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Investigating the Influence of Various Stormwater Runoff Control Facilities on Runoff Control Efficiency in a Small Catchment Area

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Received: 18 January 2018; Accepted: 2 February 2018; Published: 5 February 2018

Abstract: Urbanization causes an increase in the flood discharge because of the infiltration capacity. Furthermore, extreme precipitation events have been an increasing concern for many regions worldwide. This study aimed to investigate the influence of different outflow control facilities on runoff reduction in a small watershed. We focused on the soil-improvement technology and rainwater tanks as outflow control facilities and conducted a runoff calculation using a rainfall event of a magnitude that is likely to occur once in a hundred years. The calculation showed that the soil-improvement technology reduced runoff during long-term continuous rainfall, whereas in a concentrated short-term rainfall event, a significant difference in the runoff reduction effect between rainfall tanks of various volumes was observed. Since effective countermeasures for runoff reduction differ depending on the rainfall distribution pattern, we suggested both facilities for storing initial rainfall and initiating countermeasures for penetration improvement over the long term.

Keywords: urbanization; runoff reduction; soil improvement; rainwater tank; runoff simulation

1. Introduction

Over recent decades, urban areas around the world have rapidly expanded [1,2]. Additionally, urban land cover is expected to increase by three times from 2000 to 2030 [3]. Urbanization causes an increase in the flood discharge because of the decline of infiltration capacity by pavement and a decrease in flood concentration time through the introduction of pipeline systems and linearization of the river channel [4–7]. Urban flood disasters are becoming a global issue as 233 cities and approximately 663 million people are now exposed to the danger of urban flooding [8]. By 2030, 40% (195,000 km^2) of global urban land is projected to be located in high-frequency flood zones compared to the case of 30% in 2000 [9].

Extreme precipitation events, which often resulting in flooding, have been an increasing concern for many regions worldwide [10]. These phenomena are strongly related to temperature rise or floods in conjunction with typhoons [11,12]. Research on the relationship between climate changes and flood risks has been globally conducted on various scales [13–15]. In Japan, clear changes in hourly flood peak discharge, daily drought discharge, and monthly discharge have been reported as the effects of climate change [16]. In addition, the potential economic damage in 2100 (RCP8.5 scenario) for a flood of 100-year return period was estimated to be 107 billion USD (1.10–1.36 times greater than the current value) [17].

In Western countries, low-impact development (LID) [18,19], green infrastructure (GI) [20], and sustainable urban drainage systems (SUDS) [21,22] were introduced as methods for stormwater management in order to reduce the runoff volume and nutrient load from non-point sources. Outflow control facilities, such as green roofs, rain gardens, permeable pavements, or rainwater tanks have been introduced to store rainwater based on the fact that it is expensive to reconstruct pipeline system as measures to mitigate urban flooding [23]. Recently, research on the effects of prevention measures on sewer overflow and runoff reduction volume has been conducted [24–26]. In addition, the effects of these outflow control facilities have been confirmed not only in terms of runoff reduction effect but also in terms of improving landscapes, creating recreational spaces, energy conservation, carbon fixation, and reducing of air pollution [26,27]. These outflow control facilities have been evaluated as multifunctional infrastructure.

In Japan, basin-wide comprehensive flood disaster prevention measures that strengthen rainwater retention capacity and infiltration in the whole basin have been identified as important [28,29]. A legal system for implementing such measures was established in the Act on Countermeasures against Flood Damage of Specified Rivers Running Across Cities [30]. Furthermore, technological development and verification of the effects of rainwater retention facilities and permeable pavement have been conducted [31–34]. These facilities have been introduced by various administrative agencies. However, urban floods have caused damage as observed earlier. To further reduce the damage caused by urban floods, development of fundamental technologies such as basin-wide comprehensive flood-disaster prevention, which is inexpensive and can be easily introduced, is necessary, together with the evaluation techniques for quantitative evaluation of the effects of these technologies. In particular, techniques for evaluating the channel modifications that are intended to lower the water level have been established, whereas those for evaluating the reductions of local inundation or overflow from manholes are yet to be established.

