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Adaptation capability of rainfall hotspots in water resilient cities using QGIS: a case study of Taichung City in Taiwan

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Abstract In the context of extreme climate due to global climate transition, rainwater adaptation in resilient cities is a key issue for countries. The purpose of this study is to identify the rainfall hotspots in urban areas and investigate whether these hotspots have environmental conditions for rainfall adaptation. The study site is located in the Taichung area. This study collects rainfall data from rainfall stations at elevations below 500 m, employs QGIS (quantum GIS) to create an inverse distance weighted graphical distribution of rainfall to determine the hotspots where the maximum and minimum rainfalls occur, identifies the topography, green spaces, water areas, and buildings in the catchment, integrates the coverage area in the project, and estimates the amount of rainwater that could be directly absorbed by the land within the catchment. The results of this study show that, among the rainfall stations at an elevation below 100 m where most urban areas are located, the Taichung rainfall station is the area with the highest number of rainfall events from May to August. Without reliance on gully or river drainage, the natural infiltration of the land in the catchment could only adjust to 80 mm of heavy precipitation within 24 h of the rainfall warning level of the Central Weather Bureau.

Keywords Image recognition · Inverse distance weighting · QGIS · Resilient city · Urban precipitation

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Introduction

Extreme climate is an important issue around the globe, and the effects of global warming continue to fester in all regions. The reality of the deteriorating environment caused by natural disasters is also accompanied by a global water crisis, and this situation has become very acute. Therefore, since 2011, there has been a surge in scientific research addressing the issue of climate impacts on water resources, which indicates the growing attention to environmental changes in various countries (Orimoloye et al., 2021c; Orimoloye et al., 2021a; Orimoloye et al., 2021b). As people become more aware of environmental changes, different countries are considering various policies in an attempt to mitigate the damage caused by extreme weather.

The world is facing unprecedented environmental changes, which are likely associated with climate-related disasters, such as droughts and extremely high temperatures. Several studies have suggested that these changes will probably escalate going forward, and with more adverse environmental impacts (Dyosi et al., 2021). In recent years, climate transition has caused climatic shifts in Taiwan, which is located in a subtropical region with abundant rainfall, and often suffers from both a shortage of water and threats of flooding, which are in most part highly correlated with environmental conditions. Urban development has made it difficult for water to be stored and infiltrated, leaving the issues of water shortages, ponding, and flooding more pronounced.

In Taiwan, the concept of resilient cities has been popularized in urban planning and architectural design, especially in terms of how to mitigate and adapt to the impacts of intense rainfall. The United Nations Office for Disaster Risk Reduction (UNDRR), the international climate change organization, has mentioned that the shaping and preservation of green space can effectively reduce the damage caused by heavy rainfall (UNDRR, 2020). Climate change is one of the main factors that limits the development of vegetation in various environments; thus, it is crucial to monitor the spatial and temporal dynamics of rainfall events in the study area to achieve environmental and ecosystem protection (Orimoloye et al., 2021c; Orimoloye et al., 2021a; Orimoloye et al., 2021b). Therefore, in order to assess the resilience of the land, this study observed the rainfall distribution patterns in low-elevation areas to identify rainfall hotspots and calculated their infiltration capacity during storm events.

This study covered the Taichung area, including 29 administrative districts and 22 rainfall stations with an elevation below 500 m, and observed the catchments covered by the stations based on the stacking of rainfall station locations on the map with the respective districts in Taichung. As shown in Fig. 1, every district in Taichung is covered by one station, with the exception of Shalu, Daya, Xinshe, and Heping, which have stations at an elevation above 500 m. As the north district, west district, east district, and south district are smaller, they are consolidated with the central district and counted as one area covered by one station. As this study was mainly concerned with the accumulation of water and flooding in active development areas, the resilience of the land in areas of low elevation was considered more important than that in areas of high elevation.

