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Efficacy of rain barrels and rain gardens to reduce urban pluvial flooding in densely built-up residential areas: a case study on Miyahara-Cho in Saitama City, Japan

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Abstract

In recent years, flooding in densely built-up residential areas has tended to increase because of the increased frequency of heavy rain and climate change. Urban pluvial flooding mitigation is thus needed by reducing the runoff of sewer systems using green infrastructure solutions. In this regard, rain barrels (RBs) and rain gardens (RGs) are considered effective stormwater management methods. This study aimed to verify the effectiveness of RBs and RGs and their combined use in reducing urban pluvial flooding in densely built-up residential areas. This research undertook a case study in Miyahara-Cho, Saitama City, Japan. It involved the analysis of the total runoff of sewer systems and the flood condition in the sewer to verify the rainwater runoff control effect of RBs and RGs through simulations using the US Environmental Protection Agency's stormwater management model. This study simulates two main types of rainfall events: short duration and long duration. The results of the short duration rainfall showed that the combination of RBs and RGs is highly effective and can reduce the impact of excess runoff. In the case of the long duration rainfall, the volume and speed of stormwater runoff of the first peak rainfall were reduced.

Keywords: Stormwater management, Rain barrels, Rain gardens, Densely built-up residential area, SWMM

Introduction

In recent years, the increased frequency of heavy rains and climate change has contributed to increasing of flooding (Zbigniew et al. 2014). Such a high incidence of disasters is detrimental, particularly in densely built-up residential areas. Overflows in sewer systems due to excessive stormwater runoff mainly cause this flooding. Existing urban infrastructures are already struggling to meet existing demands and thus, understanding the capacity of natural functions to mitigate urban pluvial flooding is a necessary undertaking. Thus, there is a growing demand for small-scale, decentralized urban stormwater management approaches that rationalize natural functions (Burns et al. 2012).

Low-impact development (LID) is a stormwater management technology widely utilized recently to manage stormwater runoff (Tianqi and Yelly 2021). Thus, urban pluvial flooding mitigation can be achieved by reducing the runoff of sewer systems using green infrastructure and LID solutions. In this respect, rain barrels (RBs) and rain gardens (RGs) are considered effective stormwater management methods, especially in densely built-up residential areas (Maya et al. 2010).

LID practices are applied to minimize runoff at the source where rain falls. It helps manage the quality and quantity of stormwater. LID uses various principles, such as preserving and recreating natural landscape features and minimizing effective imperviousness, to create functional and appealing site drainage that treats stormwater as a resource rather than a waste product (Dimas 2019). The most common examples of LID technologies include RGs, bioretention gardens, RBs, pervious pavements, and green roofs. There are many pros to installing LID, such as boosting curbside aesthetics, reducing pollutant-laden stormwater reaching local waters, and protecting against flood events. LID has some drawbacks that need to be taken care of, such as the fact that it will create more contaminants if it is not designed properly. Performance degrades over time, and the question arises as to how to maintain an LID program (United States Environmental Protection Agency [US EPA], 201212).

RB designs allow rainwater to flow from roofs through gutters into the RB. They may have lids to keep mosquitoes and other insects out. The stored water can be used to replenish domestic water supplies. Compared with other LIDs, they do not require large areas of land and have few restrictions on where they can be installed. Unlike other rainwater harvesting systems, rain barrels are low-maintenance items. Moreover, their installation process is not too complicated (Díaz and Muñoz 2020; Aaron et al. 2012). The disadvantage of rain barrels is that they may attract mosquitoes and bugs, as well as too small a collection are also his main problems (Alberto 2016).

RGs include various practices designed to increase rain runoff reabsorption by the soil (Guihong 2017). They can also be used to treat polluted stormwater runoff. Compared with other LIDs, they can remove toxic substances, provide a good habitat for organisms, and be used in all soil conditions (Ishimatsu et al. 2017). But improperly installed rain gardens can experience poor drainage and can also lead to increased erosion rates.

As shown in Fig. 1, rainwater flows from the gutter into the RB and then flows out of the pipe into the RG when the RB reaches its full capacity.

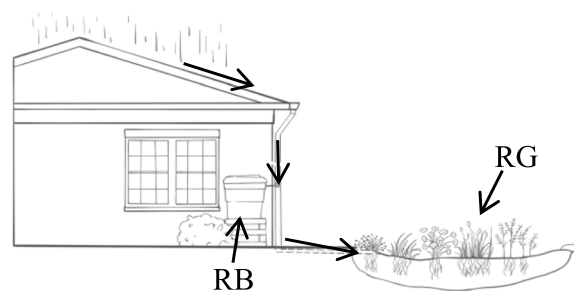


Fig. 1 Combination of RBs and RGs

Much previous research has focused on case studies on various types of green infrastructures. For example, a study of bioinfiltration RGs at Villanova University showed that 82% of the overflow from rainfall events was controlled during the 15 years when RGs were installed (Achira et al. 2020). Another study in two urbanized watersheds near Indianapolis, Indiana, installed RBs/cisterns and porous pavements. It showed that a combination of 50% RBs and 50% porous pavements was the most efficient option for reducing stormwater runoff in this watershed (Laurent and Bernard 2012). Another study in Hamilton County, Ohio, simulated experiments using the Storm Water Management Model (SWMM) for RGs and RBs under separate use (Maya et al. 2010). The study showed that RGs were more effective at reducing stormwater hazards than RBs when used alone, reducing stormwater overflow by 38%. In our previous study, we verified the effects of using six individual LID types, including RB, in the Urawa area of Saitama City (Uchiyama et al., 2022). In a study conducted in Chicago, they looked at what factors influence whether households use rain barrels in an urban environment, and the results showed that households that use rain barrels are concentrated in places with a high number of single-family buildings and a population with green attitudes (Amy and Luiz 2011). In a study conducted at Vulnerable Coastal Communities of Houston, they used SWMM to study the potential for LIDs such as bioretention basins, pervious pavement, green roofs, RB, etc., and showed that multiple LIDs within a site outperformed a single low-impact development option (Afiya and Jessica 2023).

