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The definition of urban stormwater tolerance threshold and its conceptual estimation: an example from Taiwan

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Abstract The combination of climate change and urbanization is worsening urban flooding problems. Estimating the amount of rainfall that a city can tolerate without flooding is a fundamental task that is difficult to perform, although large amounts of resources are invested in urban flood control. The purpose of this study is to determine the tolerance threshold for stormwater in a city. Based on hydrometeorological characteristics and existing flood control facilities, the urban adaptive water capacity is analyzed to determine the critical rainfall loading. Different critical levels are defined. The low critical point represents the beginning of the water accumulation, while the intermediate and high critical points are defined as flooding with heights of 300 and 600 cm, respectively, in low-lying areas. This study adopts a simple conceptual method to illustrate the critical levels instead of applying complex hydrologic and hydraulic modeling, which require high-resolution spatial data. Three cities and one township in Taiwan are used as urban case studies and to verify the conceptual method. As the capital, Taipei City utilizes the highest flood control engineering technology of our case studies; it is also the site in which the lowest rainfall thresholds cause the accumulation of water to reach the intermediate and high critical points because its small 'internal water areas' increase the height of floods rapidly. Conversely, Taichung City has a large internal water area that can disperse accumulating waters without increasing flood height. The estimations of urban storm tolerance thresholds increase the understanding of the limitations of water protection facilities. These estimations may be combined with rainfall forecasts to increase early warning functions and provide a reference point for subsequent planning related to urban flood adaptation strategies.

Keywords Urban stormwater · Threshold analysis · Critical point · Adaptation

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1 Introduction

In the face of confirmed climate change, we must find a way to coexist with the changing climate to survive in the twenty-first century and beyond. In recent years, it has become clear that a change in storm patterns is associated with these climate changes, and this new storm pattern has caused flooding disasters around the world. The report of the Intergovernmental Panel on Climate Change (IPCC) (IPCC 2012) indicates that extreme floods have caused losses of life in several developing countries and serious economic losses in developed countries. The need to understand extreme rainfall events is now more urgent than understanding the average rainfall patterns (Guhathakurta et al. 2011). The chances of light or moderate rainfall occurring have been decreasing in tandem with the number of rainy days, while the intensity of strong rain has been increasing. The increasing intensity of strong rain is associated with a higher frequency of the rainfall return period. This rapidly occurring type of rainfall has engendered a new rainfall pattern, ushering in the 'new era of storms.'

Improving urban flood management is a new trend across the world because urban flooding problems are becoming more difficult to address and the internal urban environment is becoming more fragile as a result of the changing external climate conditions. In addition to traditional water control projects, a number of countries are promoting new measures consisting primarily of strengthening local water storage and infiltration measures, such as low-impact development (LID) systems in the United States (USEPA 2000; Dietz 2007) and the total integrated flood control strategy applied in Japan. However, prior to the implementation of these various management measures, there have not been many studies that present quantitative information about how much rainfall can be accommodated based on the existing facilities in a particular city, that is, estimating the torrential rainfall tolerance threshold of the city. Climate change alters storm patterns and may affect the accuracy of future engineering designs (Seidou et al. 2012), but studies that discuss rainfall thresholds related to flooding mainly establish real-time monitoring and forecasting tools as a flood warning method (Carpenter et al. 1999; Martina et al. 2006; Norbiato et al. 2008; Montesarchio et al. 2009).

Frequent flooding is also a result of the changes in urban characteristics. Although urbanization increases economic development, the rapid construction of buildings and roads has increased the impervious area on the surface and increased the amount of surface runoff in many urban areas throughout the world. Thus, there are more surface runoff and higher peak flows in urban areas than in nonurban areas when exposed to identical rainfall situations. If the urban drainage system does not respond well, the risk of flooding in urban areas will be greater than in nonurban areas (Gupta 2007; Ntelekos et al. 2010; Hanson et al. 2011). Hydrometeorology is also critical. For example, Mirza et al. (2003) analyzed severe flooding events in Bangladesh, showing that, because Bangladesh is located in the downstream delta of 3 rivers, it receives all of the rainfall in the watershed area. In addition, because river discharge to the sea is influenced by sea level and tides, the floods do not easily retreat in this region. Marchi et al. (2010) analyzed the hydrometeorology of flash floods in Europe and demonstrated that the spatial characteristics of watersheds have a significant influence on flooding events. O' Donnell et al. (2011) attempted to link rainfall runoff to downstream flooding in discussing the effects of upstream land management practices on downstream flooding. Anselme et al. (2011) showed that cities situated on the shoreline are subject to a significant threat of flooding.

Many studies have presented good examples of the integration drainage system and urban flood inundation (Hsu et al. 2000; Cheng and Wang 2004; Chen et al. 2005, 2009, 2011; Cea et al. 2010; Kim et al. 2010; Pathirana et al. 2011; Seyoum et al. 2012). These studies usually couple a drainage model such as SWMM (Storm Water Management Model) with a 2D flood inundation model and then utilize high-resolution spatial data of the landscape geometry, for example, terrain data, digital orthophotos, and oblique aerial photos (Gallegos et al. 2009). Urban flood inundation is usually induced from the surcharge of storm sewer system. However, a broader watershed scale combining a river flood control facility and urban drainage system is rarely discussed. In this study, we intend to illustrate a city storm tolerance threshold, but not with the goal of assessing a flood inundation map of a city. The IPCC (IPCC 2012) emphasizes that disaster risk management and climate change adaptation can mitigate disaster levels, but it indicates neither how to calculate storm tolerance thresholds and disaster risks nor what level and type of rainfall conditions will cause flood disasters. Few studies address how much rainfall the current urban infrastructure context can absorb without flooding, although city officials are eager to have this information. The purpose of this study is therefore to integrate urban hydrometeorology with the capacity of flood prevention systems to determine the storm thresholds of cities. This information also serves a supplementary message for early warning systems in the future changing climate.