In this research, we focused on fundamental technologies for strengthening the infiltration and retention capacity of soil as well as the rainwater retention facilities to reduce the flow of rainwater into sewers and rivers. Soil essentially possesses a high infiltration capacity. The rainfall rate observed in nature rarely exceeds the initial infiltration capacity of soils [35]. However, artificial compaction or formation of crusting soil via waterdrop impacts [36–38] decreases the infiltration capacity of soils. Due to the anthropogenic impact and natural phenomena mentioned above, surface runoff is caused by a low rainfall rate in urban areas. The authors have developed technologies for strengthening the infiltration capacity of soils using bamboo charcoal, humus, and bamboo chips and evaluated the infiltration and retention capacity of soils mixing these materials [39,40]. This study reports the calculated runoff reduction effects for different scales of outflow control facilities (including soil infiltration improvement materials and rainwater tanks) adopted in small watersheds belonging to densely populated areas.

2. Materials and Methods

Details of the development of the runoff calculation model and the setting of the rainfall pattern have already been reported in a previous study [40]; therefore, only an outline is described below.

2.1. Location of the Study Area

The upstream area of the Zenpukuji River (belonging to the Ara River drainage system) flowing through Japan's Tokyo metropolitan area, was selected for this study (Figure 1). The urbanization of the Zenpukuji River basin is remarkable, changing from approximately 50% in 1956 to approximately 60% in 1976. Tremendous flood damage was caused by Typhoon Ida in 1958 and Typhoon Kit in 1966. In 2005, damage caused by floods to 3558 houses and 84 ha was due to rainfall exceeding 100 mm in 1 h.

In this research, we focused on the catchment area of the manhole unit at the upper reaches of the Zenpukuji River and examined the influence of the scale of outflow control facilities on the runoff reduction effect. Additionally, we investigated the catchment range of the overflow opening located at the top of the Zenpukuji River using the sewerage register released by the Tokyo Metropolitan Sewerage Bureau [41] and conducted a rainfall runoff simulation for 597 manholes and 18,087 m of pipelines.

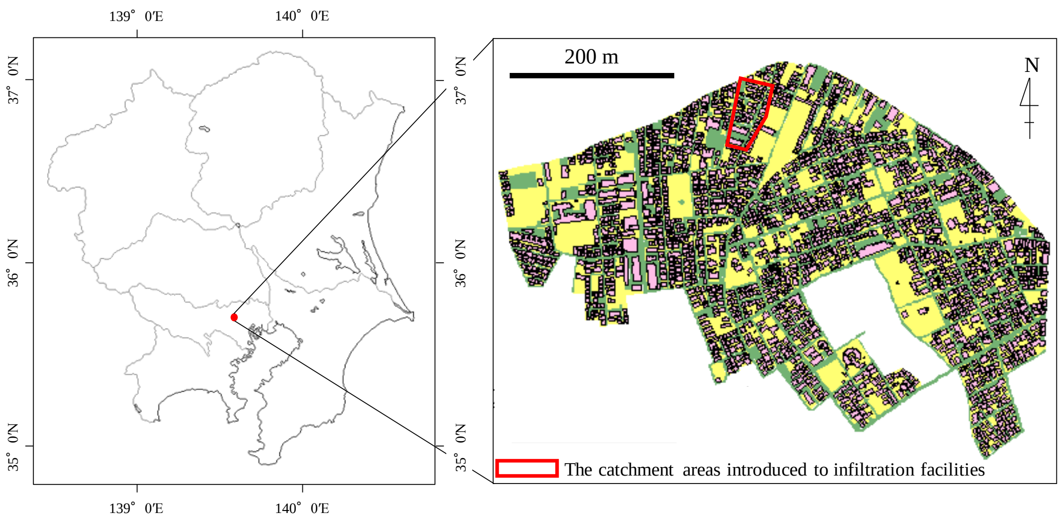


Figure 1. Location of the study area.

2.2. *Collection of Hydrological Data Through Field Observation*

Water-level gauges (HOBO U20 Water Level Logger, CO-U20-001-01, Onset Computer Corporation, Bourne, MA, USA) were installed at short distances upstream and downstream from the overflow opening to collect water-level data before developing the rainfall runoff simulation model. In addition, a rain gauge (HOBO Data Logging Rain Gauge, RG3-M, Onset Computer Corporation, Bourne, MA, USA) was installed approximately 400 m from the overflow opening to collect precipitation data. We collected water-level and precipitation data at 5-min intervals from 6 September 2013 to 27 November 2015 (including a missing period of 443 days). A discharge curve was formed based on the collected water-level data and flow discharge obtained from the equation of continuity and from Manning's equation.

