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Rainfall loads in flood-control project for urban areas

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ABSTRACT: In urban areas, since intense land use is remarkable and improvement to small and medium sized rivers and expansion of sewer drainage infrastructures are very difficult, storage facilities, which perform momentary storage of a flood water, such as a regulation pond and storage pipe, play an important role, for the urban flood control. The present projects for rivers and sewers are made based on each design rainfall scale and design hydrograph, and the present condition is that mutual adjustment and increase in efficiency are not attained. DAD analyses of time-spatial scales (approximately 10–180 minutes and up to about 100 km^2) for small and medium-sized rivers and sewer watershed are performed. Moreover, the difference in the rainfall characteristics by the rainfall sources (typhoon and thunderstorm) is clarified, and the way that should be as rainfall load for the project, which can reflect these characteristics, is proposed.

1 OBJECTIVES

The urbanization of watersheds is resulting in larger, faster discharges, leading to an increase in so-called "urban flooding", particularly cases in which brief, local downpours cause small and medium-sized rivers to overflow concurrently with sewer flooding. This urgently necessitates both improvements to small and medium-sized urban rivers and the expansion of sewer drainage infrastructures. However, because of the difficulty of securing land for such purposes in urban areas—due to exorbitant real estate prices and the intense use of land—an important role can be played by regulation ponds, storage pipes, and other facilities that temporarily store overflow from rivers and sewers. Although such storage facilities interdependently affect the discharge and storage capacity of rivers and sewers and thereby improve overall flood-control capabilities, current planning for small and medium-sized rivers and sewers has focused on the design frequency of occurrence (i.e., an *n*-year-frequency storm) and design rainfall of each type of infrastructure separately; the two have yet to be integrated and optimized for greater effectiveness and efficiency.

Therefore, the authors have analyzed the temporal-spatial properties of rainfall on the scale of the small watersheds of small and medium-sized rivers and sewers in urban areas. This work presents a method for calculating relevant rainfall for realistic, efficient flood-control plans that consider rivers and sewers as an integrated whole.

2 ISSUES IN CURRENT PLANNING METHODOLOGY

Current flood-control and rainwater-drainage planning for small and medium-sized rivers and sewers is, in general, based on rational formulas. This section discusses some of the issues relating to the analysis of design rainfall load and discharge in flood-control planning based on rational formulas.

2.1 *Rainfall load*

Planning for rivers and sewers is generally based on storms of different annual probabilities: range of the 30- to 50-yr recurrence interval for small and medium-sized rivers, and range of the 5- to 10-yr recurrence interval for sewers. Estimating capacity for floodwater storage requires a rainfall distribution, and it is often the narrowly concentrated rainfall distribution based on rational formulas that is used. However, such a rainfall distribution is at odds with the reality that the rainfall distribution differs according to the flood travel time, and that typhoons, thunderstorms, and other rainfall sources produce rainfall of differing temporal and spatial distributions. In flood-control planning that involves storage facilities, the interdependent effect of those facilities on the river and sewers in question should be properly assessed. It is questioned to form the planning using the different rainfall of each and the temporal-spatial distribution of assumed, as opposed to historical, rainfall.

2.2 *Flood discharge calculation*

Current methods that use rational formulas in flood-control planning for small and medium-sized rivers and sewers cannot depict the interdependent effect of flood control facilities on flood discharge and storage. Furthermore, rational formulas assume a uniform rainfall load over a watershed and constant rainfall during the flood travel time and so do not reflect actual conditions in small and medium-sized rivers, as having a watershed 100 to 200 km^2 in size. The need therefore exists for a flood discharge calculation method that treats rivers and sewers as an integrated whole and that accurately reflects the effects of storage facilities, relative to differing temporal and spatial distributions of rainfall.