2 Methods

2.1 Definition and classification of critical points

The analysis of critical points is performed to link climate conditions with the adaptive capacity of human societies and produce a quantitative language to describe the weather conditions that will produce particular types of disasters; this language and subsequent descriptions are then used as basic information in responding to climate changes or disasters. Climate conditions are transformed into the quantitative external loading pressure (loading), while the responsive capacity of human societies is transformed into the quantitative internal adaptive capacity (capacity). Thus, the critical point represents the comparison between loading and capacity. Once loading becomes larger than capacity, overloading occurs.

Using Fig. 1 as an example, loading exhibits variability, while capacity is theoretically a fixed value. When loading exceeds capacity, damage or disasters will occur. Therefore, the simple definition of the critical point is $loading > capacity$. Each time loading is greater than capacity, it represents a critical point; however, when the differences between these two parameters are different, the sizes of disasters are also different. Therefore, the critical point shows scalability. Considering different levels of flooding, this study classifies critical points into 3 levels:

1. Low critical point: Water accumulation begins, but the area can recover within 1 day. This situation is considered light water ponding. When a storm begins instantaneously and exceeds the drainage capacity, water accumulates, and small-scale flooding occurs because of poor drainage. Because of the low runoff rate, the water will retreat within 1 day, and no damage occurs. The associated loading is that rainfall intensity exceeds the drainage system and usually indicates a storm of a 2- to 5-year return period according to design regulations in Taiwan.

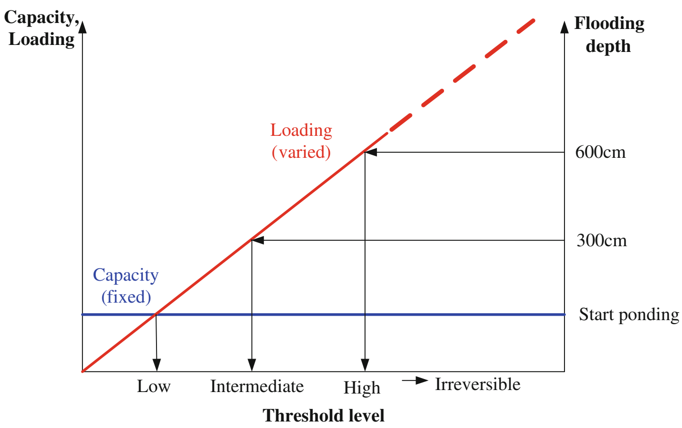


Fig. 1 Concept map of critical points (comparison between external loading and internal adaptive capacity)

2. Intermediate critical point: Accumulation of water 300 cm deep occurs, and the area recovers after several days. The 300 cm height is a typical one floor height in Taiwan. Citizens encountering flood depths greater than 50 cm may apply for relief funds from local governments based on the standard of application of natural hazards relief fund, which has different standards in local governments. For example, Taoyuan County Government provides different relief fund for affected citizens flooded over 50, 100, and 300 cm deep, and other governments usually provide relief fund for affected people of flooded height over 50 and 100 cm. In order to mitigate flood damage, elevating the lowest floor is the most common approach (FEMA 2006). The Federal Emergency Management Agency in the United States suggested adding freeboard to elevated 1 foot or more above the base flood elevation to lessen flood and wave destructions, but many people decided to elevate a full story, far exceeding the least requirement (FEMA 2005). Water that is 50–300 cm deep causes damage in the form of loss of furniture and electrical equipment on the first floor, but residents can move to the second floor to avoid life and property loss. Therefore, abandonment of one floor is treated as a level boundary. Once this occurs, the design and use of housing might be changed. For example, the ground floor is considered no longer usable as a living space but is usable for parking. Flooding reaching 300 cm represents a moderate flooding disaster. The public water and electricity supplies may be interrupted, and life-support systems are affected. Fortunately, neighboring regions can support relief efforts, and the appearance of the affected region may be recovered from several days to 1 week. The associated loading is a storm of a 50- to 100-year return period, depending on local facility design.
3. High critical point: Water accumulation 600 cm deep occurs; some areas can recover after several weeks, but some areas do not recover. Flooding that reaches 600 cm, which is the height of two typical stories in Taiwan, is considered a severe flooding disaster, and lives are at risk and property is likely to be seriously damaged. Because some areas cannot recover, people abandon those areas and relocate, making it an irreversible disaster for that area. A storm such as this may occur once over a 200- to 500-year return period.

2.2 Measurement of loading

In this study, only storm events are considered external loadings, including the hourly rainfall intensity and cumulative rainfall. Other external loadings, such as wind speed, temperature changes, earthquakes, and tsunamis, are not utilized in this study. This investigation uses only torrential rains or typhoons to represent external loading because flooding problems in Taiwan are associated primarily with typhoons.

2.3 Measurement of capacity

Capacity is the ability to adapt to external loadings. There are various measures for adapting to storms that can be divided into measures in the 'external water area' and the 'internal water area' of a watershed area, as shown in Fig. 2. The external water area represents regions outside the populated area in the catchment, while the internal water area indicates the population settlement area, which is usually located in the downstream or low-lying regions of a catchment. If the water in the external water area is not properly managed, it may flow into the low-lying area, causing even more flooding in the internal water area. The goal of stormwater management in the internal water area is to rapidly discharge water. The general practices applied for this purpose are the installation of rainwater sewer systems, detention ponds, and local infiltration facilities. Similarly, management of external water requires sufficient drainage channel sections to accommodate floods and to convey water to open seas. The facilities commonly used for this purpose include structures such as embankments and water storage reservoirs.