2.3. *Development of the Rainfall Runoff Simulation Model*

Land use information was obtained from basic map information published by the Geographical Survey Institute and constructed by the geographic information system (GIS, ArcGIS Desktop 10.2, Environmental Systems Research Institute, Inc., Redlands, CA, USA). Based on the penetration function, we divided land use into three categories: roof surface, roadway surface, and pervious area. The roof surface accounted for 24.4 ha (34.5%), the roadway surface accounted for 19.0 ha (26.8%), and the pervious area accounted for 27.4 ha (38.7%).

In this research, runoff simulation was conducted using InfoWorks ICM 4.0, a distributed flow-routing model. A model linking the land use data organized by GIS to the structure of manholes and sewage pipes was constructed. Using the measured rainfall data, the inflow volume at the overflow-opening point was calculated by reproducing sewer pipe's flow rate downstream. In addition, the volume of rainfall accumulated in each manhole was established by Voronoi tessellation. The behavior of running water in the sewage pipe was calculated by unsteady-flow analysis based on the Saint Venant equations.

With regard to penetration parameters, the initial loss and final infiltration capacity were employed for each land use category. We investigated the initial loss and the final infiltration capacities of roof surfaces, roadway surfaces, and pervious areas based on the procedures reported in previous studies [42–54] and adopted the outflow discharge values with the highest reproducibility at the overflow-opening point in the range between the lower and upper limits.

2.4. Development of a Hyetograph

To evaluate the influence of outflow control facilities of various scales on the runoff reduction effect during heavy rainfall events, we set the scale of the rainfall event to have an annual exceedance probability of 1/100. Furthermore, as the rainfall pattern influences the runoff reduction effect, two types of rainfall patterns (i.e., long-term continuous pattern and short-term concentrated pattern) were applied to the calculation. Among the rainfall events for which measurements were obtained, two types of rainfall patterns with a relatively large amount (i.e., long-term continuous pattern: 15 October 2013; short-term concentrated pattern: 24 June 2014) extended the amount of rainfall to an annual exceedance probability of 1/100. Based on the report of the Tokyo Metropolitan Government, the amount of rainfall corresponding to an annual exceedance probability of 1/100 was calculated as 327.4 mm/24 h and 97.4 mm/h [55].

2.5. Introduction of Outflow Control Facilities

The introduction of rainwater tanks to buildings and soil infiltration improvement materials to the penetration area was considered as an effective runoff control method because 34.5% of the calculation target catchment was covered by roof surfaces and 38.7% by the penetration area. To evaluate the influence of the scale of outflow control facilities on the runoff reduction effect, rainwater tank capacities were set to be 0.1, 0.05, and 0.02 times that of the roof surface area. In addition, soil infiltration improvements were considered involve a composition of 70% decomposed granite and 30% humus (humus mixing soil), which showed the highest value of infiltration ratio in previous research, and a composition of 100% decomposed granite, which showed the lowest value of infiltration ratio in previous research. Furthermore, humus mixing soil had an initial infiltration capacity of 243.3 mm and a final infiltration rate of 36.9 mm/h. For decomposed granite, these values were 106.8 mm and 8.5 mm/h, respectively [50]. In addition to the six different combination cases of rainwater tank capacity and soil infiltration improvements, the case without outflow control facilities was targeted for the runoff calculation.

Furthermore, to investigate the difference of runoff reduction ratio among outflow control facilities, runoff reduction ratio of each case was analyzed with the one-way ANOVA and Tukey HSD test. These analyses were conducted using the statistical analysis software R.