3 RAINFALL PROPERTIES ON THE SCALE OF SMALL AND MEDIUM-SIZED URBAN RIVER AND SEWER WATERSHEDS

Using comparatively dense telemetric data from rainfall observation stations in the Kanda River watershed in Tokyo, Japan, we conducted depth–area–duration (DAD) analysis on the temporal-spatial scale of small to medium-sized river and sewer watersheds (i.e., durations of 10 to 180 minutes and areas up to 100 km^2). Clear differences in rainfall properties were used according to rainfall source (e.g., typhoon and thunderstorm), and these properties were incorporated into planning for the relevant rainfall.

3.1 *Subject of investigation*

The subject of our investigation was the Kanda River (watershed size: 105 km^2), a small to medium-sized river system typical of the Tokyo area (Fig. 1). We examined seven different sub-basins in this river system, including tributaries and sewer mains and ranging in surface area from 7 to 105 km^2 (Table 1).

As rainfall data, we used rainfall statistics on 91 rainfall incidents occurring in the Tokyo area over a 17-year period (1979 through 1995). Ten-minute rainfall was measured at intervals of 3 to 5 km by the rain

Table 1. Data on the watershed investigated.

Watershed	Watershed area (km^2)	Approximate travel time (minute)
Kanda River	105	180
Upstream of Minami Kotaki Bridge	47	120
Upstream of Wadami Bridge	30	100
Myoshoji River	22	90
Zenpukuji River	19	80
Upstream of Kanda River and Zenpukuji River confluence	11	60
Momozonogawa Sewer Main	7	40

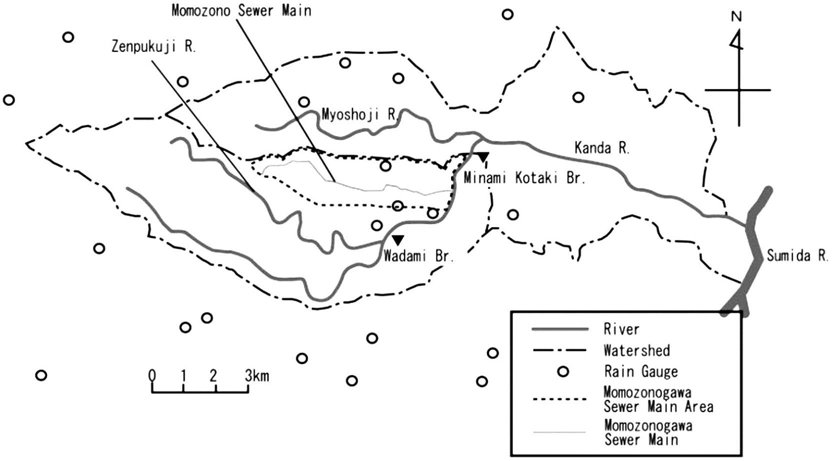
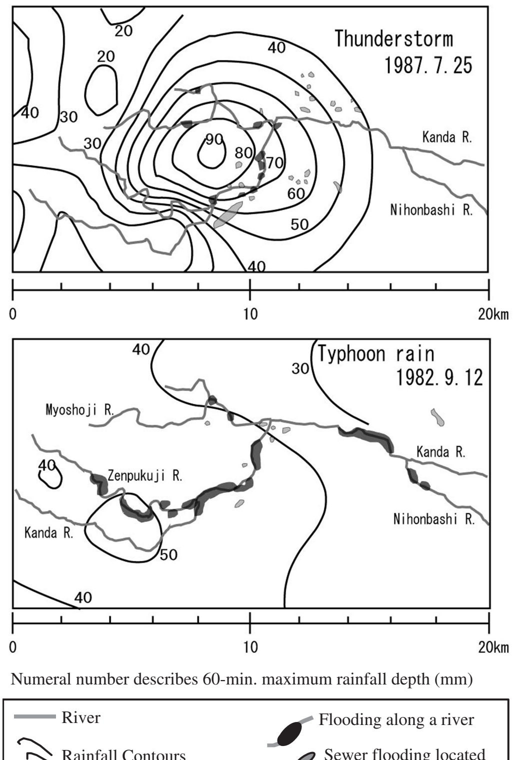


Figure 1. The watershed investigated.

gauges shown in Figure 1. Weather maps for the days in question and other meteorological data were used to categorize the rainfall sources as “thunderstorm” or “typhoon or other source.”