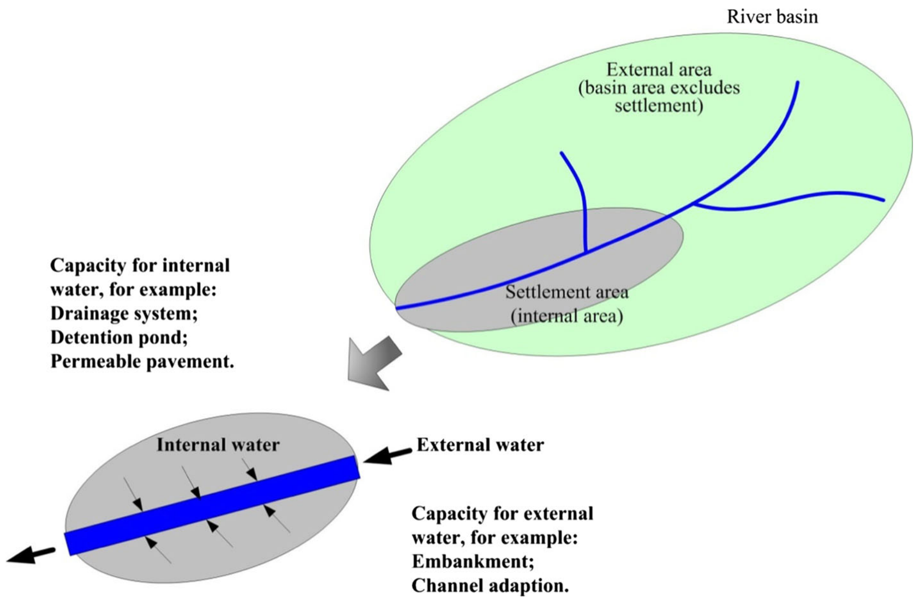


Fig. 2 Schematic diagram of adaptive capacity

2.4 Measurement of critical points

After defining loadings and capacity, it is important to integrate loadings (rainfall), capacity, and critical points. The key is to estimate loadings using a defined critical point, and loadings should be assessed by considering existing capacity. Following the previous definition, loading for the low critical point is the maximum storm drainage rate. For the intermediate and high critical points, which are defined as fixed flood inundation heights, we must trace the rainfall scenario that causes the defined flood inundation situation. A coupled overland and sewer system model is usually used to analyze flood inundation, for example, a 2D diffusive overland-flow model and SWMM (Hsu et al. 2000) or a 2D shallow-water model and SWMM (Cea et al. 2010). However, the critical point with high flood inundation considered in this study is caused not only by the surplus from the storm drainage system in the internal water area but also by the runoff overflowing from embankments in the external water area. This study uses a simple conceptual method to demonstrate the intermediate and high critical points, which also can be regarded as the worst-case scenario. It presents a standing-water flood, not a moving-water flood, such as the flood hazards caused by Hurricane Katrina (Mckenzie and Levendis 2010). Once the water from external area flow into internal low-lying area, the water stays and not flows out. The method for calculating critical points is described below.

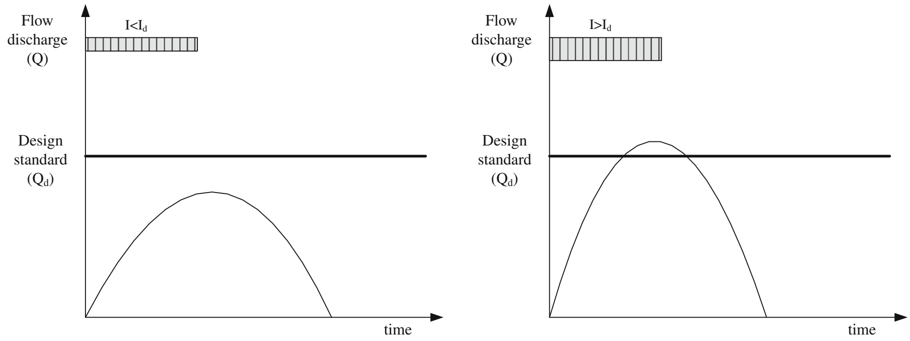
2.4.1 Low critical point

The low critical point represents the threshold under which the internal water area begins to accumulate water, which is directly associated with the drainage rate and rainfall intensity. If the rainfall intensity (mm/h) is greater than the drainage rate (mm/h), water begins to accumulate.

Taiwan's water sewer systems have different design standards in different administrative regions. The township areas use a 1- to 2-year return period, while county-controlled cities use a 2- to 3-year return period, and provincial cities use a 5-year return period. According to official guidelines (WRA 2006), the rainfall intensity within the return period in each area is calculated using a Horner equation. The conceptual illustration is shown in Fig. 3.

2.4.2 Intermediate and high critical points

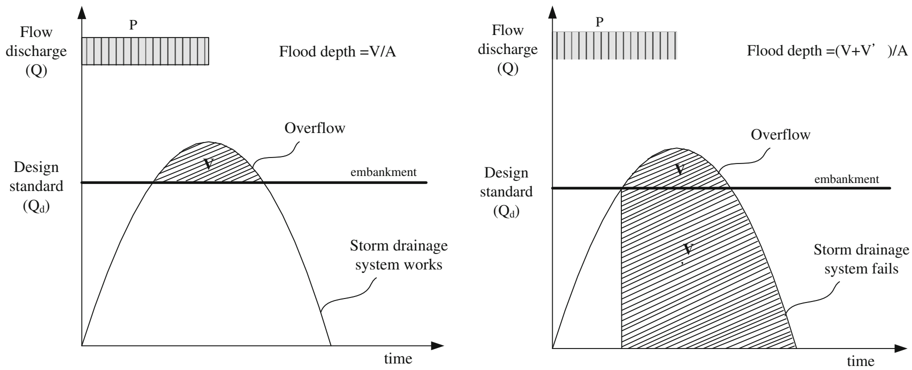
The intermediate and high critical points represent floods with heights of 300 and 600 cm in the internal water area, respectively. The precipitation in a small internal water area cannot accumulate enough rainfall to result in such high flood depth, so that the water from external area in the same watershed is considered. Two situations may occur. The first is where there is runoff overflow from the embankment, but the storm drainage system in internal water area still works. The overflow water flowing into the internal area will drain out later, so that the flood is temporary. The flood depth is the overflow volume (V) divided by the internal area (A_i) (Fig. 4a). When analyzing this situation, a dynamic flow hydrograph is necessary to measure V. The second situation assumes that the protection of the embankment fails and the stormwater drainage system no longer works. After the external and internal capacities have failed simultaneously, the following precipitation concentrates and is retained in the low-lying area, causing severe floods. The flood depth is total water volume ($V + V'$) divided by the internal area (A_i) (Fig. 4b). This situation can also be