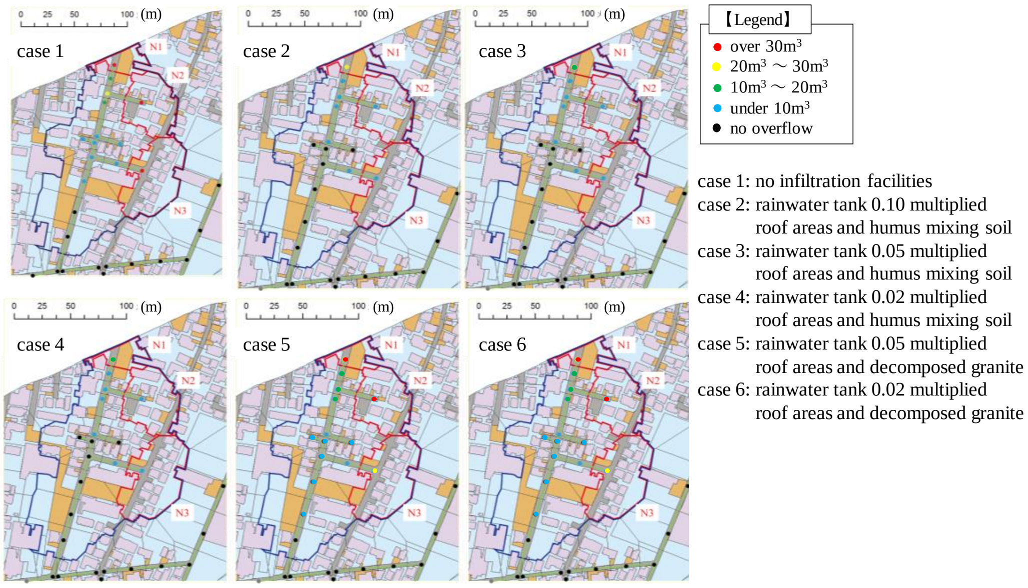
3. Results

3.1. Compatibility of the Rainfall Runoff Simulation Model

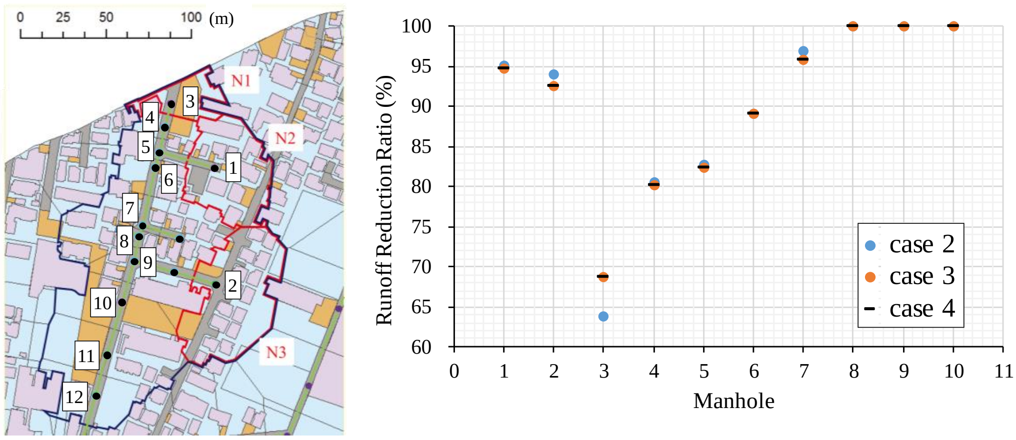
As a comparison of the calculation and observation results for the rainfall event of 15 October 2013, the calculated first peak flow rate almost corresponds to the observation result (calculation: 3.08 m^3/s; observation 3.15 m^3/s), and the second peak flow rate was 4.55 m^3/s in the calculation and 4.08 m^3/s in the observation. In addition, the total runoff amount was observed to be 65,044 m^3 compared to a calculated value of 69,943 m^3. Therefore, we determined that the runoff simulation model had high reproducibility and conducted the following calculation.

3.2. Verification of the Effect of Introducing Runoff Control Facilities

Figure 2a indicates the calculated runoff conditions for a long-term continuous rainfall event (15 October 2013). The catchment areas introduced to outflow control facilities were marked with red lines (N1–N3). As a result of the runoff calculation, over 30 m^3 of outflow occurred in catchments N1–N3 when no outflow control facilities were introduced. In contrast, the outflow volume remarkably decreased in cases with humus mixing soil (cases 2–4). In addition, the runoff reduction effect was the same regardless of the capacity of the rainwater tank. Furthermore, runoff reduction was not confirmed in the N1 and N2 catchment areas when decomposed granite was introduced. Moreover, the differences in the run off reduction effect between rainwater tanks of various volumes were confirmed.



(**a**)



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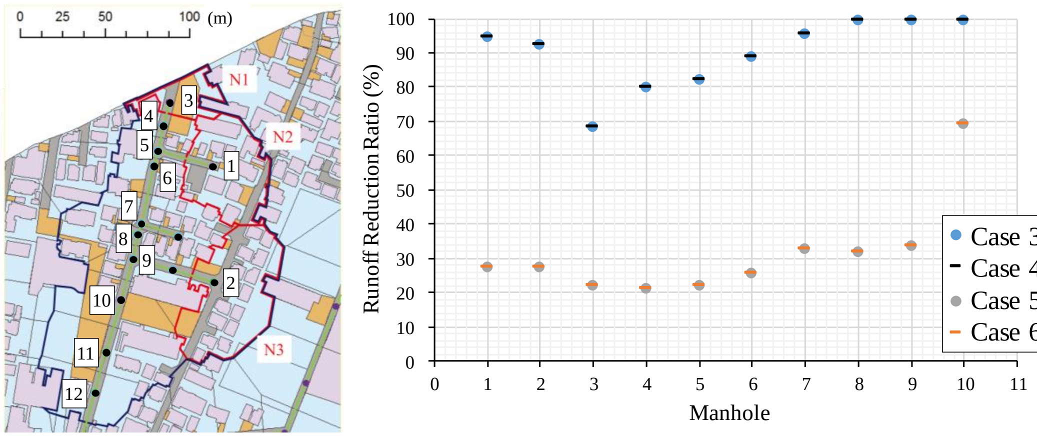