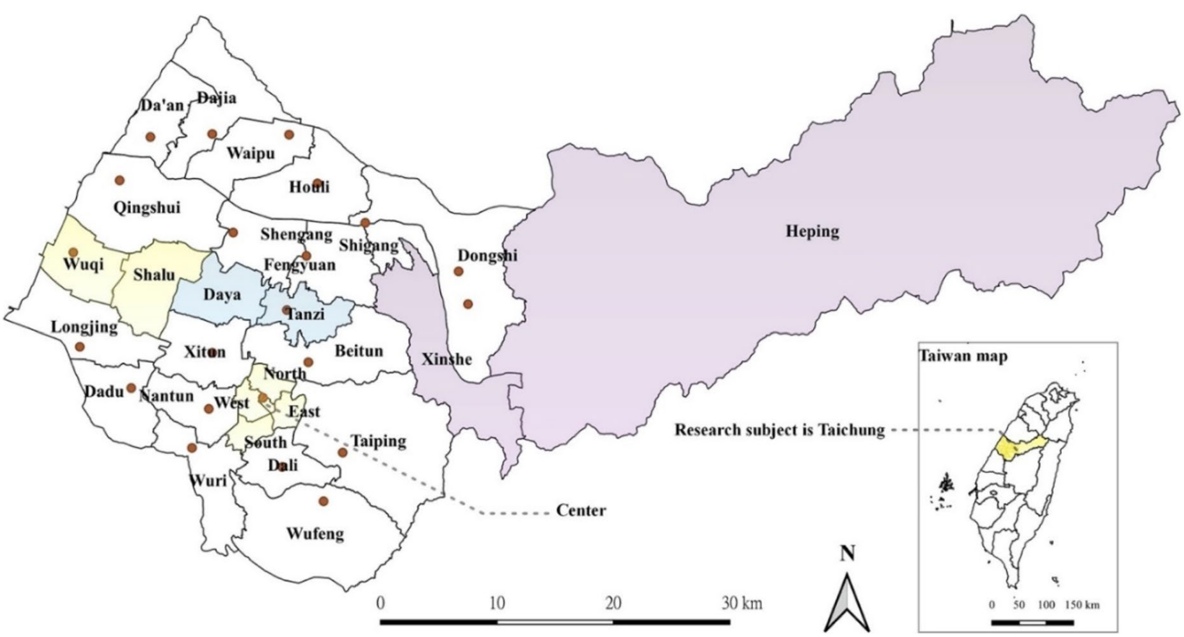


Fig. 1 Taichung rainfall station locations and coverage area

Literature review

Definition and development of resilient cities

The issue of coexistence between the environment and human beings has been discussed since the Stockholm Declaration, and countries are still trying to reflect on how to coexist with the environment. Among the meetings held to date, the Hyogo Framework for Action in 2005 and the Sendai Framework for Disaster Risk Reduction in 2015 highlight the significance of resilience as the basis for disaster risk reduction under climate change (UNDRR, 2021; United Nations, 2004). The 2015–2030 strategic framework emphasizes the importance of sustainable development and disaster risk reduction (UNDRR, 2015). Global platform meetings for disaster risk reduction have also been convened multiple times since 2009, proposing the importance of resilience in various fields under extreme climate conditions.

According to the Intergovernmental Panel on Climate Change (IPCC), there are two approaches to addressing climate transition: mitigation, which is the reduction of greenhouse gas emissions in the atmosphere, and adaptation, which is the adjustment to climate change (Bizzotto et al., 2019). The Organization for Economic Co-operation and Development (OECD) explains that resilient cities can promote sustainable development and are capable of absorbing, recovering from the shock, and preparing for future shocks (Klein et al., 2007).

The UNDRR defines resilience as the ability to withstand or recover from a catastrophic hazard. The ability of a community to respond to a hazardous event depends on the necessary resources being available to the community and its ability to organize itself before and during the event (Figueiredo et al., 2018). The International Council for Local Environmental Initiatives (ICLEI) describes a resilient city as one that is ready to absorb and recover from any shock and stress, while maintaining its basic functional structure and characteristics, adapting to development under constant environmental change, and increasing its capacity to resist, adapt, and prepare for emergencies (UNDRR, 2009).

International water resilient cities

Changes in the natural and built environment affect the likelihood of flood risk for residents, and topography and land use are key factors related to risk. While cities have many facilities to direct water flow to lowlands, the distribution of blue and green spaces may also contribute to local flood events (Dewan & Yamaguchi, 2009).

In many flood-prone areas in Europe, governments have favored spatial planning and non-structural facilities for ecological rivers rather than basic defensive measures (Glaus et al., 2020). The enhancement of sustainable land use, regional cooperation, and land vulnerability assessments are key factors in improving regional adaptive capacity (Schilling et al., 2020).