(a) Rainfall intensity is smaller than designed drainage rate

(b) Rainfall intensity is larger than designed drainage rate

Fig. 3 Determination of low critical point. **a** When rainfall intensity (I) is smaller than designed drainage rate (I_d), the actual flow (Q) is less than designed flow (Q_d) and no water flows out to the surface; however, **b** once rainfall intensity is greater than the designed drainage rate, surface ponding occurs, which represents the low critical point



(a) **(b)**

Fig. 4 Determination of intermediate and high critical points. **a** Flow discharge in the river channel overflows the embankment, but the storm drainage system in internal water area still works and overflow volume (V) will be drained out later. The temporary flood depth is overflow volume (V) divided by internal water area (A_i). **b** Flow discharge in the river channel overflows the embankment and assumes that the embankment fails at the identical point. The storm drainage system in the internal water area fails too. Total water volume ($V + V'$) accumulates in the internal area and the flood depth is water volume ($V + V'$) divided by internal water area (A_i)

regarded as the worst-case scenario and should attract significant attention. To not underestimate flood damage, it is preferable to use the second scenario to determine the threshold of the critical point.

Whereas rainfall intensity is used for the low critical point, total rainfall amount is used for the intermediate and high critical points. The Water Resources Agency of the Ministry of Economic Affairs of Taiwan states that the river flood control standard for rivers supervised by the central government is 100 years, while that for rivers supervised by local governments is 50 years. However, the standard for the Tamsui River, which flows through the capital, Taipei City, has increased to the 200-year-flood frequency standard. The design of the flood control capacity (the embankment) is based on the empirical formula of the US Natural Resources Conservation Service (triangular unit hydrograph procedures) (WRA 2006), which is listed below:

$$Q_p = 0.208 \times A \times R_e / T_p \tag{1}$$

where Q_p is peak flow (cms), A is river basin area (km^2), R_e is effective rainfall (mm), and T_p is the time required to reach peak flow (h), which is calculated by the following equation,

$$T_p = D/2 + 0.6T_c \tag{2}$$

where D is rainfall duration (hr), and T_c is concentration time (hr). The concentration time is obtained by the following equation:

$$T_c = (0.87L^3/H)^{0.385} \tag{3}$$

where L is the longest flow route (km), and H is the maximum relief (m).

The designed Q_p for rivers in Taiwan were previously calculated based on their flood control standard. With the known peak flow, Q_p, the actual rainfall R to cause the Q_p is then obtained. According to the Eq. (1), it implies that the rainfall lasts at least T_p hour. In the case studies, the T_p is ranged at 24–48 h and mostly in 24 h. Therefore, the rainfall R causing Q_p should be in one event and less than 48 h. If the rainfall in the catchment area is below R, then the river has sufficient protection capacity for flood discharge; when the rainfall is over R, the excess discharge would overtop the embankment and flow into the internal water area. At this time, because the soil in the catchment area is saturated and water storage facilities are full, hydrologic losses are not considered; thus, the subsequent rainfall becomes effective rainfall and completely converts into surface runoff. The rainfall over the R value will accumulate throughout the entire catchment area and be transported to low-lying areas in the internal water area. In other words, the rainfall over the R value transforms to the water volume $V + V'$ in Fig. 4b. Thus, the amount of rainfall in the catchment area required for the flood heights in the internal water area to reach 300 or 600 cm can be calculated as the threshold for reaching the intermediate or high critical point, respectively.

3 Study cases and their capacity

Taiwan is an island nation with an average annual rainfall of approximately 2,500 mm; there are more than 4 typhoons every year, and almost every typhoon results in flooding disasters. Historical data also show that the trend of climate change is significant in Taiwan (CWB 2009; Wu et al. 2010). Taipei, Taichung, and Kaohsiung are 3 large cities in northern, central, and southern Taiwan, respectively, and all have suffered serious flooding. In addition, Su-ao Township in Yilan County in northeastern Taiwan experiences intense storms with an extremely high frequency because it is on the coastline of the Pacific and is affected by the northeast monsoon. The four cases are used to present storm threshold analyses, and the results are validated using data on real typhoon events. As a result of the administrative division adjustment at the end of 2010, the total areas of Taichung and Kaohsiung have increased; the area addressed in this study is the extent of these cities prior to adjustment.

The sewer design standards for these 4 cases are different and are summarized in Table 1. Taipei, Taichung, and Kaohsiung use a 5-year return period as the standard for water sewer design, while Su-ao uses a 2-year return period. The design value of the rain

Table 1 The design values of the rainwater sewer systems in the study cases

Cases	Rainfall intensity formula (mm/h)	Design value (mm/h)	Sewer implementation rates in 2010 (%)
Taipei	5-year return period: $I_5 = \frac{8{,}606}{t+49.14}$	78.8	96.66
Taichung	5-year return period: $I_5 = \frac{7{,}831}{t+47.23}$	73*	64.85
Kaohsiung	5-year return period: $I_5 = \frac{8{,}059}{t+52.76}$	70.9	96.85
Su-ao	2-year return period: $I_2 = \frac{256}{t^{0.346}}$	62.0	57.50

* The value of 74.3 mm/h is applied

water sewers represents the internal water drainage speed in that particular city or township. The highest design value of the rain water sewer system is 78.8 mm/h in Taipei and the lowest is 62.0 m/h in Su-ao. It should be noted that the sewer implementation rates until 2010 in Taichung and Su-ao are only 64.85 and 57.50 %, respectively, implying that the actual drainage capacity may be lower.