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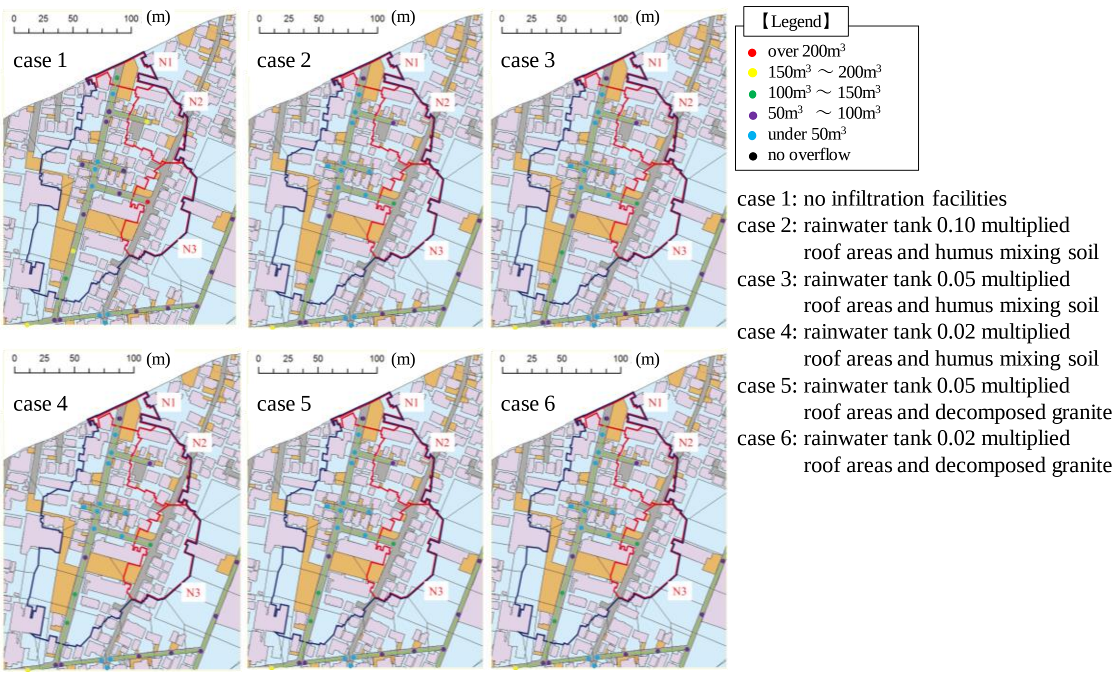
Figure 2. (**a**) Calculated runoff conditions for a long-term continuous rainfall event. (**b**) Runoff reduction ratio of each manhole when humus mixing soil was introduced during a long-term continuous rainfall event. (**c**) Longitudinal runoff reduction ratios in long-term continuous rainfall cases with humus mixing soil and only decomposed granite.

Next, the runoff reduction effect of each manhole when humus mixing soil was introduced in the long-term continuous rainfall event is shown in Figure 2b. Here, the runoff reduction ratio is defined by dividing the runoff reduction volume (obtained by subtracting the runoff amount in the case involving outflow control facilities from that in case without outflow control facilities) by the runoff volume calculated in the case without infiltration facilities. As the results of the one-way ANOVA show, significant differences were not confirmed among outflow control facilities. The runoff reduction ratio was found to be 5% higher at the uppermost reach of pipeline (No. 3) in the case wherein the rainwater tank capacity was 0.10 of the roof area in comparison with other cases. In contrast, differences in the runoff reduction ratio were not found in other manhole catchments because in the uppermost catchment, runoff occurred due to backwater from down reaches. Therefore, the volume of the tank does not appear to significantly influence runoff.

