasibility of HRGs without harming the profits of the main water plants. Therefore, more players can be involved in an alliance to achieve mutual benefits. For example, more RWHs, GWRs, and HRGs with different scales that cannot achieve economic benefits in non-cooperative scenarios can seek cooperation with the main water plants within the framework of the cooperative game. In this cooperation, such decentralized water reuse systems can ask for investment from the main water plants by increasing the water tariffs within their service area, and each system can supplement non-potable water to each other when these systems cannot meet the non-potable water demand of buildings, to reduce the dependence on the main water plants. On the other hand, more public organizations can participate in the cooperation with HRGs and main water plants. For example, many countries have implemented centralized reclaimed water plants to treat domestic wastewater for non-potable water reuse in buildings. Therefore, the profits of centralized reclaimed water plants and main water plants are in conflict, whereas the implementation of HRGs can simultaneously affect the profits of centralized reclaimed water plants and main water plants. In the cooperation among the three players, HRGs can negotiate water tariffs and reclaimed water tariffs with the main water plants and reclaimed water plants, respectively, and the main water plants and reclaimed water plants can jointly bear the investment cost of HRGs to achieve mutual benefits.

The limitation of this chapter is that it only considered the cooperation between HRGs and the main water plants and ignored the cooperative potential with other organizations. For example, HRGs can reduce rainwater runoff, which can effectively reduce the expected annual damage cost of the catchment area [48, 49]. Additionally, the reduction in wastewater flow caused by HRGs can improve the concentration of pollutants in sewage systems [50, 51]. Therefore, evaluating the cooperative potential between HRGs and other urban water supply systems may result in higher economic benefits to promote the sustainable character of the society quickly.

6.6 Summary

In this chapter, we proposed a cooperative game method between HRGs and main water plants to explore the economic potential of HRGs. We selected an HRG on a campus in Japan to evaluate its water-saving efficiency and economic benefit. Additionally, we examined comprehensively the feasibility and driving factors of the cooperative game between the HRG and the main water plants. The conclusions are as follows.

The implementation of an HRG can meet almost all of the non-potable water demands of the campus. However, the high initial investment cost makes the HRG economically unfeasible during a 15-year life cycle.

The implementation of the HRG caused a decline in the profits of the main water plants. However, a cooperative game between the HRG and the main water plants can be mutually beneficial. The cooperative game theory can efficiently solve the economic unfeasibility obstacle when promoting HRGs.

Four parameters drive the cooperative game, the GSR, GVS, BT, and IR. In terms of external incentives, GSR affects the success of cooperative games more than GVS, whereas GVS affects the minimum profit of the alliance. In terms of internal negotiations, IR determines the willingness of both players, whereas BT determines the overall profit of the alliance. These four parameters not only balance the cooperative initiative between each player under the macro-control of the government but also provide a reference for the government to introduce policies for water conservation.

The HRG and the main water plants can achieve economic benefits more quickly and efficiently under the most unfavorable cooperation than under non-cooperation. HRGs have more economic potential by seeking cooperation with the main water plants.

Overall, the cooperative game can solve the economic unfeasibility of HRGs from the perspective of mutual benefits to accelerate the development of such systems. The government should strongly support HRGs in cooperation with municipal water supply organizations to efficiently achieve sustainable development. HRGs are expected to further improve the economic benefits by attracting more players in future cooperation.

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Chapter 7

CONCLUSION AND PROSPECT

Contents

8.1 Conclusion

Water scarcity, especially urban water scarcity, has seriously restricted the economic development of society and threatened human life. On-site reuse of rainwater and graywater by decentralized water reuse systems in buildings is one of the most effective methods to alleviate urban water scarcity because most water demands of buildings do not require high-quality potable water. A hybrid rainwater-graywater system (HRG) is a decentralized water reuse system that can simultaneously collect, retreat, and distribute rainwater and graywater to provide non-potable water to buildings. Such systems can not only achieve superior water-saving efficiency in buildings but avoid the limitation of separately reusing rainwater and graywater. HRGs also have some disadvantages, such as simultaneously reusing rainwater and graywater may be oversized and economically unfeasible in some buildings. The detailed evaluation and targeted optimization for HRGs are essential for implementing such systems in buildings. However, the development of HRGs is still in infancy and the evaluation method and optimization model for HRGs is still a largely underexplored domain.

This research is committed to comprehensively evaluating the advantages and limitations of HRGs in buildings and proposing tailored evaluation and optimization models for HRGs to improve the feasibility of such systems in buildings. In addition, the drive factors affecting the feasibility of HRGs in buildings were explored based on the proposed simulation model to the most efficiently implement such systems.