Although many studies discussed the effectiveness of using RGs and RBs individually, no study has examined the application of RBs and RGs and their combined use. Thus, this study aimed to verify the effectiveness of RBs and RGs and their combined use in reducing urban pluvial flooding in densely built-up residential areas. This study can help policy makers to better target the use of RB and RG in combination with existing programs and policies to achieve urban pluvial flood reduction.

Method

This study has three stages: selection of the study area, setting up the model of the map with RBs and RGs, and analysis of the model to verify the effectiveness of RBs and RGs.

Selection of the study area

This research undertook a case study of Miyahara-Cho, one of the densely built-up residential areas of Saitama City, Japan (Fig. 2) (Geospatial Information Authority of Japan, 2022). The area of Miyahara-Cho is 9.89 km², with 13,192 households (29% of which have detached houses) and a total population of 30,376 (City of Saitama, 2022a). The Sakasagawa River flows in the north direction through the western edge of the study area.

The study area belongs to the Pacific climate zone, with an average annual temperature of 16.0°C, total annual rainfall of 1371.3 mm, and average monthly precipitation of about 114.28 mm. The monsoon blows from the southeast in summer and the northwest in winter. The climate is generally mild throughout the year.

According to the permeability capacity map of Saitama City, Miyahara-Cho has many suitable locations for installing stormwater infiltration facilities (City of Saitama 2021). The higher the saturated hydraulic conductivity, the more suitable the area is for installing stormwater infiltration facilities. The saturated hydraulic conductivity in the vicinity

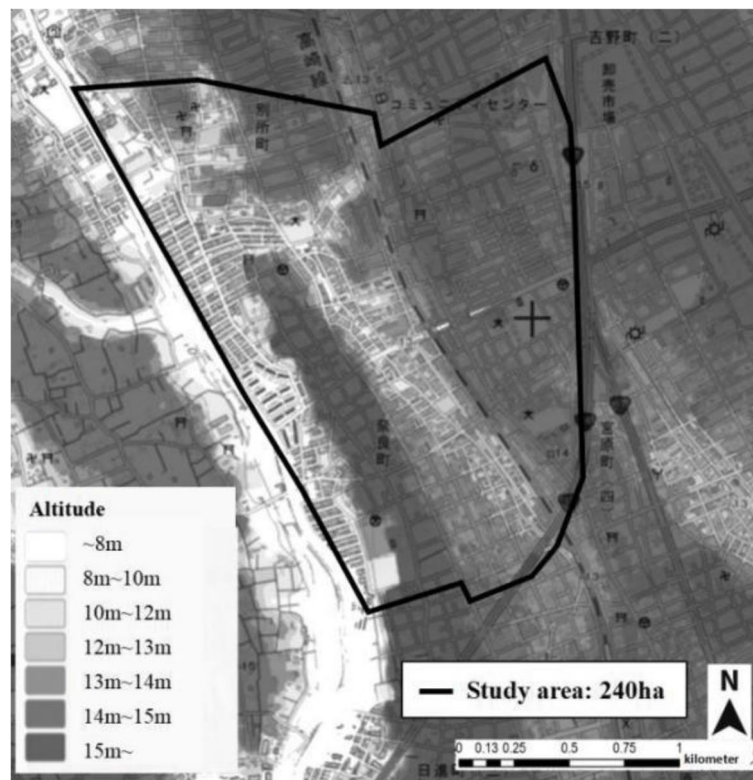


Fig. 2 Study area

of the subject area is 3.0×10^{-5} m/s. Moreover, according to the inundation hazard map of Saitama City (City of Saitama 2021), Miyahara-Cho can have flood depths exceeding 1 m in many study areas during heavy rainfalls, which can cause damage around the residential area.

Setting up the model

EPA's SWMM is used worldwide for planning, analysis, and design related to stormwater runoff, combined and sanitary sewers, and other drainage systems. It can be used to evaluate gray infrastructure stormwater control strategies, such as pipes and storm drains, and create cost-effective green/gray hybrid stormwater control solutions (US EPA, 2012).

The modeling of sewer pipes and catchment areas in the study area on SWMM was based on the sewer map from the Sewerage Management Division of the Northern Saitama City Construction Office and Geospatial Information Authority maps (City of Saitama 2022c) (Fig. 3).

When setting up stormwater pipes in SWMM, the parameters were mainly set for three aspects: manholes, sewers, and outfalls. *Invert El* (Invert Elevation) for manholes and outfalls was set to the bottom height of the sewer pipe in the sewer register, *Max-depth* for manholes and sewers was set to the depth of the sewer pipe (pipe diameter), and *Length* was set to the length value of the sewer pipe.