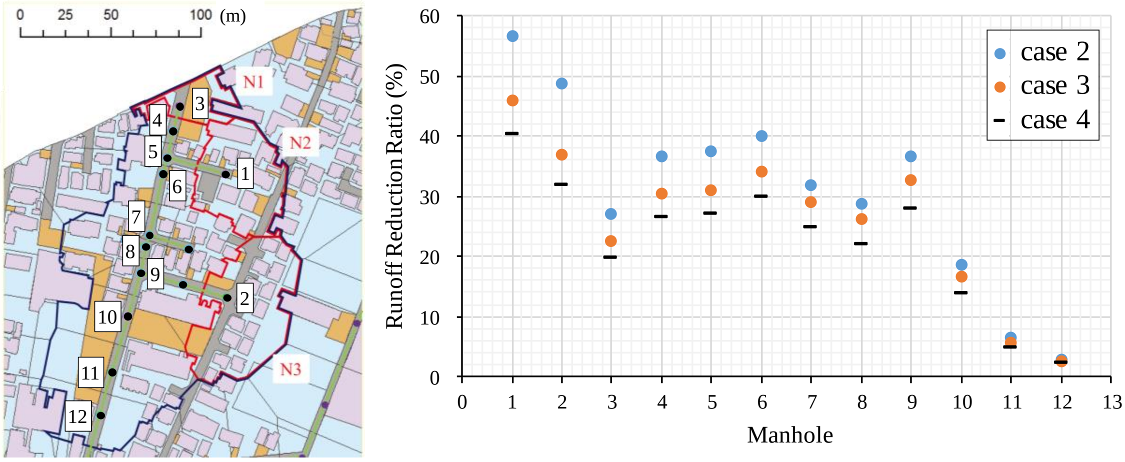
Figure 2c indicates the longitudinal runoff reduction ratio in cases with humus mixing soil and only decomposed granite for the 15 October 2013 rainfall event. The results of the Tukey HSD test indicates the significant differences among outflow control facilities excluding between the pairs of case 3 and 4, and case 5 and 6 ($p < 0.001$). In both cases, the tank volume did not influence the runoff reduction ratio. In contrast, the soil-improvement technology strongly affected the runoff reduction effect. In the case of humus mixing soil, the runoff reduction ratio was over 65%, whereas in the decomposed granite case, this ratio was less than 40%, except for the lowest reach catchment.

Figure 3a indicates the outflow condition for a short-term concentrated rainfall event (24 June 2014). As in the long-term case, outflow control facilities were introduced to the catchment marked with red lines. The outflow was found to exceed 300 m^3 for N3 and over 100 m^3 for N1 and N2 in the case involving no outflow control facilities. Among the cases of humus mixing soil, there was no significant difference in the runoff reduction ratio between case 2 (0.1 times the roof area) and case 3 (0.05 times the roof area). However, the runoff reduction ratio was low for the N2 catchment in case 4 (0.02 times the roof area).



(**a**)

Figure 3. *Cont.*



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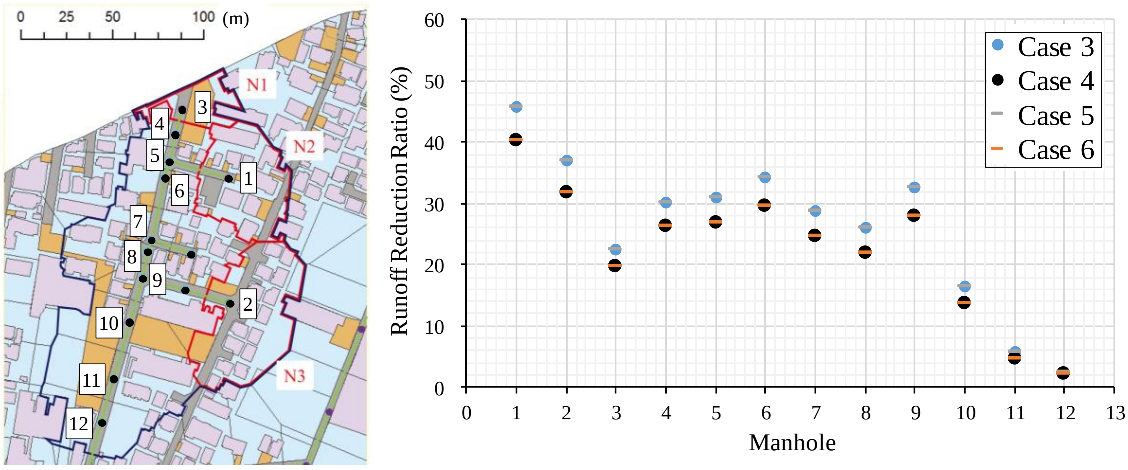

(**c**)

Figure 3. (**a**) Calculated runoff conditions for a short-term concentrated-rainfall event. (**b**) Runoff reduction ratio of each manhole when humus mixing soil was introduced during a short-term concentrated rainfall event. (**c**) Longitudinal runoff reduction ratio when humus mixing soil and only decomposed granite were introduced during a short-term concentrated rainfall event.