Climate change has posed water issues with ecological and socio-economic impacts. Studies in Africa used remote sensing techniques to monitor and classify lakes and their surroundings, and the analysis results showed the shrinkage of lakes and revealed that the impact on watersheds, the ecology, and socioeconomics was extremely alarming (Onamuti et al., 2017). In Nigeria and Sudan, scholars have employed remote sensing techniques to assess the health index of vegetation and rainfall index to understand the areas affected by drought in the regions (Ekundayo et al., 2020). As they influence the surrounding climate and affect habitats and human life, the waters and green spaces in the environment play an important role.

Arnhem, a municipality in the Netherlands, has shifted its strategy of flood risk management towards flood resilience to improve the flood resilience of urban areas by observing social-spatial changes and modifying the urban environment to adapt to future high-intensity rainfall events (Forrest et al., 2020).

The National Greening Program (NGP) was established in 2019 in the Philippines for disaster mitigation and adaptation to flooding. The program includes plans to improve the natural environment of the region and enhance mitigation and adaptation to climate change (UNDRR, 2019). Regarding reforestation, the key success factors are revegetation and reforestation protection (Le et al., 2014). This approach helps to improve the water quality of rivers and the irrigation of agricultural lands, reduce the threat of flooding, increase water and carbon sequestration, and lay the foundation for the timber industry.

The use of the global database platform in South Africa was combined with remote sensing techniques to assess seasonal changes in vegetation and rainfall, in order to provide a useful tool for regional drought events, thus, enabling the assessment of variations in the time-dependent environment and the prediction of potential regional risks (Orimoloye Belle, & Ololade, 2021c; Orimoloye et al., 2021; Orimoloye, Ololade, et al., 2021). Remote sensing techniques not only analyze present and past regions affected by environmental changes, such as uninterrupted data updates, but also facilitate the observation and prediction of potential future risks and monitoring of environmental changes.

In Vietnam, a multi-disciplinary approach to extreme rainfall has been applied to assess the impact of rivers on residents in metropolitan areas, determine the recurrence period of heavy rainfall and floods using geoinformatics, infer the extent of future climate impacts, and further rationalize the allocation of urban land use and administer protection, in order to provide a friendly living environment for residents (Nguyen et al., 2021). Furthermore, Vietnam has adopted hydrological modeling and GIS analysis to assess the vulnerability of cities to floods and propose the capacity of transportation to mitigate the potential impact of floods on cities (Duy et al., 2019).

Climate change has triggered water issues with ecological and socio-economic impacts. Studies in Africa have applied remote sensing techniques to monitor and classify lakes and their surroundings and analyze the shrinkage of lakes, and the results revealed that the impact on watersheds, the ecology, and socio-economics was extremely alarming (Orimoloye et al., 2017). In Nigeria and Sudan, scholars have also employed remote sensing techniques to assess the vegetation health index and rainfall index to understand the areas affected by drought in the regions. As they influence the surrounding climate and affect the habitats and human life in the environment, waters and green spaces play an important role.

Most countries respond to heavy rainfall events by focusing on urban spatial distribution and development instead of relying excessively on river management and infrastructure planning, by understanding that heavy rainfall events do not disappear under extreme weather conditions, and by focusing on the adaptive capacity of the land.

Water resilient cities in Taiwan

Taiwan's 2019 Water Resilient Cities Assessment Reference Manual for Local Government Heads introduced the methodology for assessing water resilient cities (Yu et al., 2019), which is divided into four main components, resources and investment capacity for disaster prevention and relief, people's awareness of potential disasters, critical infrastructure resilience, and economic capacity to withstand and recover from risks. Among these four components, critical infrastructure resilience refers to the green space areas and blue zones in the city, which indicates the importance attached to them, while the other components focus on the ability to provide relief and compensation in case of disasters.

Methodology and theory

This study adopted quantum GIS (QGIS) to analyze urban rainfall and urban elements and employed the inverse distance weighting method and image recognition to create relevant maps to integrate the data of hotspot areas and observe their characteristics. The analysis process consisted of observing the precipitation in the catchment of stations at elevations of 500 m and 100 m, presenting the data graphically, counting the stations with the highest number of rainfall events at the 100 m elevation, examining the regional environmental conditions of the hotspots, and analyzing the resilience of urban elements in the area to rainstorm events through graphical analysis.