We calculated the 60-minute maximum rainfall distribution and inundation damage distribution for those rainfall incidents that resulted in flood inundation damage due either to typhoon or thunderstorm; an example is shown in Figure 2. The data show that thunderstorm-related local downpours have a very high degree of local concentration of rainwater, and that centered around this zone of concentration are sporadic occurrences of sewer flooding (i.e., sewer or storm-drain overflow that results in the inundation of roads and other surfaces) located a distance from the river. This sewer flooding happens because the brief, intense rainfall associated with thunderstorm-related local downpours quickly overwhelms the drainage capacity of sewers, which indicates that river capacity is not reached in such situations because of the failure of massive volumes of floodwater to reach the rivers. In contrast, the short-term intensity of typhoon-related rainfall is not as great as that of thunderstorms. Consequently, sewers designed for brief, high-intensity rainfall according to rational formulas gradually drain away the rainwater, causing discharge to concentrate in the river and thereby causing the river to overflow its banks. This, too, indicates the need of countermeasures to consider the difference of rainfall distribution and different regional distributions according to interdependent discharge in rivers and sewers, storage conditions, and rainfall source.



Numeral number describes 60-min. maximum rainfall depth (mm)

Figure 2. Example distribution of the rainfall investigated.

3.2 *Relationship of travel time of observed rainfall* (Tanioka,Y., Fukuoka, S. 2003)

Figure 3 shows the relationship of, for instance, 30-minute and 180-minute maximum rainfall observed at ground rainfall observation stations in the Tokyo area. Here, the 30- and 180-minute points roughly correspond to the flood travel times in a 2-km^2 sewer and a 100-km^2 river. The data clearly show the difference in rainfall properties between thunderstorm rain and typhoon rain: Typhoons result in a rainfall distribution that is large relative to travel time in rivers, whereas thunderstorms result in a rainfall distribution that is large relative to travel time in sewers. This difference between types of rainfall is also apparent in the differences in flood patterns shown in Figure 2. Figure 3 also shows the probable rainfall depth at the 30- and 180-minute points, with a dashed line indicating the point of intersection for the same return period. This line represents rainfall depth with a narrowly concentrated-rainfall distribution, i.e., the rainfall depth for each travel time. It can be seen that such rainfall occurs only very rarely.

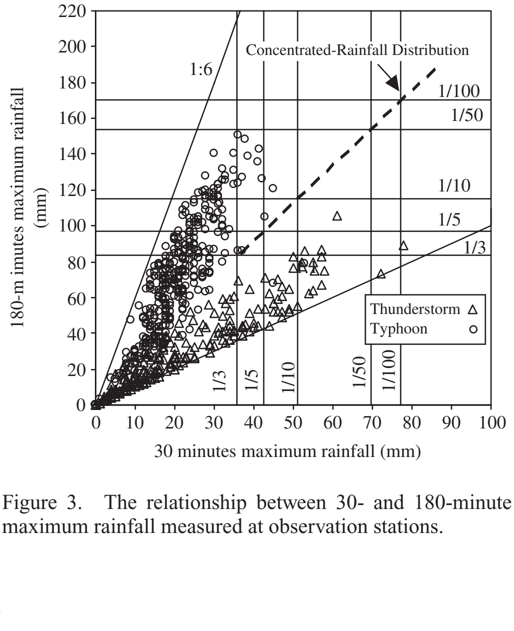


Figure 3. The relationship between 30- and 180-minute maximum rainfall measured at observation stations.

3.3 *Relationship between travel time and rainfall intensity during travel time*

Figure 4 shows the relationship between travel time and watershed-averaged rainfall intensity during travel time for the thunderstorm and typhoon data shown in Figure 2. As can be seen, thunderstorms produce a rainfall intensity that falls sharply in a short period, whereas typhoon rainfall intensity is large but declines in intensity at a slower rate over time.