Figure 3b shows the runoff reduction effect of each manhole for the case with humus mixing soil during a short-term concentrated rainfall event (24 June 2014). As the results of the one-way ANOVA show, significant differences were not confirmed among outflow control facilities. The runoff reduction ratio was the highest in case 2 (0.1 times the roof area), followed by case 3 (0.05 times the roof area) and case 4 (0.02 times the roof area). The onsite runoff reduction effect was particularly remarkable, and approximately a 20% difference occurred between cases 2 and 4 in catchments N2 and N3.

Figure 3c shows the longitudinal runoff reduction ratio when humus mixing soil and only decomposed granite were introduced during a short-term concentrated rainfall event (15 October 2013). As the results of the one-way ANOVA show, significant differences were not confirmed among outflow control facilities. Soil-improvement technologies were not confirmed to have any effect on the runoff reduction ratios. In contrast, the rainfall tank volume influenced the runoff reduction ratio and it was 5% higher in cases 3 and 5 (0.05 times the roof area) at the upper catchment.

4. Discussion

4.1. Relationship between Outflow Control Facilities and Runoff Reduction Effect

Our simulations indicated that effective countermeasures for runoff reduction vary according to the rainfall patterns. Thus, for long-term continuous rainfall events, tank volumes did not appear to have a significant effect on runoff reduction; however, there was a remarkable difference between soil-improvement technologies. This is because the final infiltration value strongly influenced the runoff reduction effect during long-term continuous rainfall; however, the differences in the tank volume contributing to the initial rainfall loss did not influence the runoff reduction effect. On the contrary, the soil-improvement technologies introduced herein varied the final infiltration capacity (humus mixing soil: 36.9 mm/h; only decomposed granite: 8.5 mm/h), thereby exhibiting different runoff reduction effects in this rainfall scenario.

In the short-term concentrated rainfall event, a significant variation in runoff reduction occurred between rainfall tanks of various volumes; however, no difference was observed between soil-improvement materials. Since the initial rainfall loss is important for reducing runoff during a short-term concentrated rainfall event, the rainfall tank volume considerably influences the runoff reduction effect. On the contrary, the variation in the runoff reduction effect in accordance with rainfall tanks of various volumes in the uppermost catchment (N3) was smaller than that in other catchments. In N3, the outflow appeared to occur due to backwater from the lower reaches; therefore, the effect of onsite water storage was smaller than that in other catchments.

Because effective countermeasures for runoff reduction differ depending on the rainfall distribution patterns, we suggested the use of both facilities for storing initial rainfall and initiating countermeasures for penetration during a long-term rainfall event.

4.2. Evaluation Cases of Local Rainwater Outflow-Restraining Facilities

In this study, we focused on fundamental local technologies for preventing urban flooding. Local rainwater outflow-restraining facilities have been recently recognized as elemental technologies for LID, SUDS, and GI. Although there are a few cases, evaluation of the runoff reduction effect or the cost-benefit performance of green roofs, rain gardens, or permeable pavements has been conducted. Hathaway et al., (2008) measured the runoff discharge of green roofs. They indicated that approximately 80% of rainfall was reduced and the outflow time was delayed [56]. Hatt et al., (2009) monitored the effect of three biofiltration sites and indicated that these facilities have a runoff peak-cutting ability of around 80% [57]. In addition, Montalto et al., (2007) revealed that the combination of green roofs, permeable pavements, and treatment wetlands in LID can reduce the CSO by 70%, which is more cost-effective than the conventional method [58]. Similarly, as a case of evaluating a combination of countermeasures, Miquel (2013) clarified that the runoff volume can be cut by 52%–85% by six types of GI, including green roofs and bioinfiltration [59]. However, these examples solely exhibited the onsite runoff reduction effect and did not clarify the effects of local countermeasures on downstream sites. On the contrary, as in this study, an example of evaluating the downstream effects of countermeasures was provided by Pappalardo et al., (2017). They studied the effects of green roofs and permeable developments as the elemental technologies in SUDS using a hydraulic model. Green roofs were found to have a runoff reduction ability higher than that of the permeable pavements, suggesting that the effect is limited only to the measures in public places [60]. In the public sector implementation of local urban flood mitigation technologies, it is necessary to compare cost-effectiveness with more conventional methods. Therefore, the onsite and basin-wide verification of the runoff reduction effect, including the verification of downstream sites, is required for the introduction of elemental technologies.