Figure 2 shows the relationship between rainfall station location and elevation. The climatic environment in Taiwan is characterized by heavier rainfall at higher altitudes. In Taiwan, the altitude of 1800–2500 m above sea level is called the South China Cloudy Rainfall Zone, which is a major cause of rainfall and an important water source for water storage and plant growth in high mountains. This study observed that there was an obvious steep slope in the area at 500 m above sea level, where the altitude rose rapidly and the climate temperature gradually decreased during the climbing process to reach a certain level of cooling, then the water vapor in

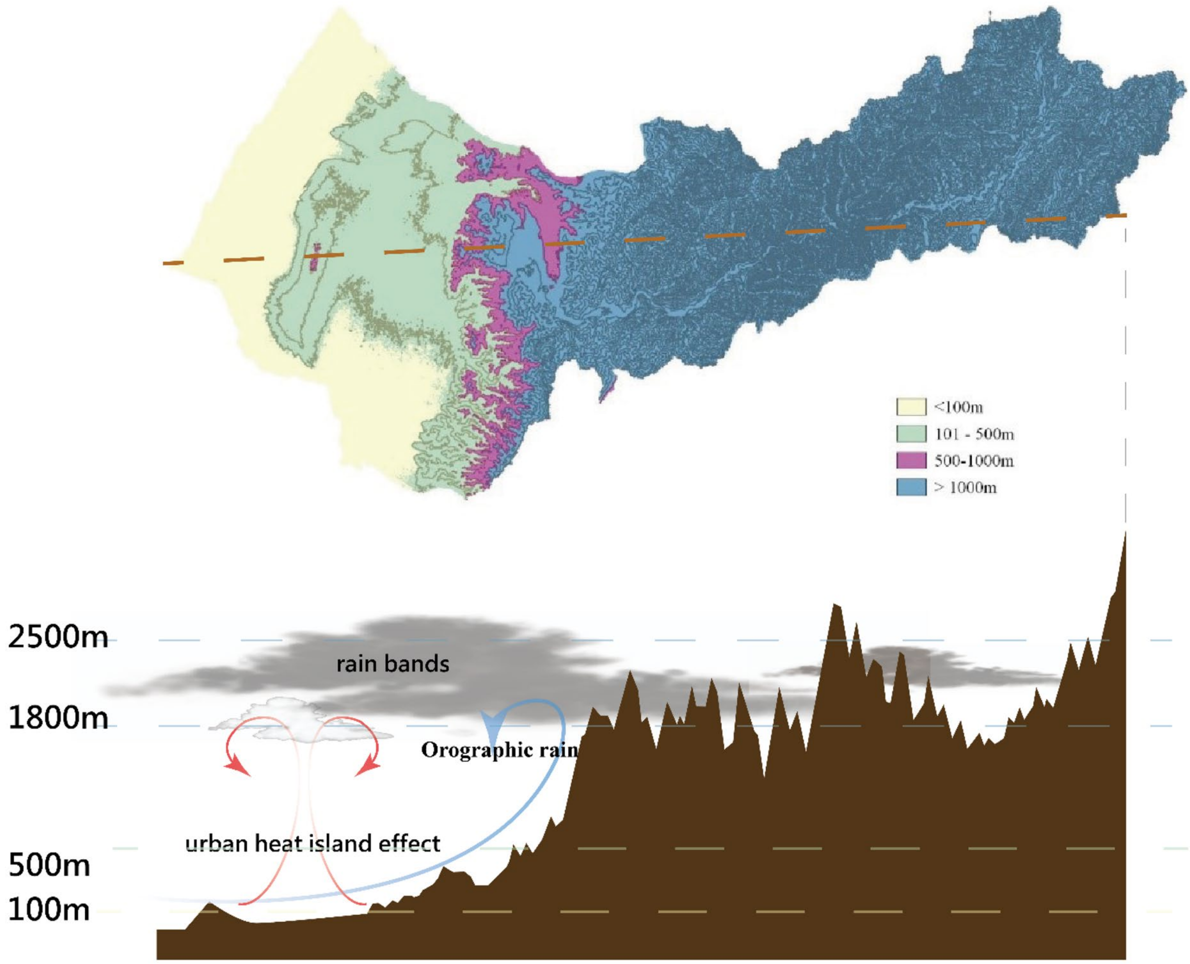


Fig. 2 Elevation and rainfall station location

the warm and humid air began to condense, which caused the cloud and rain bands to spread and form rainfall, thus, creating a great amount of rainfall in the area. In Taiwan, according to the Soil and Water Conservation Law (Council of Agriculture, Executive Yuan, 2016), a sloped area is defined as an area with an altitude of more than 100 m above sea level, and land developers are required to submit relevant documents to the relevant authorities for review, in order to preserve soil and water resources, conserve water, mitigate disasters, and promote rational land use. Therefore, flatter terrain below 100 m elevation is where human development and human activities are more active, which also contributes to the urban heat island effect. Moreover, the intensity of heat convection enhances the intensity of rainfall. Therefore, the natural infiltration function of urban water storage and drainage facilities will affect the safety of residents in the area.

Rainfall data collection

As most of the current stations were established after 2013, the rainfall data were observed from 2013 to 2020. However, urban development in Taiwan is usually carried out below elevations of 500 m, and densely populated areas are mainly located at the 100 m elevation. Therefore, this study integrated the stations at elevations below 500 m and at 100 m and loaded the total rainfall data for each month into the Geographic Information System to observe the characteristics of rainfall distribution graphically.

Inverse distance weighting method

A myriad of international studies on rainfall have used the inverse distance weighting method and the Kriging method, and one study assessed 15 different spatial interpolation methods for estimating the concentrations of pollutant waste plants. Based on the observation of data, the inverse distance weighting method yielded better results than the Kriging method (Weber & Englund, 1992).

Turkey applied three interpolation methods to analyze the regional rainfall distribution, and the results showed that ordinary Kriging (OK) was the best choice, followed by inverse distance weighting (IDW) and splines (Yavuz et al., 2012).