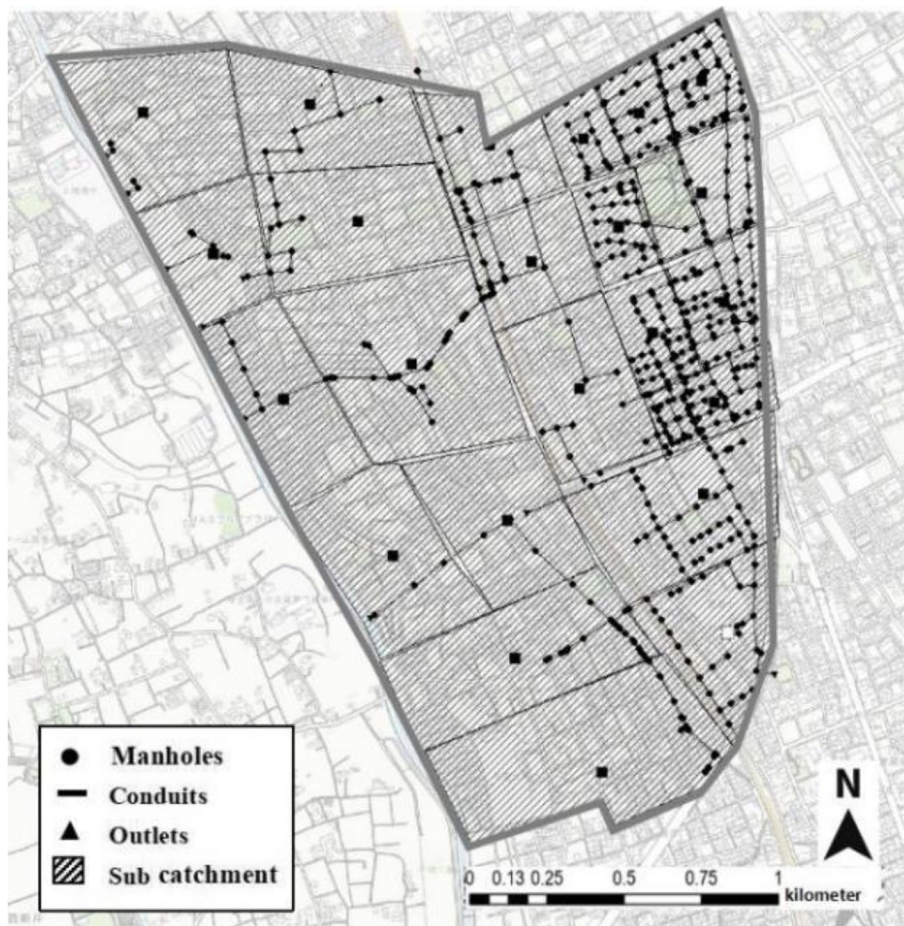


Fig. 3 Sewer pipes and subcatchment areas

Catchment areas were set using Geographical Survey Institute maps and Google Earth Pro data. Three main parameters were set when setting up catchments in SWMM: *Area*, *Width*, and *%Imperv*. *Area* was the area data of each catchment measured using Google Earth Pro. Meanwhile, *Width* was calculated using the formula $Width = 0.8 \cdot \sqrt{Area}$. *%Imperv* (runoff coefficient within the catchment) was set to 60%. This was determined using the Saitama City infiltration capacity map and the SCS Curve Number method.

1. Precipitation Scenarios.

This study simulates two main types of rainfall events: short duration and long duration. A short duration rainfall event is a precipitation event that lasts less than 3 h and has peak precipitation intensity well above the hourly average precipitation. In comparison, a long duration event is a continuous precipitation event that lasts more than 10 h (Daisuke et al. 2021).

Rainfall data for the first half of 2021, as observed by Japan's Automated Meteorological Data Acquisition System, were used for the simulation (Fig. 4), with the highest daily rainfall in the first half of 2021 being on July 2, 2021 (long duration rainfall)

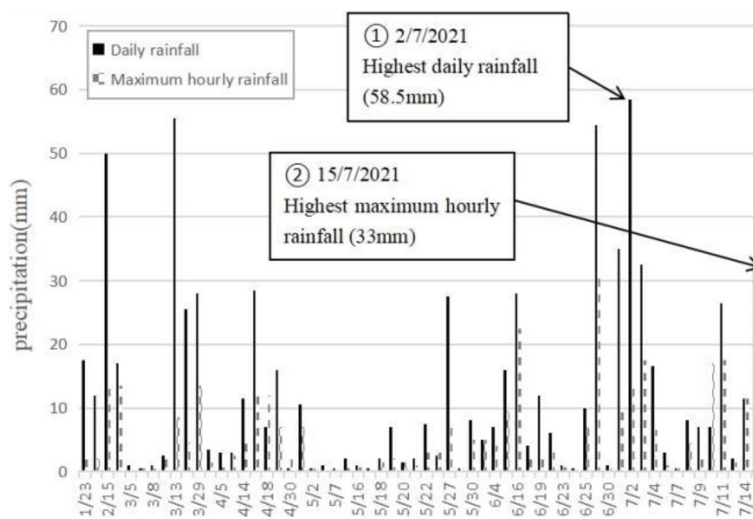


Fig. 4 Daily rainfall data of Saitama City

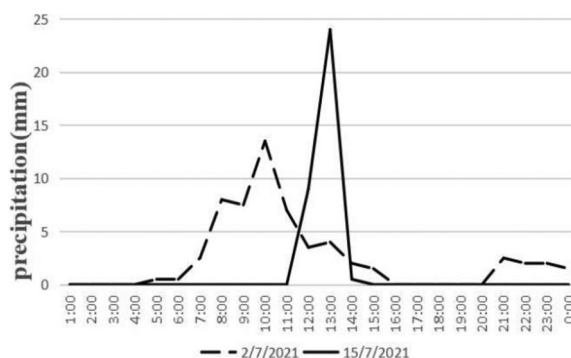


Fig. 5 Precipitation scenarios

and the highest maximum hourly rainfall being on July 15, 2021 (short duration rainfall).

Figure 5 shows the hourly rainfall on July 2, 2021, and July 15, 2021. As shown in the figure, July 2 had a long period of continuous rainfall, whereas July 15 had a short period of concentrated rainfall, where the maximum rainfall of 24 mm/h occurred at 13:00.