Furthermore, although green roofs and permeable pavements have been researched as examples of GI or SUDS, few studies have focused on the infiltration capacity of the soil examined herein. In countries located in the Asian monsoon area, a runoff reduction method using soil improvement appears to be effective because these countries require whole-basin countermeasures against heavy rainfall. In addition, the runoff reduction effect was calculated for an occurrence probability of once per century in this study and runoff reduction effects of 95% for a long-term continuous rainfall event and 60% for a short-term concentrated rainfall event were measured for a combination of rainfall tanks and soil improvements. Since these methods were effective, establishing a runoff control technique using soil improvement and ensuring a general-purpose evaluation method can reduce runoff for urban flood mitigation.

4.3. The Importance of Complex Measures and the Establishment of Evaluation Techniques

This study showed that the onsite runoff reduction effect was at the most 60% during short-term concentrated rainfall events. Further, this effect declined while moving downstream; at a distance of 100 m downstream, it became approximately 10%. This result indicates that the local runoff reduction technology alone cannot completely prevent outflow. Multiple countermeasures of local technologies and intensive facilities, including large-scale flood control reservoirs or channel improvements, are required for complete mitigation of urban flooding. Recently, the effects of local runoff reduction facilities have been considerably researched; however, research on multiple countermeasures of both local technologies and intensive facilities has not been conducted. Parameters such as the inundation process, height, duration, and economic loss have been considered as evaluation indicators for multiple facilities; however, they cannot be easily standardized because the scale of the floods used for evaluation differed between the local and intensive facilities. Furthermore, a relatively large-scale runoff simulation model is required to evaluate multiple countermeasures, but to evaluate the effects of local technologies, it is necessary to reduce the mesh size and consider the calculation costs. In addition, local technologies, including green roofs or soil improvements, may possibly degrade permeability over time. Integrating these factors into a runoff simulation model can constitute a problem when establishing an evaluation technology. It is also important to establish evaluation techniques for quantitatively assessing the effectiveness of multiple countermeasures.

5. Conclusions

This study aimed to investigate the influence of various outflow control facilities on runoff reduction in a small watershed. We focused on soil improvement and rainwater tanks as outflow control facilities and conducted a runoff calculation using a rainfall event with an occurrence probability of once per century. The following results were obtained:

1. The runoff reduction ratio was 95% during a long-term continuous rainfall event and 60% during a short-term concentrated rainfall event in the case with the most effective facilities (humus mixing soil and rainfall tanks having a capacity of 0.10 times that of the roof area). In contrast, the runoff reduction ratio was 30% for a long-term continuous rainfall event and 40% for a short-term concentrated rainfall event in the case with the least effective facilities (decomposed granite and rainfall tanks having a capacity of 0.02 times that of the roof area).
2. The runoff volume during a long-term continuous rainfall event varied little with the tank volume but significantly with the soil-improvement technology. However, during short-term concentrated rainfall events, there was a significant difference in the runoff reduction effect between rainfall tanks of various volumes. On the contrary, this difference was observed between soil-improvement materials. Since the effective countermeasures for runoff reduction differ depending on the rainfall distribution patterns, we suggested the installation of both facilities for storing initial rainfall and initiating countermeasures for penetration improvement during a long-term rainfall event.
3. Recently, the effectiveness of local runoff reduction facilities has been considerably researched; however, research concerning runoff reduction for multiple countermeasures of both local technologies and intensive facilities has not yet been conducted. The reason for this is that

the techniques for evaluating runoff reduction in the latter case have not been established yet. Thus, it is important to establish evaluation techniques for quantitatively assessing the effectiveness of multiple countermeasures.

Acknowledgments: This work was supported by Gesuido Academic Incubation to Advanced Project, managed by the Ministry of Land, Infrastructure, Transport and Tourism.

Author Contributions: R.I. integrated the research program and wrote this paper. Y.O. conducted the runoff calculation. Y.I. conducted the field survey and data reduction. T.S. established runoff calculation model.

Conflicts of Interest: The authors declare no conflict of interest.

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