3.4 *Relationship between watershed size and rainfall intensity*

As shown in Figure 5, which presents the tendency of watershed-averaged rainfall intensity to decline as watershed size increases, the decline in rainfall intensity with watershed size is extremely sharp in the case of 30-minute thunderstorm rain on the small temporal-spatial scale of small and medium-sized rivers and sewers. In comparison, typhoon rain does not decrease in watershed-averaged intensity as sharply as watershed size increases.

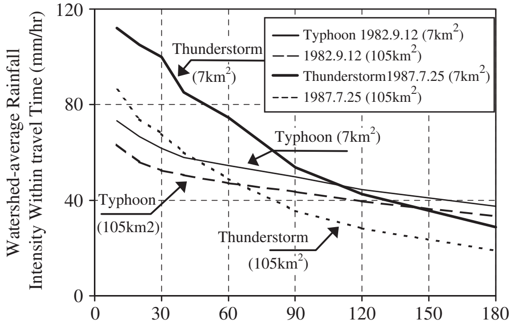


Figure 4. The relationship between travel time and rainfall intensity during travel time.

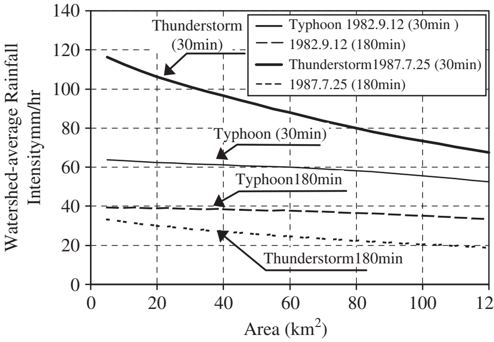
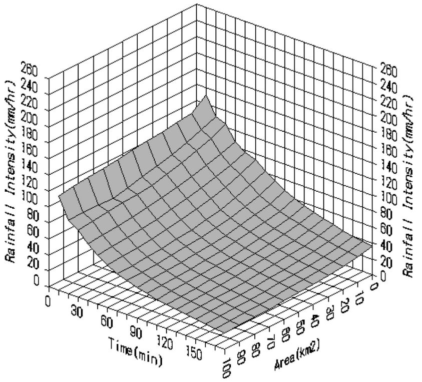


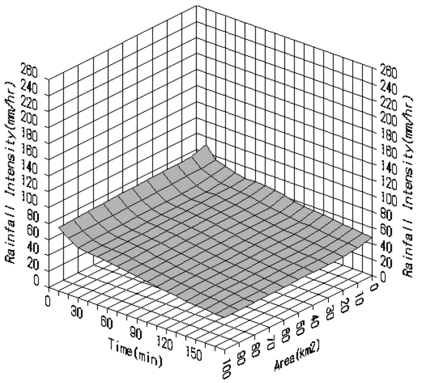
Figure 5. The relationship between watershed size and rainfall intensity.

3.5 *Relationship between DAD for historical and probable rainfall*

The relationship between watershed size, travel time, and intensity for historical rainfall (Figure 6) is such that thunderstorm rainfall is highly concentrated in a brief time period and a small area, as indicated by its sharp temporal-spatial form. We categorized the historical rainfall data mentioned above as either "thunderstorm-related intense downpour" or "typhoon or other rain." For the seven watershed sizes listed in Table 1 (ranging from 7 to 105 km^2), we calculated the greatest watershed-averaged rainfall volume for eight different travel times (from 10 to 180 minutes) and performed hydrological statistical analysis according to the rainfall source. An example is given in Figure 7: temporal-spatial distribution of probable rainfall intensity according to watershed size and travel time for a 30-year storm. The DAD relationship of probable rainfall from thunderstorms and typhoons shown in Figure 7 corresponds well with the temporal-



(a) Thunderstorm Rainfall (1987.7.25)



(b) Typhoon Rainfall (1982.9.12)

Figure 6. Example DAD relationship in historical rainfall.