2. Model Calibration and Validation.

To verify the accuracy of the simulation model, the results of the depth of the water level at the outlet simulated by SWMM were compared with the observed data from the Saitama City water level information system (Saitama City, 2022b) as shown in Fig. 6.

In this study, we verified the accuracy of the SWMM model using the coefficient of determination r^2 criteria (Niyonkuru et al. 2018). The coefficient of determination is a number between 0 and 1 that measures how well a statistical model predicts an outcome. A value of zero means no correlation at all whereas a value of 1 means that the dispersion of the prediction is equal to that of the observation (David et al. 2015).

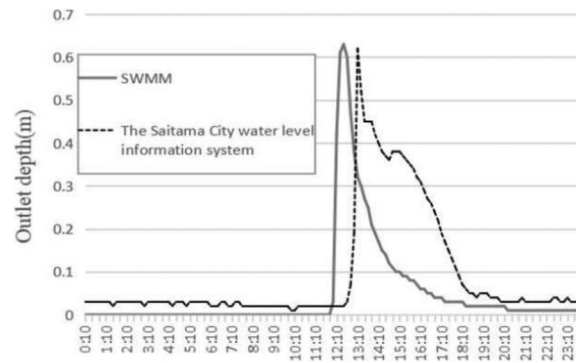


Fig. 6 Comparison of water level at the outlet

Table 1 Parameters of rain barrels used in the study

Rain barrels (RBs)			
Storage		Drain	
Barrel height (mm)	1000	Flow coefficient	0
Area of unit (m ²)	0.2	Flow exponent	0.5
		Offset (mm)	6
		Drain delay (h)	6

Usually, the r^2 value of 0.70 is considered good (Krause and Boyle 2005). In this case, the r^2 value for water level data near the peak range was calculated to be 0.85. The water level data for both cases were similar at the peak, indicating that we can accurately simulate the flood damage situation for peak times.

The reason for the lag between the model output and the observed data can be thought to be due to the water level data of the Saitama City Water Level Information System being at the river water level instead of at the water level of the outlet.

Simulation scenarios

This study used three simulation patterns. The location and parameters of the three patterns of LIDs introduced in "Selection of the study area" section were set according to the study area.

1. **RBs.**

As this study examined a dense residential area, an RB with a height of 1000 mm, a bottom area of 0.2m², and a total capacity of 200 L was installed in each detached house in the study area. In a previous study conducted in a residential area in the Hii River watershed in Japan, 61% of the participants felt that a 200 L rain barrel capacity was just right (Ryoichi et al. 2015). A total of 9600 RBs were installed; therefore, the

total used area of RBs was 1920 m². Table 1 shows the detailed parameters of the RBs used in the simulation (Maya et al. 2010).

2. RGs

Table 2 shows the detailed parameters of the RGs used in the simulation. This study used RGs with a berm height of 200mm from the surface, a 700-mm-thick soil, and 87-mm/h conductivity. In other words, an RG took approximately 12h for all the rainwater to infiltrate after the RG has reached its capacity. The specific parameter settings for RB and RG refer to the data for Storm Water Management Model Reference Manual Volume I.

Figure 7 shows the locations of the houses where RGs can be installed. Our study installed RGs with an area of 20 m² in each location. Therefore, for a total of 1080 RG installations, the total area covered was 21,600 m².

3. Combination of RBs and RGs.

In the case of the combination of RBs and RGs used in this study, rainwater flows from the roof through a pipe into an RB, and when the capacity of the barrel is exceeded, the rainwater then flows out of the pipe and into an RG. We created a new catchment area in the SWMM to achieve the effectiveness of this simulation pattern (Fig. 8).

The areas circled in bold black are gardens and open spaces where RGs will be installed. The area with black diagonal lines is the park where no LID will be installed. The other areas are buildings where RBs will be installed. As mentioned earlier, rainwater flows into the RBs in the catchment areas of the buildings, and once the barrels reach their capacity, the rainwater flows out of the pipes into the RGs in the garden catchment areas. Rainwater that falls in the park catchment area flows directly into the sewer system. The parameters for the RBs and RGs used in the simulation are the same as those shown in Tables 1 and 2.

Results

The three simulation patterns described in "Selection of the study area" section are compared in terms of the total runoff of the sewer systems and the flood condition in the sewer to verify the rainfall control effect of RBs and RGs.

Table 2 Parameters of rain gardens used in the study

Rain gardens (RGs)			
Surface		Soil	
Berm height (mm)	200	Thickness (mm)	700
Vegetation volume fraction	0.1	Porosity (volume fraction)	0.5
Surface roughness (Mannings n)	0.1	Field capacity	0.2
Surface slope (%)	0.5	Wiring point	0.1
		Conductivity (mm/h)	87
		Conductivity slope	10
		Suction head (mm)	106