The river flood control of the four cases is presented in Table 2. In addition to the entire river watershed, the internal water area, which is the area below an elevation of 20 m, is indicated. In each case, two to three rivers are located, each of which is estimated separately. Cumulative rainfall was obtained from the peak flow design of the rivers in which the effective rainfall (R_e) is used. The R_e is actual rainfall (R), less interception, infiltration, and depression storages. Such information was cited from the original engineering design of each river.

It is worth noting that the amount of flood control capacity is not completely related to rainfall. When the flood control capacity of a city is greater, it does not indicate directly that the city can tolerate that much more rainfall. The ratio of the internal and external water areas in the watershed area also must be considered. When the external water area is large and the internal water area is small, the amount of accumulated rainfall required to reach the identical flooding height is lower, and it is easier for flooding to occur. Therefore, a greater designed flood control capacity does not necessarily correspond to a better adaptive flooding capacity for a city.

Table 2 The design values of the river flood control capacities in the study cases

Cases	River	External area (basin area) (km^2)	Internal area (km^2)	Concentration time T_c (h)	Peak flow Q_p (cms)	Associated rainfall R (mm)
Taipei	Keelong	491.0	53.77	9.62	6,720	790
	Hsindian	921.0	58.12	11.08	10,300	743
Taichung	Fazi	132.6	71.00	5.63	1,460	372
	Dali	400.7	78.70	12.00	8,440	1,517
Kaohsiung	Hojing	76.7	25.83	8.66	500	339
	Love	64.5	23.62	6.08	510	289
	Chaizhen	54.0	19.12	9.06	397	400
Su-ao	Hsinchen	50.5	12.16	8.00	895	851
	Su-ao	29.7	6.43	1.74	680	239
	Naao	311.7	17.23	24.00	3,580	1,654

4 Results and discussion

4.1 Results of threshold analysis

Taipei is the capital of Taiwan and has a population of more than 6 million people. It is located in the Taipei Basin in northern Taiwan and is surrounded by hills and high mountains. The human population is mainly concentrated in the plain area of the Taipei Basin. The city belongs to the Tamsui River watershed area, and its main tributaries, the Hsindian and Keelong Rivers, pass through the municipality. The Hsindian River is located along the southern border of Taipei with a watershed area of 921 km^2; an upstream reservoir on this river provides a source of water to the city. The Keelong River flows through Taipei from east to west, with a watershed area of 491 km^2; it is a meandering river, and the areas along its banks are easily flooded. Figure 5a presents a schematic diagram of Taipei.

The drainage standard of the rain water sewers in Taipei is 78.8 mm/h, which indicates that when the rate of rainfall exceeds the drainage speed, water begins to accumulate. The flood control standard of the Keelong River watershed can withstand accumulated rainfall of 790 mm in one event (less than 48 h), while the Hsindian River can withstand 743 mm of accumulated rainfall. According to the classification of critical points provided in this study, when the accumulated rainfall in the Hsindian River watershed area reaches 930 mm in one event (less than 48 h), flooding in the internal water area will reach 300 cm; if the accumulated rainfall increases to 1,120 mm, flooding will reach a height of 600 cm. The thresholds associated with experiencing the critical points for the Keelong River are higher; the cumulative amounts of rainfall required to reach the intermediate and high critical points are 1,120 and 1,450 mm in one event (less than 48 h), respectively. A detailed analysis of these results is shown in Table 3. The threshold under which the low critical point occurs is highest for Taipei. However, because Taipei is located in a basin and because the difference between the internal water area and the external water area in this region is significant, once the rainfall exceeds the river flood control capacity, water will overflow into the internal water area, causing the flooding height in the internal water area to increase rapidly. Therefore, the rainfall thresholds required to reach the 1-story and 2-story flooding heights are lower than those in the other metropolitan areas, and the chances of reaching the intermediate and high critical points are higher.

Taichung is the largest city in central Taiwan. In our study, the area of Taichung prior to 2010 was used, when the population was over 1 million people. Eastern Taichung consists of mountains, while the Taichung Basin is located centrally, and the western part of this city is a plateau. The main rivers are the Fazi River and Dali River. There is more than a fivefold difference between the water flow in the high-water period and the low-water period. Because all the rivers and creeks within Taichung are situated close to one another and form a web-like pattern, storms often occur too rapidly for effective drainage to occur. In addition, heavy rain from neighboring counties and cities flows downward across the terrain, causing the river water to concentrate on Taichung.

If the hourly rainfall intensity in Taichung exceeds 74.3 mm/h, water will begin to accumulate. It should be noted that because the construction of sewers has not yet been completed in this city, the threshold required for water accumulation to occur may be even lower than these numbers. The flood drainage capacities of the Fazi River watershed area and the Dali River watershed area were designed using 50- and 100-year return periods, respectively. The planned flood drainage capacity of the Fazi River is nearly 1/5 that of the Dali River. The cumulative rainfall amounts required for the Fazi and Dali Rivers to reach