spatial distribution properties of historical rainfall shown in Figure 6. This, too, indicates the clear difference between the temporal-spatial distribution properties of thunderstorm and typhoon rain. Figure 8 is a rainfall-intensity curve generated from the relationship between approximate travel time and watershed size shown in Table 1. This shows that thunderstorm rainfall is more intense when approximate travel time is shorter than 60–100 minutes and watershed size is less than 20–30 km^2, but at longer travel times and larger watershed sizes, typhoon rain is more intense. Because probable rainfall intensity differs greatly according to the watershed size and travel time in the river or sewer and according to the rain source, it is necessary to select the appropriate storm magnitude (i.e., frequency of occurrence) and to identify the rainfall source in question.

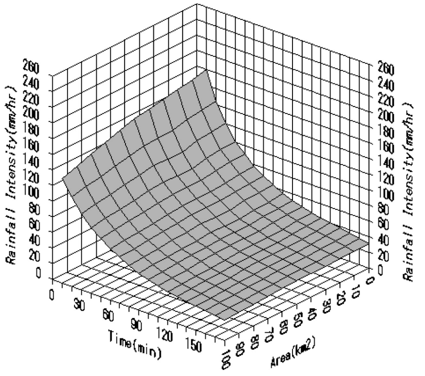
4 A METHOD FOR ESTABLISHING RAINFALL LOADS IN FLOOD-CONTROL PLANS FOR URBAN AREAS

Consolidating everything discussed in the preceding sections about rainfall loads, temporal-spatial distribution properties, and the discharge and flooding of rivers and sewers, we will now consider a method of establishing rainfall loads in flood-control plans that takes all of these factors into account.

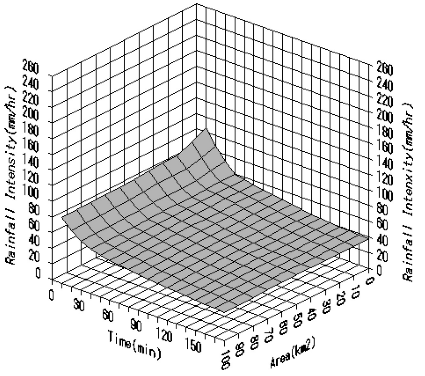
Figure 9 is the flood-control planning process for urban areas that the authors propose. Instead of using rational formulas to determine rainfall loads and discharge, we propose DAD analysis that, in analyzing rain properties, also takes into account rain sources in the investigated area and that uses historical rainfall data for the rainfall relevant to the flood-control plan. Furthermore, discharge calculation is conducted using a flood flow and flood inundation model that treats rivers and sewers as an integrated whole, that calculates the mutual impact and effect of storage facilities and other infrastructure, and that also takes sewer flooding into account. This section describes the authors' method.

4.1 *Analysis of rainfall properties*

Conventional flood-control planning based on rational formulas uses the rainfall-intensity curve of a single representative location in a watershed to determine the rainfall load and consequently assume a uniform distribution of rain throughout the watershed during the travel time in question. In actuality, however—particularly in the case of local downpours caused by thunderstorms – watershed-averaged rainfall intensity tends to be lower in larger watersheds. Furthermore, thunderstorm and typhoon rain have considerably



(a) Thunderstorn Rainfall
(Recurrence Interval 30 years)



(b) Typhoon Rainfall and other
(Recurrence Interval 30 years)

Figure 7. DAD relationship in probable rainfall.

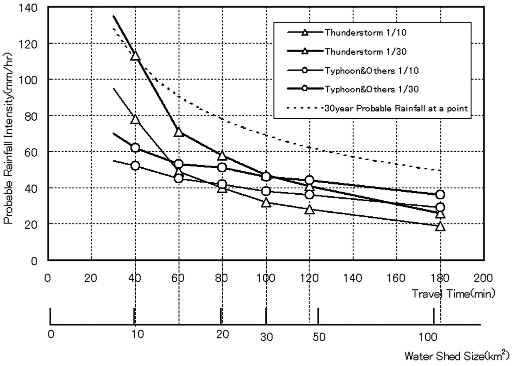


Figure 8. The relationship between travel time, watershed size, and probable rainfall intensity. (For comparison, probable rainfall intensity (Tokyo Met. Gov. 1985) at the Tokyo Observation Substation of the Tokyo Weather Station is indicated by a dashed line.)

different temporal-spatial properties. Design rainfall loads must properly reflect all of these factors.