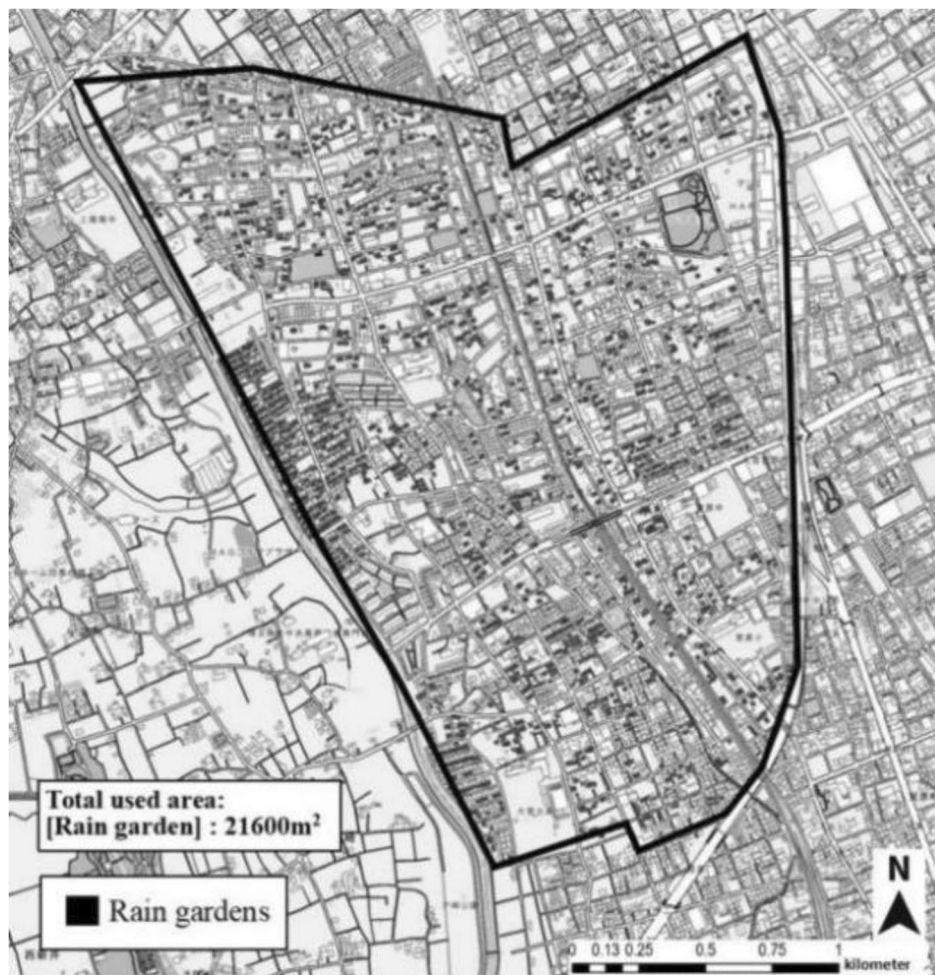


Fig. 7 Location of RGs

Total runoff of the sewer systems

1. Short Duration Rainfall (July 15, 2021).

The simulation results for a short duration rainfall (July 15, 2021) showed that the peak stormwater runoff time was delayed by 10 min when RGs were used (Fig. 9). The decreases in flood volume rate when using RBs and RGs were 0.93% and 13.32%, respectively.

When the combination of RBs and RGs was used, the decrease in flood volume rate was found to be 29.26%. The effect of reducing the total runoff of the sewer systems was higher when using RBs and RGs in combination than when using them individually. Also, the combination of RBs and RGs reduced the peak flow rate and total volume of stormwater runoff. Thus, this combination of RBs and RGs can effectively reduce the load on wastewater treatment facilities from such events as localized rainstorms.

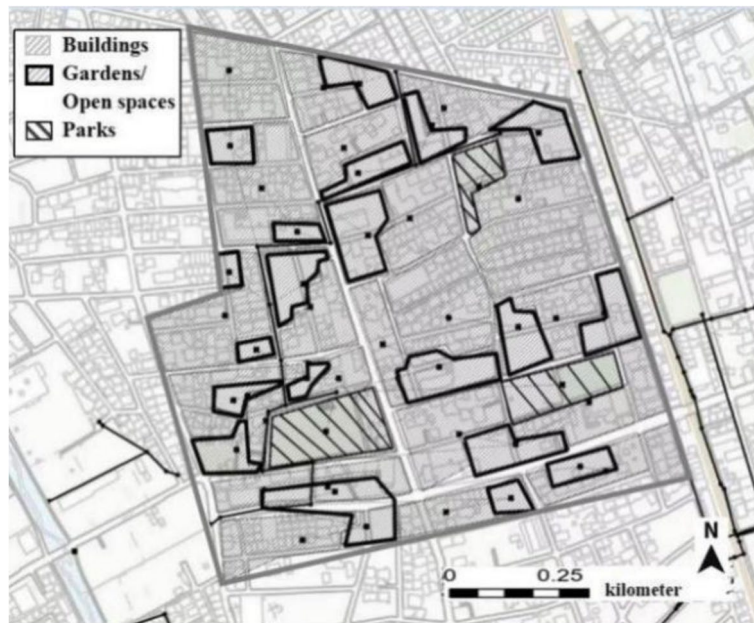


Fig. 8 Subcatchment area (combination of RGs and RBs)

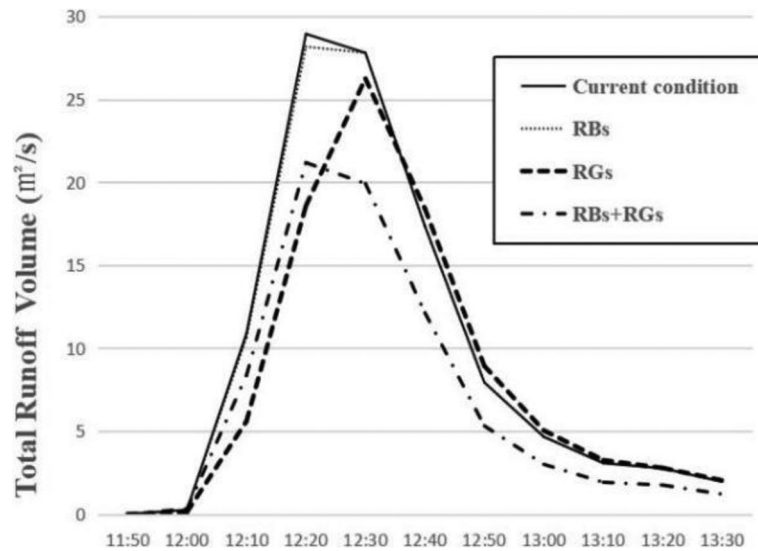


Fig. 9 Total flood volume (short duration rainfall)