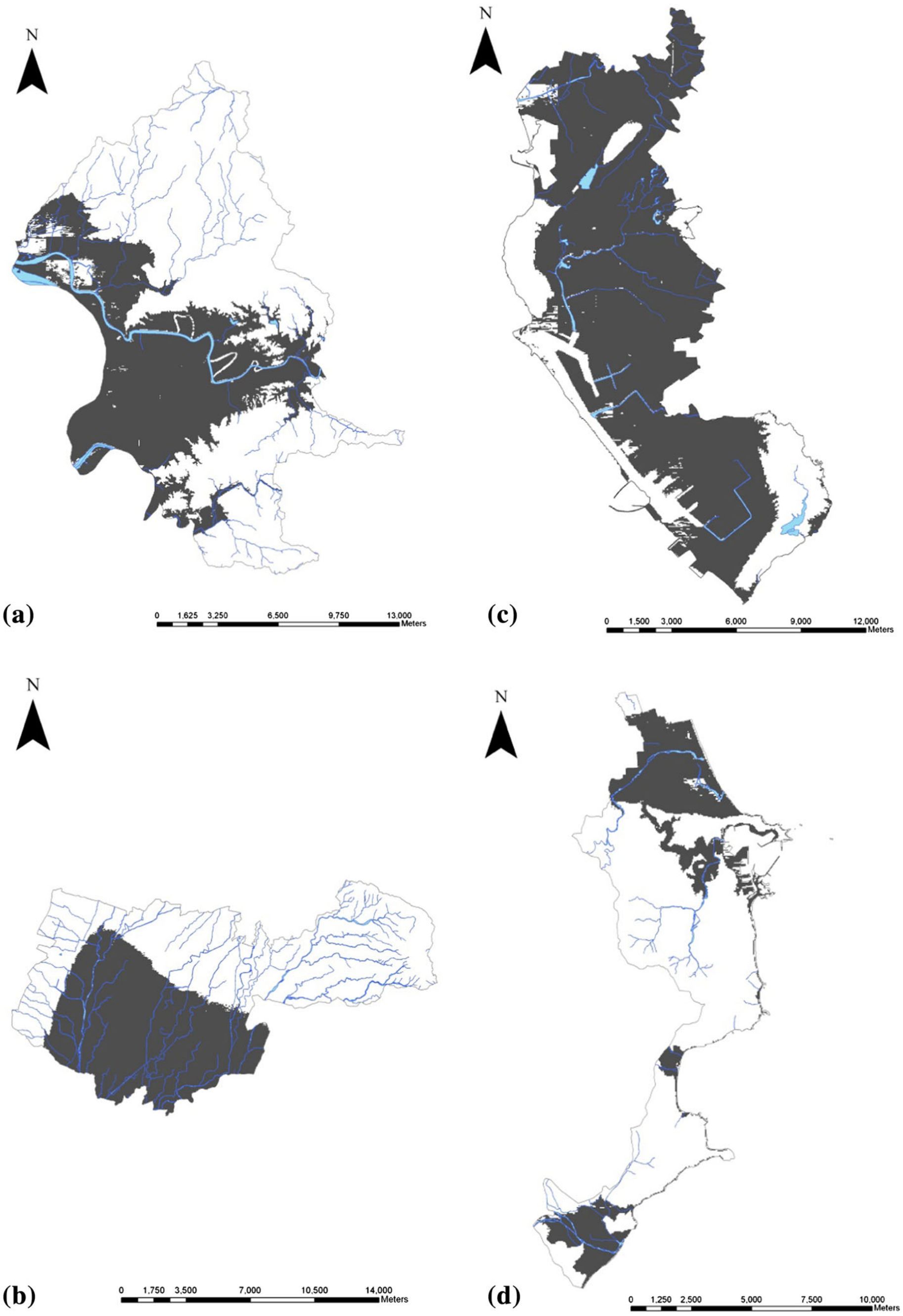


Fig. 5 Schematic diagrams of the case studies (The *shaded area* is the internal water area.). **a** Taipei City, **b** Taichung City, **c** Kaohsiung City, **d** Su-ao, Yilan

Table 3 Results of the analysis of torrential rainfall critical points for the case studies

Cases	Basins	Low critical point (rainfall intensity, mm/h)	Intermediate critical point (accumulative rainfall in one event (less than 48 h), mm)	High critical point (accumulative rainfall in one event (less than 48 h), mm)
Taipei	Keelong	>78.8	1,120	1,450
	Hsindian	>78.8	930	1,120
Taichung	Fazi	>74.3	1,980	3,590
	Dali	>74.3	2,100	2,700
Kaohsiung	Hojing	>70.9	1,350	2,360
	Love River	>70.9	1,390	2,490
	Chaizhen	>70.9	1,460	2,520
Su-ao	Hsinchen	>62	1,574	2,297
	Su-ao	>62	890	1,540
	Naao	>62	1,820	1,985

the flood drainage capacity are 372 and 1,517 mm in one event (less than 48 h), respectively. Therefore, compared to the Dali River watershed area, the Fazi River watershed area is more easily flooded and is more likely to be a critical point. However, the Fazi River watershed area is small (132.6 km^2) compared to the Dali River watershed (400 km^2). Once the cumulative rainfall exceeds the flood drainage capacity of the Dali River, a large amount of water will flow into the internal water area and cause severe flooding. Thus, the high critical point is reached much more readily for the Dali River than the Fazi River.

Kaohsiung is located in southern Taiwan and is the second-largest city in Taiwan. The 2010 administrative region was used in our study, which had a population of approximately 1.5 million. Most of Kaohsiung is situated on an alluvial plain. Its topography is flat and low-lying, and most of the city is located at an elevation between 1.6 and 4 m. The discharge of the drainage system is influenced by tidal effects. There is no large river of great length or wide watershed in the area. The major rivers are the Love River at the city center, the Hojing River in the north, and the Chaizhen River in the south. As a result of urban development, depressions and ponds have been filled in and developed, resulting in the loss of the original flood storage and water retention function of the plain.

The low critical point threshold is reached when the hourly rainfall in Kaohsiung exceeds the 70.9 mm/h drainage standard of the rain water sewers. When the cumulative rainfall is between 289 and 400 mm in one event (less than 48 h), breaks in the embankments are likely to occur. When the cumulative rainfall is over 1,350 mm in one event (less than 48 h), the internal water low-lying area will be flooded more than 300 cm; when the cumulative rainfall is over 2,360 mm, the flooding will reach 600 cm in the internal water area.