4.1.1 *DAD analysis to determine rainfall properties*

It is necessary to collect historical rainfall data on small watersheds (small to medium-sized rivers and sewers) measured at short (5- to 10-minute) intervals, organize the data according to the temporal-spatial rainfall properties of the rainfall source, and then identify and analyze the rainfall properties of the watershed in question.

4.1.2 *Probable rainfall intensity according to rain source, watershed size, and travel time*

Probable rainfall intensity is calculated by statistically arranging watershed-averaged rainfall intensity by watershed size and travel time. When doing so, because the time and geographic distribution properties of rainfall differ greatly according to rainfall source (e.g., thunderstorm or typhoon), it is important to calculate the probable rainfall separately for each source so as to produce a plan that reflects reality.

The aim is to determine, on the scale of the river and sewer watersheds in question, how frequently and with what sort of temporal-spatial distribution rain will fall.

4.2 *Determining the relevant rainfall*

4.2.1 *Extracting historical rainfall distribution according to rainfall source*

To determine the rainfall that is likely to occur in the future, data on historical rainfall are analyzed to identify the different rainfall sources. Figure 10 is an example of the data used in this identification process. In this case, the authors plotted the relationship of sewer-watershed-averaged rainfall intensity during the flood travel time (e.g., 30 minutes) and of the river-watershed-averaged rainfall intensity during the flood travel time (e.g., 180 minutes) in order to identify the respective ranges of the thunderstorm and typhoon rain (encircles with dashed lines in the figure). Within these ranges of data, the relevant rainfall was identified by