2. Long Duration Rainfall (July 2, 2021).

In the case of a long duration rainfall (July 2, 2021), little effect was observed when the amount of precipitation exceeded the storage capacity of the RGs. The rainwater exceeded the storage capacity of both the RBs and RGs during peak time (2). The decreases in flood volume rate when using RBs and RGs was 0.2% and 7.79%, respectively, during peak time (2). This means that surface runoff was effectively reduced at

Table 3 Flood volume reduction rate

Peak time (1)	Current condition	RBs	RGs
Total flood volume (m ² /s)	29.54	29.48	27.24
Rate of decrease		0.20%	7.79%
Peak time (2)	Current condition	RBs	RGs
Total flood volume (m ² /s)	11.48	10.97	9.45
Rate of decrease		4.86%	18.04%

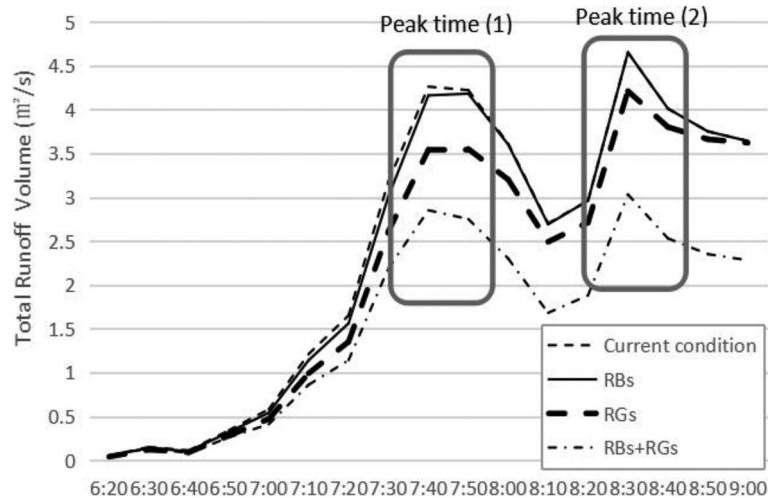


Fig. 10 Total flood volume (long duration rainfall)

the peak time (1). The decreases in flood volume rate when using RBs and RGs were 4.86% and 18.04%, respectively, during peak time (1) (Table 3).

In both rainfall scenarios, the combination of RBs and RGs delayed the first peak stormwater runoff time by approximately 10–20 min. The discharge was commensurate with the runoff capacity of the river, reducing the river’s burden.

The effect of reducing the total runoff of the sewer systems was higher when using RBs and RGs in combination than when using them individually. The reduction rates in the two peak periods were 36.36% and 30.88%, respectively (Fig. 10).

Although it is said that the use of RB in singular is not effective, we can see in the results of Fig. 10 that the reduction in the two peaks when using RB + RG is 36.36% and 30.88% respectively, which is far superior to the use of RG alone. It can even reach almost twice the reduction rate. Therefore, we think that the combination of RB + RG is the best effect.

Flood condition in the sewer systems

1. Long Duration Rainfall (July 2, 2021).

SWMM can show the hourly change of conduit capacity and flood volume from man-holes with different colors.

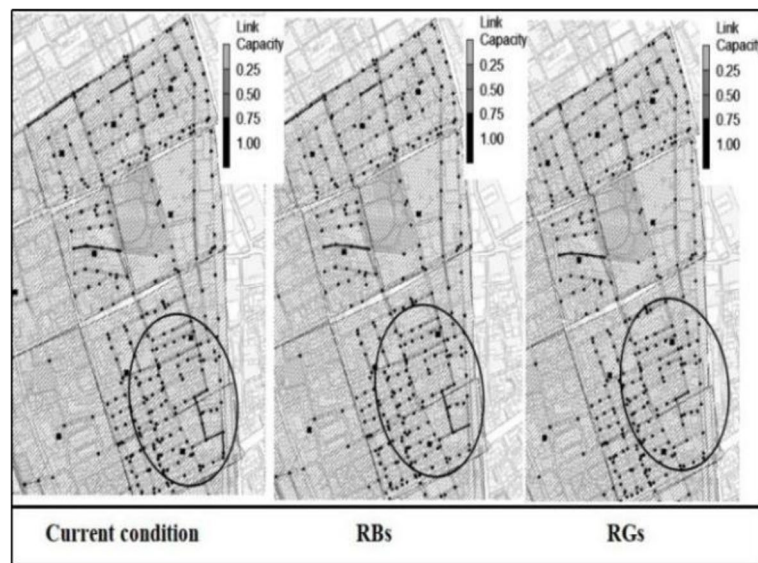


Fig. 11 Conduit capacity using RBs and RGs (long duration rainfall) (peak time 7:50)

Thus, the effectiveness of stormwater control in flooded areas can be verified by comparing flooding scenarios under current conditions with those after using RBs and RGs. Figure 11 shows the conduit capacity in the sewer system during the long duration rainfall peak time (7:50). In Fig. 11, the middle figure and the left graph show the situations after using RBs and RGs, respectively. The color of the circled area changed compared with the current condition figure on the left. Notably, in the case of RGs (as seen in the middle of the figure), almost all conduits had flow depths of less than 1 m, indicating that almost none of the conduits overflowed. This indicates that the use of RBs and RGs reduced the volume of stormwater in the sanitary sewer system and, thus, reduced the load on the sewer system. Additionally, the effect is greater in the case of RGs than in the case of RBs.