Su-ao is a small town in southeastern Yilan County surrounded by mountains on 3 sides and the sea on 1 side. It is located between 2 major mountain ranges, and more than 50 % of the town is 100 m above the sea level. Because of its terrain, if rain water in mountainous areas flows down continuously, severe flooding will occur.

The low critical point threshold for Su-ao is reached when the hourly rainfall exceeds 62 mm/h. The Naao River forms a large watershed area, and its only downstream region is located in Su-ao. The embankments of this river will break when the cumulative rainfall exceeds 1,654 mm in one event (less than 48 h). The watershed area of the Su-ao River is small but includes almost all of the main populated areas of Su-ao; once the cumulative rainfall exceeds 239 mm in one event (less than 48 h), this river's flood control capacity will be exceeded. However, because the catchment transit time is short, water can be discharged into the sea quickly. The embankments of the Shincheng River watershed will break when the cumulative rainfall in a single torrential rainfall event is over 850 mm. The conditions under which the intermediate and high critical points are reached in Su-ao are cumulative amounts of rainfall over 890 and 1,540 mm in one event (less than 48 h), respectively.

4.2 Comparison of the results of the threshold analyses and realistic typhoon events

The results obtained were compared with actual rainfall events and disasters, as summarized in Table 4. In Taipei City, Typhoon Nari in 2001 brought severe flooding and damage. However, the maximum hourly rainfall of Typhoon Nari did not exceed 78.8 mm, indicating that the drainage design should have withstood this rainfall intensity, and water should not have accumulated. According to a review undertaken at that time, the flood control facilities might not have been fully functional because pump failures occurred and water valves were not closed in a timely manner, thus causing an influx of external water from Keelong River. Coinciding with high tide, the water level in the river mouth increased, so the river water could not be discharged. The recorded total cumulative rainfall from Typhoon Nari did not reach the 930 mm intermediate critical point, implying that the flood protection should have been sufficient at this event. If the external water protection capacity and internal water drainage capacity were functioning normally, they should have been able to accommodate the rainfall from Typhoon Nari. Figure 6 shows the effect of unexpected failures of storm control facilities on the threshold analysis. If the storm control facilities are not maintained or operating within their designed performance range, the surface overflow occurs earlier and additional water volumes (ΔV) increase flood depth. This is the primary reason that Typhoon Nari brought unexpected flood damage to Taipei City. The unexpected failure can be regarded as a capacity uncertainty. Once the uncertainty taken into account, it should be noted that all critical points would be less than the determined values (Fig. 7). For a risk-based perspective, the effects of uncertainty can be concerned.

The results for Taichung were compared with actual rainfall events and disasters, such as Typhoon Kalmaegi in 2008. The hourly rainfall from Typhoon Kalmaegi exceeded

Table 4 Records of severe flooding events in the subject cities

Cases	Typhoon	Date yy/mm/dd	Maximum rainfall intensity (mm/h)	Total rainfall (mm)	Maximum rainfall in 24 h (mm)	Maximum flooding depth (cm)*
Taipei	Nari	2001/09/16	77	834.7	603.8	350
Taichung	Kalmaegi	2008/07/16	149	497.4	478.9	150
Kaohsiung	Fanapi	2010/09/17	74	506.0	490.5	300
Su-ao	Megi	2010/10/21	181	1195.9	1018.5	400

Source: Taiwan typhoon database http://photino.cwb.gov.tw/tyweb/mainpage.htm

* The flooding depth is summarized by reports and news

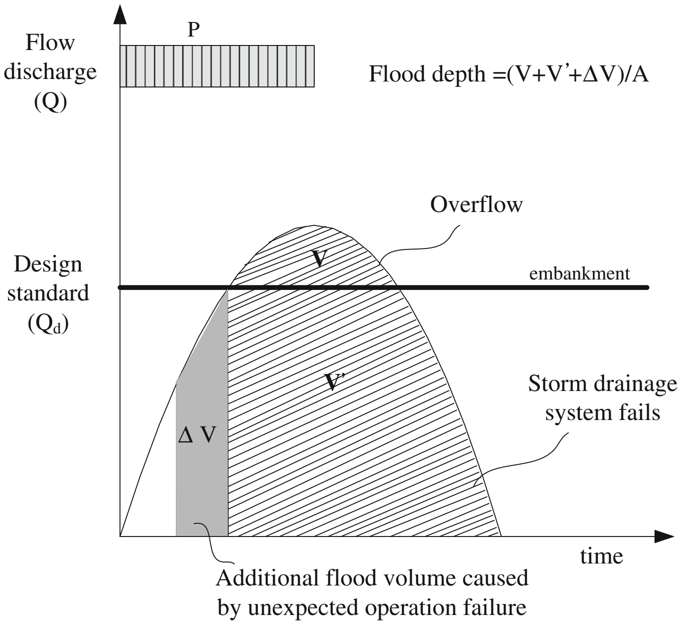


Fig. 6 Determination of high and intermediate critical points taking into account unexpected operations failure, which means that the flood control facility does not function normally, causing water volume to be added into the low-lying area and resulting in greater flood depth

74.3 mm, which met the threshold of the low critical point. The total rainfall recorded at the Taichung weather station was 478.9 mm, which did not exceed the intermediate critical point, indicating that the Fazi River watershed area would flood but that the flooding would not reach 300 cm. This prediction is consistent with the actual peak flooding height of 150 cm.

The results obtained for Kaohsiung were compared with data from actual rainfall events and disasters, such as Typhoon Fanapi in 2010. The hourly rainfall from Typhoon Fanapi was greater than 74 mm, exceeding the 70.9 mm drainage speed of the sewers and which should have resulted in reaching the low critical point. The total rainfall recorded at the Kaohsiung weather station was 506 mm, which was above the amount of rainfall that should have resulted in breaks in the embankments but not exceeding the intermediate critical point. Therefore, flooding would have occurred, but the flood depth would be predicted to be under 300 cm, which was similar to the actual flooding height of 50–100 cm in low-lying internal water areas. The maximum recorded flooding height was 300 cm along the riverside area, which contains the lowest areas and accumulates the most runoff.