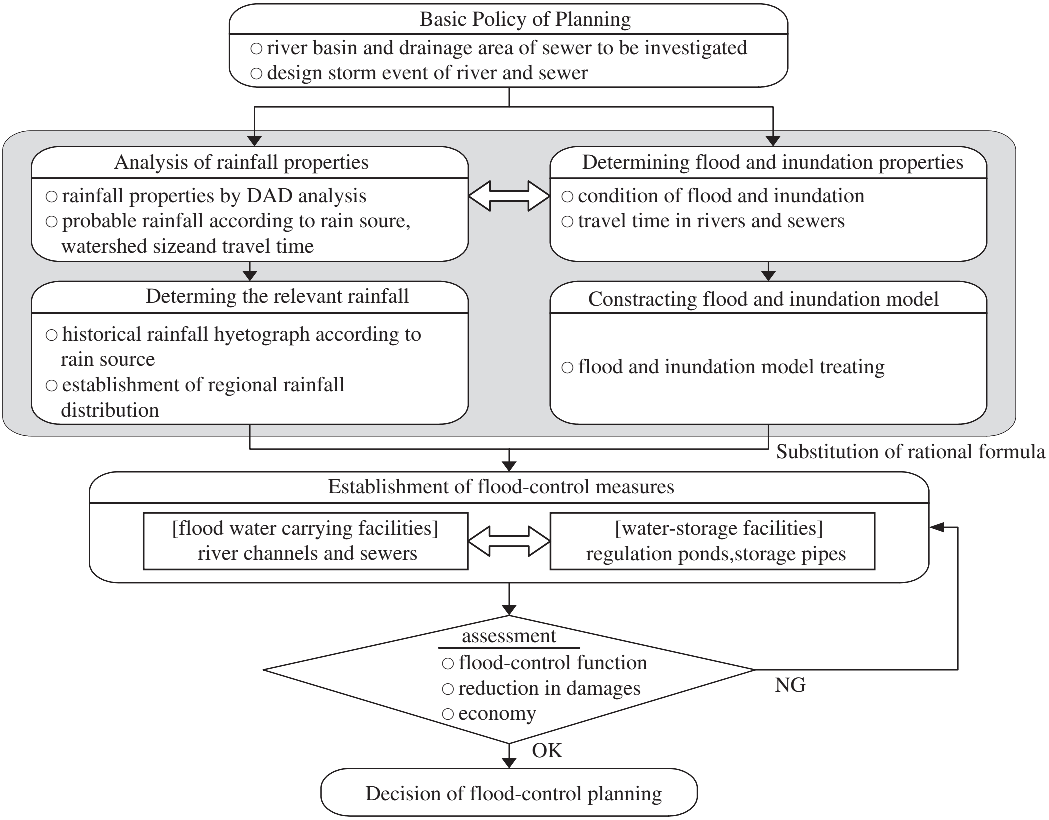


Figure 9. The flow chart of flood-control planning for urban areas.

determining the areas (A through D) in the figure of historical rainfall that correspond to the probable rainfall intensity of the design storm event (e.g., 30-year storm for rivers and 10-year storm for sewers) determined separately for each rainfall source using hydrological statistical analysis, as mentioned earlier. Table 2 lists the types of rainfall and notes on each. Essentially, a flood-control plan should be designed so that sewer systems will not be flooded by typhoon or thunderstorm rain produced by the sewer's design storm event (10-year storm). In the case of rivers, floodwater equivalent to the river's design storm event (30-year storm) should not result in river overflow. At the same time, other measures are necessary to handle rainfall that exceeds sewer capacity, such as monitoring sewer overflow and taking steps to minimize the intensity and extent of damage.

4.2.2 *Establishing regional distribution*

Discharge varies greatly depending on the regional distribution of rainfall (Tanioka,Y., Fukuoka,S., et al. 1998). On the scale of a small to medium-sized river or sewer watershed, it is not known where in the watershed the rainfall will be concentrated. Figure 11 is a proposed method of determining the rainfall distribution in a watershed.

In the case of a typhoon, uniform rainfall throughout the watershed can be assumed because almost no variation in rainfall intensity occurs. In the case of a thunderstorm-related local downpour, however, the location of greatest concentration can determine whether the runoff concentrates in the sewers or in the river system. This necessitates considering scenarios in which rainfall is concentrated in locations considered

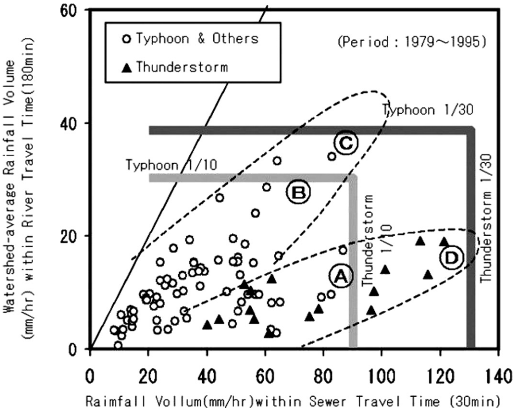


Figure 10. The relationship between watershed-averaged 30- and 180-minute maximum rainfall intensity.

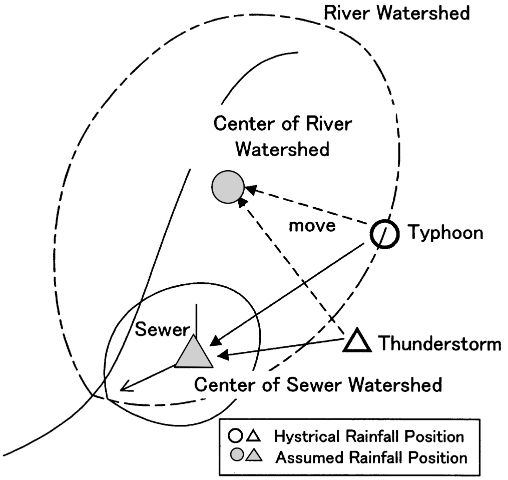


Figure 11. Conceptual diagram of determining the area of concentration of design storm rainfall.