Figure 12 shows the conduit capacity in the sewer system during the long duration rainfall peak time (8:30) when using the combination of RBs and RGs.

The figure on the left represents the situation when no LID was installed. As shown in the figure, the sewer capacity in the flooded area was exceeded. With the combined use of RBs and RGs, the volume of rainwater in the sewer was reduced, indicating that the sewer load was reduced.

2. Short Duration Rainfall (July 15, 2021).

Figure 13 shows the conduit capacity in the sewer system during the short duration rainfall peak (12:20).

As with the long duration rainfall, the middle graph and the left graph show the situations after the use of RBs and RGs, respectively. Compared with the current condition on the right, not many flood mitigative events can be observed in these two graphs after using RBs and RGs.

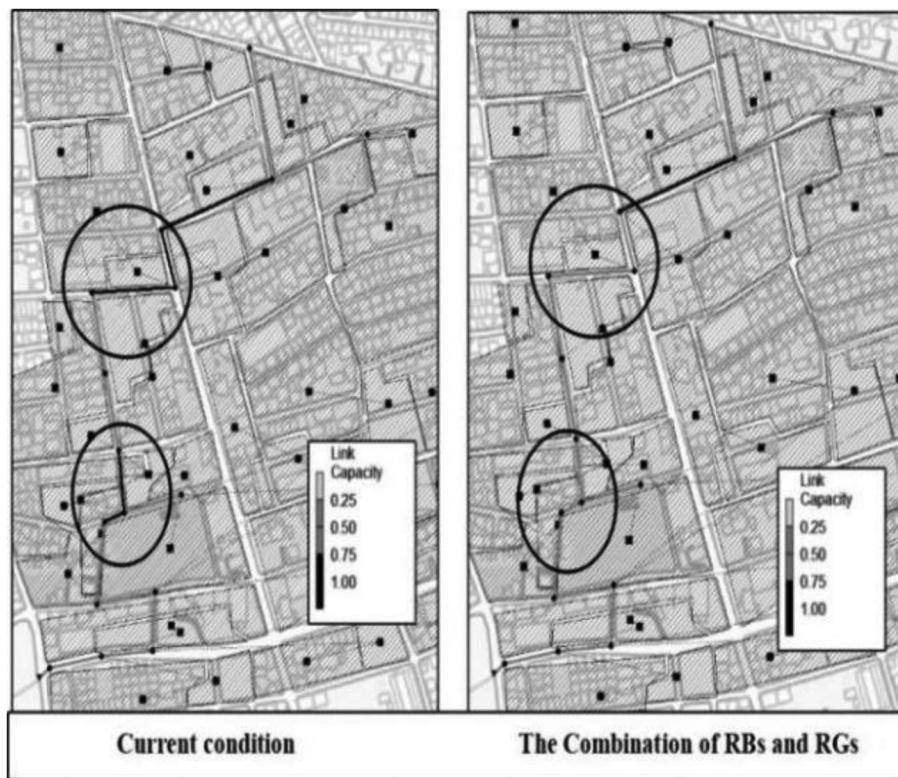


Fig. 12 Conduit capacity using the combination of RBs and RGs (long duration rainfall) (peak time 8:30)

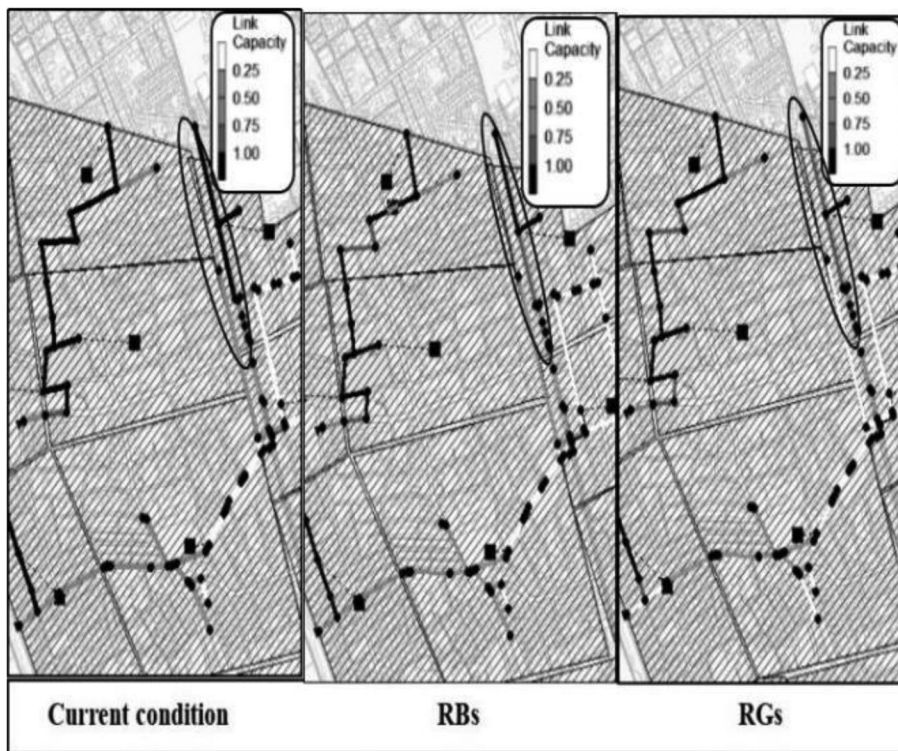


Fig. 13 Conduit capacity using RBs and RGs (short duration rainfall) (peak time 12:20)