The results obtained for Su-ao were compared with actual rainfall events and disasters, such as Typhoon Megi in 2010. The maximum hourly rainfall during Typhoon Magi was 180 mm/h, which far exceeded the threshold to exceed the low critical point. The total rainfall recorded at the Su-ao weather station was 1,195.9 mm, which exceeded the intermediate critical point for the Su-ao River and would predict that over 300 cm of water would accumulate in the Su-ao River watershed area, which is consistent with the flooding in the actual event. Typhoon Megi caused major flooding in the center region of Su-ao Township. Certain sections of roads experienced flooding almost reaching 600 cm. In

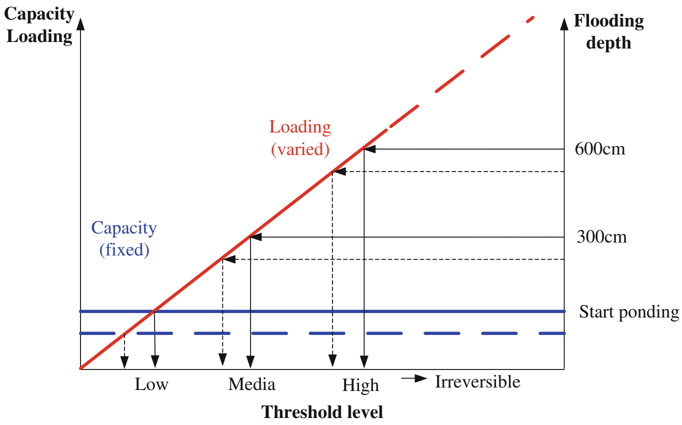


Fig. 7 The effects of capacity uncertainty on threshold determination. If the capacity is below the expected value (*solid lines* become *dot lines*), start ponding and flooded at 300 and 600 cm would occur earlier and all critical points would be less than the expected values

2011, Typhoon Nalgae generated the co-movement effect with its outer-region circulation and front and caused 1,600 mm of rain to fall in the mountainous area of Yilan, the neighbor watershed of Su-ao. If this amount of rain fell on Su-ao, it would have exceeded the threshold for the high critical point of the Su-ao River watershed to occur and would have been expected to have caused flooding with a height of 600 cm.

According to the results shown in Table 3, the average cumulative rainfall must be larger than 2,000 mm in one event to reach the high critical point and cause 600 cm flood heights. Such heavy rainfall did not occur in these urban areas in Taiwan. However, in 2008, Typhoon Morakot brought cumulative rainfall of nearly 3,000 mm. This reached the high critical point threshold in all 4 subjects included in this study, with the exception of the Fazi River watershed in Taichung. We must make improvements in our preparation, and we must work to better understand the limitations of our man-made control facilities to survive in our unpredictable and changing climate.

5 Conclusions

This study proposes a methodology that integrates rainfall data and existing flood control engineering capacities to determine critical points for different flooding events. This information will help the government and the public understand the thresholds of existing facilities and should be helpful for climate change adaptation projects. In the era of climate change, adaptation is a work that should be performed by the government and by the general public. However, a common language for communicating the needs of these two groups is often missing. With the assistance of the Taiwan Delta Electronics Foundation, these study results have been openly discussed in press conferences and seminars and have received enthusiastic responses from the scientific community and the public. It is valuable for the public to know how much rainfall their city can accommodate, and it is equally valuable for the government to know the most vulnerable places in which it should invest.

A conceptual method to determine urban flood threshold was provided and the method was applied to Taipei, Taichung, Kaohsiung, and Su-ao, Yilan. A comparison of the obtained results with data from actual flooding events confirmed that the method proposed in this study can indeed determine the flooding thresholds of a city. Based on the differences between external pressure and internal adaptive capacity, critical points are associated with different levels. Among the case studies addressed herein, Su-ao applies the lowest design standards; therefore, the threshold for its low critical point to be reached is the lowest among those studies. If the poor 57 % sewer implementation rate is also considered, the threshold for the low critical point will be decreased even further. The capital city, Taipei, has the highest flood control design standards of the areas studied. However, it is situated in a basin, and the external water area is much larger than the low-lying internal water area. Once the embankments surrounding Taipei break, a large amount of external water will pour in, causing a rapid increase of flooding in low-lying areas. Among the 4 study cases, Taipei is where the intermediate and high critical points are most likely to be reached. The designed flood control capacity of Taichung City is large and its internal water area is not small, so it has the highest thresholds for the intermediate and high critical points. The terrain across all of Kaohsiung is flat and there are no large rivers; its external water area is also too small to accumulate considerable amounts of rainfall.

When applying this method, its limitations should be considered. This study addresses urban storm thresholds with a simple and conceptual method. The simple method has an advantage in that detailed landscape geometry data are not required, so this method may be broadly applied as a preliminary study. If the critical points related to flooding in a finer spatial scale, such as villages or communities, are discussed, more exact data on topographic heights and drainage pipe networks are necessary, and precise hydrologic and hydraulic models will have to be applied. About dam-break flood risks, new studies, such as Peng and Zhang (2012), Butt et al. (2013) and Yang et al. (2013), would be good references.

The results of this study can be combined with data from climate forecasting systems to help the public better understand the relationship between rainfall and flooding and to increase early warning functions. These results may also help the public and the government respond in advance to reduce the likelihood of disasters. Although this study is a preliminary analysis, its core value is the integration of weather data and engineering data to determine the critical point as a communication tool. The storm threshold is represented because the public understands rainfall more easily than they understand than an engineering design value. In addition to examining flooding disasters, the thresholds for extreme temperatures, sea-level increases, or even food and water resources could also be identified to explain other types of tolerance thresholds of human societies.

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