The main works and results can be summarized as follows:

In Chapter 1, RESEARCH BACKGROUND AND PURPOSE, the research background and purpose were introduced. First, the current status of water scarcity around the world and in the urban was introduced. Secondly, the water scarcity in Japan and measures to conserve water were introduced. Thirdly, the advantages and necessity of implementing HRGs were proposed by introducing the origin and development of decentralized water reuse systems. Then, a critical literature review about HRGs was carried out to point out the limitation of implementing HRGs in buildings. From the literature review, HRGs are unsuitable in buildings that only alone reusing rainwater or graywater can achieve enough water-saving efficiency, although HRGs in other buildings are also economically unfeasible. Simultaneously, there are still fewer optimization methods to improve these deficiencies of HRGs. In addition, the review also proposed that previous evaluation methods for HRGs are so idealistic that they will misestimate the performance of such systems in buildings. Finally, the research purpose and logical framework of this research were concluded.

In Chapter 2, CONFIGURATIONS AND COMPONENTS OF HRGs, the configurations and components of HRGs were introduced and the optimal configurations and the components of HRGs used in this research were presented. First, the advantages and disadvantages of different HRG configurations including mixed rainwater and graywater in a water tank and separately treated rainwater and graywater were introduced. The configuration of HRGs that separately treated rainwater and graywater has been recommended because of the flexible operation and wider feasibility. Then, the available components of the rainwater subsystems, graywater subsystems, and disinfection equipment of HRGs were presented. Finally, the components of the HRG used in this research were determined.

In Chapter 3, SIMULATION MODEL OF HRGS BASED ON THE WATER BALANCE MODEL, a simulation model of HRGs to evaluate and optimize the scale of HRGs was proposed. The water balance model, which is widely used to simulate rainwater harvesting systems, was selected as the base model for modeling the simulation model of HRGs. According to the "Yield before spillage" (YBS) and "Yield after spillage" (YAS) algorithms of the water balance model, the water balance of rainwater tanks, wastewater tanks, and graywater tanks of HRGs was proposed to obtain the integrated algorithm for simulating HRGs. Then, the integrated algorithm was coded using MATLAB and used to simulate an HRG on a campus. Finally, the simulating results from the simulation model were used to fit with the actual monitoring data of the HRG from the campus to verify the accuracy of the model. The fitting results show that the simulation model of HRGs can accurately and simply reappear the operation of HRGs to evaluate and optimize the performance and scale of such systems. The proposed model can provide a new method for the design and optimization of HRG in the future and simplify the calculation process of HRGs.

In Chapter 4, ENVIRONMENTAL AND ECONOMICAL BENEFITS OF HRGS IN PUBLIC BUILDINGS, a comprehensive evaluation of HRGs was carried out. In this chapter, a campus in Japan was selected to evaluate the feasibility of HRGs in public buildings. The simulation model based on the water balance model with an hourly time step was performed to quantify the performance of the rainwater and graywater subsystems in the HRGs. Second, the electricity consumption of the HRGs was evaluated. Then, a detailed life cycle cost model was designed to calculate the economic benefit of the HRGs under the current and optimization scenarios. Finally, the results obtained are compared with HRGs in residential and commercial buildings to discuss the advantages of HRGs in public buildings. The results indicate that the promotion of HRGs in public buildings can not only achieve higher water-saving efficiency than other building types with 57.44% of water-saving efficiency and 83.29% of reliability but also reduce 22.05% of electricity consumption in comparison with the traditional water supply methods. The economical unfeasibility of HRGs is caused by the waste of excess graywater and high maintenance costs. HRGs in public buildings has the potential to be promoted preferentially in regions where the water tariff is higher than 880 JPY/m^3 or the non-potable water tariff is set to at least 200 JPY/m^3.

In Chapter 5, DIMENSIONLESS PARAMETER METHOD FOR GENERAL EVALUATION OF HRGS IN BUILDINGS, a general evaluation model of HRGs was proposed to properly implement HRGs in buildings without the requirement of individual evaluating such systems in each building. This chapter proposes a dimensionless parameter method for the evaluation of three decentralized systems in buildings with stable and seasonal daily non-potable water demands: rainwater harvesting systems (RWHs), graywater recycling systems (GWRs), and hybrid rainwater-graywater systems (HRGs). Japan was selected as a case study to illustrate the feasibility of this method. The results indicate that the favorable precipitation patterns in Japan support the use of RWHs and HRGs rather than GWRs for conserving water, especially in buildings with seasonal daily non-potable water demands. Upgrading the existing systems to HRGs when RWHs and GWRs cannot meet the demand can increase the maximum water-saving efficiency by 40% in buildings with a d_r between 1 and 10 and a d_g between 0 and 1. Thus, the method can effectively determine the optimum scenarios and configurations of RWHs, GWRs, and HRGs and provide policy guidance for the regional implementation of decentralized water reuse systems.