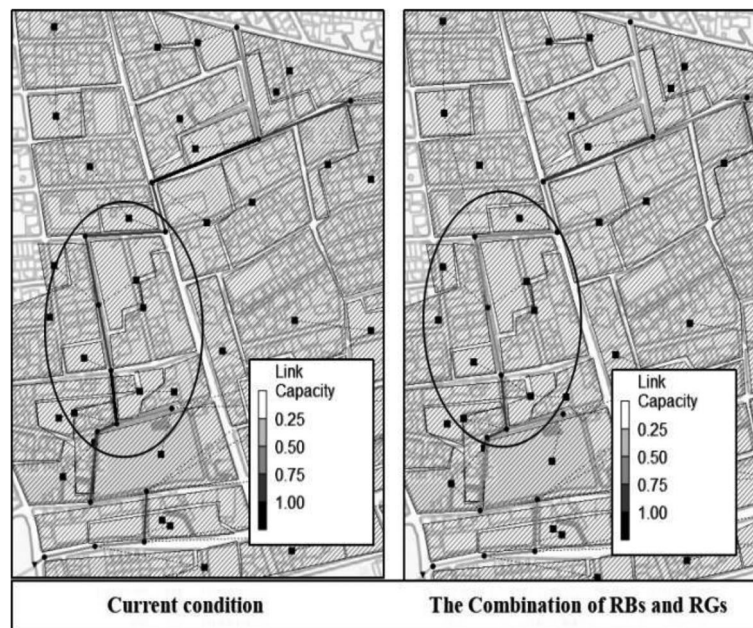


Fig. 14 Conduit capacity using the combination of RBs and RGs (short duration rainfall) (peak time 12:50)

Figure 14 shows the conduit capacity in the sewer system during the short duration rainfall peak time (12:50) when using the combination of RBs and RGs. After the installation of RBs and RGs, the depth of the conduit became significantly lower than when both the barrels were not installed.

Analysis

For the short duration rainfall event on July 2, 2021, the peak runoff volume changed when RGs were used. Our analyze shows that the RG effectively reduced the depth of the outlet and delayed the peak stormwater runoff by approximately 10 min. This allowed the discharge to match the runoff capacity of the river, reducing the burden on the river.

Meanwhile, when RBs were used, no change in peak runoff volume or time of occurrence was observed. From the simulations using RBs of different capacities, we presume this to be due to the amount of rainwater flowing into the RBs greatly exceeding their storage capacity. Using a combination of RBs and RGs, however, effectively lowered the depth of the outlet.

For the long duration rainfall on July 15, 2021, RBs and RGs effectively reduced sewer capacity overflow during the first peak. However, little effect was seen during this later peak time because the LID storage capacity was likely exceeded. However, the effect of RGs was greater than that of RBs.

Thus, the combination of RBs and RGs works better than using RBs or RGs alone. Using a combination of RBs and RGs is more effective in reducing the water table and the total stormwater runoff and peak flows. Thus, its usage in densely built-up residential areas can effectively reduce flooding damage for short- and long duration rainfall events.

Conclusion

This study aimed to verify the effectiveness of RBs and RGs in reducing urban pluvial flooding in densely built-up residential areas. We came to three main conclusions.

1. Our results demonstrate that both RB and RG are able to reduce the total rainwater outflow for both short-term and long-term rainfall events, with RG being a slightly better effect than that of RB.
2. However, at the second peak of long-term rainfall, the effectiveness of using RB or RG alone is significantly reduced, and in the case of RB there is almost no effect on attenuating the total rainwater outflow.
3. In contrast, the combined use of RBs and RGs has a significantly higher capacity to reduce the total rainwater outflow compared to implementing RB or RG alone, and a significant effect was observed even in the second peak of long-term rainfall.

This is because, as the rainfall precesses the RBs reach their total capacity and while the infiltration capacity of the RG also decreases to counted this, we can: use an RB with a larger capacity, increase the water volume and placements of the RBs, increase the area of the RG, or change the materials used in the RG to increase the infiltration rate. In this study, we designed rainwater flows out of the pipe into the RGs when the RBs reached their total capacity. Thus, the combination of RBs and RGs can better reduce urban pluvial flooding risk, especially in dense residential areas in the suburbs of Tokyo, such as Miyahara.

Saitama City has introduced some policies in the past 2 years to promote using RB, including the promotion of lids and subsidies for the purchase and installation costs for families who choose to install RBs (City of Saitama 2023). Saitama City subsidizes one-half (up to 30,000 yen) of the amount spent on the purchase and installation of RBs for those who use the tanks properly and make efforts to preserve the environment. Given the results of this study, additional incentive measures that promote the combined installation of RB and RG may yield higher benefits in mitigating future urban pluvial floods.

The location and number of RBs and RGs that can be installed vary depending on the area's location and the dynamic situation. Therefore, we expect that the development of more area-specific policies based on the actual situation of the target area can better reduce flooding. Private adoption of outdoor domestic water management technologies may be affected by imperfections in the urban market and more complex environmental characteristics, which must also be considered (Amy and Luiz 2011).

In the future, we would like to study the feasibility and challenges of installing them based on the conditions in the target districts and make proposals accordingly to maximize their effectiveness.

Authors' contributions

The authors confirm contribution to the paper as follows: J.L. made contributions to the conception of the work, data analysis, and interpretation and drafted the original manuscript. S.U., Y.B., and H.N. contributed to the revision of the manuscript drafts. All authors approved the submitted version of the manuscript.

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Availability of data and materials

Not applicable.

Declarations

Competing interests

The named authors have no conflict of interest, financial or otherwise.

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