Belgium utilized a variety of variogram models for studies, and the results showed that spatial interpolation using IDW was significantly better than interpolation using Thiessen polygon; thus, it was often adopted in various hydrologic models. As they provide the lowest of root mean square error (RMSE) values for almost all cases, OK and IDW are considered to be the best methods (Ly et al., 2011).

In a study related to extreme flooding events in Peninsular Malaysia, five interpolation methods were used for testing and comparing rainfall, and the results showed that when the OK and IDW methods were used to calculate the average area precipitation, the values of all methods were very consistent with the revealed results (Soo et al., 2019).

The applicability of each spatial interpolation method may depend on the density of the stations, the measured area, the distance between the stations, the amount of data from the rainfall stations, and the objectives of the study. This study applied the inverse distance weighting method by reducing the calculation of station locations within the study area according to their altitude, in order that the location of rainfall hotspots could be readily identified on the images under the limitation of altitude.

Inverse distance weighting is a type of deterministic method used to estimate the value of unknown elements according to the combination of the linear weights of the sampling points, as based on the values of known points in proximity. After weighting, the distance between the points is affected, where the farther the distance, the smaller the impact, as expressed in Eq. 1 (Bartier & Keller, 1996):

$$\int (x,y) = \left[\sum_{i=1}^{n} w_i(d_i) z_i\right] / \left[\sum_{i=1}^{n} w_i(d_i)\right] \tag{1}$$

where $w_i(d_i)$ is the weight equation; z_i is the rainfall value of the station; and d_i is the distance from station x to station y.

Inverse distance weighting can be used to estimate any missing rainfall values at a certain station based on the recorded values from other stations (Ramesh et al., 2005). The optimal parameters for rainfall data are applied with a radius of 10–30 km and an optimal power between 0 and 5 (Chen & Liu, 2012). This study performed the inverse distance weighting method according to the above-proposed parameter settings.

Image recognition

This study utilized SPOT5 satellite images with a 2.5 m panchromatic band and a 10 m multispectral slope band (Boggs, 2010), which were cross-calibrated with map data from the National Land Survey Center to show the characteristic images of the map. This study applied image recognition and classification methods to identify the vegetation, natural soil, and river channels that could infiltrate rainwater into the city, and analyzed the area of land that could effectively infiltrate rainwater into urban areas. The normalized difference vegetation index (NDVI) equation is shown in Eq. 2:

$$\mathrm{NDVI} = \frac{p_{\mathrm{nir}} - p_{\mathrm{red}}}{p_{\mathrm{nir}} + p_{\mathrm{red}}} \tag{2}$$

where p_{red} is the infrared reflected radiant flux, while p_{nir} is the near-infrared reflected radiant flux.