In Chapter 6, ECONOMICAL OPTIMIZATION METHOD FOR IMPROVING THE ECONOMIC BENEFITS OF HRGS, an economic optimization model was proposed to improve the economic feasibility of HRGs. This chapter proposed a comprehensive economic analysis based on the cooperative game theory to explore the economic potential of HRGs. An HRG on campus in Japan was selected as a case study to evaluate the water-saving performance. Then, the economic feasibility of the HRG was analyzed based on the life cycle cost model. Finally, considering the implementation of HRGs has weakened the profit of main water plants, the cooperative feasibility and its drive factors between the HRG and main water plants for mutual benefits were explored based on the cooperative game theory. The results highlight that the construction cost significantly reduces the economic benefit of HRGs. HRGs have more substantial economic benefits in the cooperative game than in non-cooperation. Therefore, the economic benefit of HRGs can be improved in the cooperation with main water plants without frequently soaring the local water tariffs. Besides, the subsidy of the government for HRGs is easier to drive the success of cooperation, whereas the subsidy of the government for main water plants can improve the minimum profit of the alliance. This chapter provided a new idea for improving the economic feasibility of HRGs but also provided policy orientation to the government for promoting decentralized water reuse systems.

In Chapter 7, CONCLUSION AND PROSPECT, a critical summary of each chapter was concluded and the future research about HRGs was recommended.

In summary, this research carried out a detailed life-cycle assessment of HRGs to determine the limitation of implementing such systems in buildings and proposed the simulation and optimization models for correctly and efficiently implementing HRGs to conserve water.

According to the feasibility evaluation of HRGs in buildings, HRGs can achieve superior water-saving efficiency in public buildings in comparison to other building types because public buildings have a higher non-potable water demand throughout the year. However, the economical unfeasibility of HRGs exists in all building types, which hinders the implementation of such systems for conserving water. Oversized systems and high life cycle costs are the main reason that makes HRGs economically unfeasible. Therefore, optimizing the scale and economic benefits of HRGs can actively promote the development of such systems.

The integrated simulation model for HRGs proposed in this research can efficiently obtain the design curves of HRGs to determine the optimal HRG scales based on calculating the water balance of rainwater tanks, wastewater tanks, and graywater tanks. In addition, based on the integrated simulation model, the dimensionless model proposed in this research can quickly derive the buildings that are suitable for implementing HRGs in a region and their optimal scale, without requiring to evaluate each building individually. The proposed dimensionless model avoids the impact of different building sizes on the results when evaluating the feasibility of HRGs in different building types. Finally, the dimensionless model also determines the optimal buildings to implement HRGs are a d_r between 1 and 10 and a d_g between 0 and 1 in Japan, whether the water demand of the buildings is stable or seasonal throughout the year.

The cooperative game model between HRGs and main water plants can improve the economic feasibility of HRGs without frequently soaring the local water tariffs. HRGs and main water plants can more quickly and efficiently achieve economic benefits under the most unfavorable cooperation than non-cooperation. In the cooperative game, GSR affects the success of cooperative games more than GVS, whereas GVS affects the minimum profit of the alliance. In addition, IR determines the willingness of both players, whereas BT determines the overall profit of the alliance. These four parameters not only balance the cooperative initiative between each player under the macro-control of the government but also provide a reference for the government to introduce policies of water conservation.

8.2 Prospect

In prospect, with the increasing awareness of water conservation and the development of HRGs, the water scarcity in urban will be further alleviated and the limitation of implementing HRGs in buildings will also be further improved.

At present, the development of HRGs is still in infancy and a lot of additional benefits of implementing HRGs have yet to be fully exploited. For example, HRGs can simultaneously reduce the stormwater flows and wastewater flows to relieve the pressure of municipal facilities and reusing rainwater and graywater in buildings can efficiently reduce the emission of carbon dioxide by centralized treatment water in main water plants. Deeply exploring these benefits of HRGs can further promote the feasibility of such systems.

Secondly, some regions have built centralized reclaimed water plants to reuse domestic wastewater for buildings and lay a reclaimed water pipeline independent of the municipal pipeline network. Therefore, integrating HRGs with the reclaimed water pipeline has great potential to improve the oversized scale of such systems as well as connect more buildings to use non-potable water.

The cooperation between HRGs with other municipal organizations is also valuable to explore for improving the economic benefits of HRGs. Considering the unpredictability of future water tariff changes, cooperation in a small area can not only effectively increase the investment attractiveness of HRGs but also free the implementation of HRGs from government intervention, which helps to attract more stakeholders and investors to invest HRGs in buildings for water conservation. This is conducive to further encourage the development of urban water conservation.