Table 2. Extraction of relevant types of rainfall with notes on each.

Sewer	Thunderstorms	Typhoon rains	Remarks
Sewers (1/10 plan)	Ⓐ : Thunderstorms 1/10 • Is it possible for sewers to discharge or store flood water when thunderstorm of 10-year storm attacks in the sewer drainage area?	Ⓑ: typhoon 1/10 • Possible for sewers to discharge out or store flood water against high level of river water?	• Flood-control plan is made not so as to arise sewer flooding
Rivers (1/30 plan)	Ⓓ: Thunderstorms 1/30 • Do rivers floods locally • Does sewer flooding cause a huge damage in inhabitant areas.	Ⓒ: typhoon 1/30 • Possible for rivers to discharge flood flow? • Does sewer flooding cause a huge damage due to high level of river water.	• Flood-control plan is made not so as to arise river flooding. • Countermeasures to prevent huge damage from sewer flooding.

the most dangerous (e.g., the center or downstream reaches of a watershed or the upstream reaches of water-storage facilities).

4.2.3 *Determining discharge and flood properties and constructing a discharge calculation model*

It is crucial to use data on historical water levels and discharge in rivers and sewers—including data on river overflows and sewer flooding—to identify discharge and flooding phenomena, determine the causes, and generally ascertain actual conditions in the watershed in question. Once this is done, instead of using rational formulas, it is necessary to construct an integrated model of discharge and flooding in the river and sewer systems that incorporates the regional and temporal distributions of the rain load. A precondition is the ability to accurately incorporate the effects of storage facilities. In addition, because of the large impact of sewer flooding on river discharge (Fukuoka, S., Tanioka, Y. 2001), the model should be able to determine how extensive sewer flooding will be and what effect it will have on the river and sewer systems. Furthermore, the model should also reflect the temporal-spatial distribution of historical rainfall, which is considered in analyzing rain load.

5 ISSUES FOR FUTURE INVESTIGATION

5.1 *How to draft flood-control measures*

Flood-control measures should use the appropriate combination of floodwater-carrying facilities (e.g., river channels and sewers) and water-storage facilities (e.g., regulation ponds and storage pipes). Furthermore, combinations of different types of water-storage facilities are also needed depending on the rain source—for instance, to control sewer flooding in the case of thunderstorm-related local downpours, and to prevent river flooding in the case of typhoon-related rain. Flood-control measures should also strive to interlink various facilities throughout a watershed, such as tunnel-type water-storage facilities, underground rivers, and diversion channels, thereby ameliorating regional variation in rainfall and affording flexibility (Tanioka, Y., Fukuoka, S. 2003).

5.2 *Systematization of flood-control planning methods for urban areas*

The methods of flood-control planning discussed in this paper are by no means applicable to every type of river or sewer system or every set of geographic or meteorological factors. These techniques must be systematized to yield logical, appropriate flood-control plans that also strive to use existing infrastructure more effectively. The availability of only limited historical data on short-term rainfall properties, sewer flooding, and other information about small and medium-sized rivers, sewer systems, and other small watersheds may present difficulties in the investigation of rainfall, discharge, and flooding properties in those watersheds. Nevertheless, the calculation of simple, general design indices (e.g., DAD analysis on rainfall) for local areas should further the formulation of more logical plans in the future.

5.3 *Accumulation and utilization of observations and data*

In many cases, very little data are available on the temporal-spatial scale of rain, discharge, and flood properties of a small river or sewer watershed. Consequently, an important issue in designing more appropriate flood-control plans is conducting detailed, appropriate measurements and monitoring to gather and archive such data.

5.4 *Flood-control planning that also utilizes rainwater storage and percolation facilities*

In addition to rainwater-storage facilities for rivers and sewers, watershed-wide rainwater-storage and infiltration facilities and other technologies will also play an important part in the urban flood-control planning of the future. Therefore, these techniques should also be systematized into a coordinated whole for use in realizing comprehensive flood-control plans for urban areas.

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