NDVI is useful for predicting natural hazards to provide damage assessment and protection strategies (Grandhi et al., 2015). Vegetation shows a steep rise in the reflectance spectral curve between 0.7 μm and 0.8 μm in the red band, which indicates significant differences between vegetation and non-vegetation; clean water bodies are significant in the 0.4 μm to 2.5 μm band (Chao et al., 2017). This study utilized this feature to adjust the image parameters to clearly show the vegetation distribution. Information from the National Land Surveying and Mapping Center was used to provide relevant maps of urban buildings, topography, and conservation areas, as well as data for calculation.

Rainfall load assessment

This study analyzed the spatial distribution of rainfall hotspots using the rainfall data from the Central Weather Bureau and the published rainfall warning levels (Central Weather Bureau, 2020) to calculate the maximum rainfall capacity of the area every 1, 3, and 24 h. The equation is mainly based on the method for assessing the water retention of land in the design of building sites in Taiwan. The ultimate infiltration rate (f), as shown in the equation, takes reference from the values in the Taiwan Green Building Evaluation Manual (Architecture and Building Research Institute, 2019).

The following equations were used to calculate the coverage area and precipitation of each district.

$$P_a = P_w + P_d \tag{3}$$

$$P_w = \sum_{i=1}^{n} P_{W1} + P_{w2} \tag{4}$$

$$P_d = \sum_{i=1}^{n} P_{d1} + P_{d2} \tag{5}$$

P_a in Eq. 3 is the regional area. This study classified the areas according to their permeability and divided them into permeable (P_w) and impermeable (P_d) areas. In Eq. 4, the permeable area (P_{wi}) is natural areas, such as green space, soil, and watershed; in Eq. 5, the impermeable area (P_{di}) is developed areas, such as buildings, roads, and hard pavement.

By multiplying the respective areas of P_a, P_w, and P_d by the ultimate infiltration rate (f) and rainfall delay (t) in units of m/s and s, respectively, Eq. 6 gives the total precipitation of the area $\left(P_a\right)$. Equation 7 gives the precipitation of permeable water in the permeable area $\left(P_w\right)$ in the unit of m^3 within the period. This study assumed that the impermeable area $\left(P_d\right)$ was completely impermeable, meaning the infiltration rate was zero.

$$P'_a = P_a ft \tag{6}$$

$$P'_w = \sum_{i=1}^{n} P_{W1} ft + P_{w2} ft \tag{7}$$

The above P'_a and P'_w can be used to obtain the regional overload precipitation (P), as shown in Eq. 8. In this study, some areas could not be identified during image recognition due to adjustment of the recognition parameters, and the error interval (D_e) for regional precipitation is defined in Eq. 9.

$$P = P'_a - P'_w \tag{8}$$

$$D_e = \left[P_a - \left(P_w + P_d\right)\right] f' t \tag{9}$$

The class interval of the regional rainfall capacity generated in this study was a conservative value rather than a fixed value; thus, the regional infiltration rate (f') in the error interval equation of this study referred to the impermeable area.

Results—rainfall hotspot analysis

Rainfall distribution at stations below 500 m

The rainfall distribution and concentration, as observed from the graphical rainfall data in Fig. 3, indicate that the more intense the color of each district, the more extreme the rainfall accumulation would be in a single month. The observations of this study include the rainfall distribution characteristics at stations below elevations of 500 m.

According to the integration and analysis of the rainfall at the stations, the rainfall measured at Xinbogong was the highest among the stations at the 500 m elevation, as well as the area with the highest number of rainfall events. As it is surrounded by high mountains, the heavy rainfall was a consequence of its geographical location and topography. The most rainfall was concentrated at Xinbogong rainfall station in the mountainous area, while the rainfall at lower altitudes was less than that at higher altitudes, which implies that precipitation is proportional to the altitude. The districts with less heavy rainfall were covered by the Xitun, Taichung, Daan, and Longjing stations (except for Xitun, which is located at an altitude of 100 m above sea level). This study found that the most rainfall occurs from May to August, which results in a wide gap compared with other months, and shows the phenomenon of extreme rainfall, meaning rainfall at high altitudes combines with rivers and flows rapidly to lower altitudes.

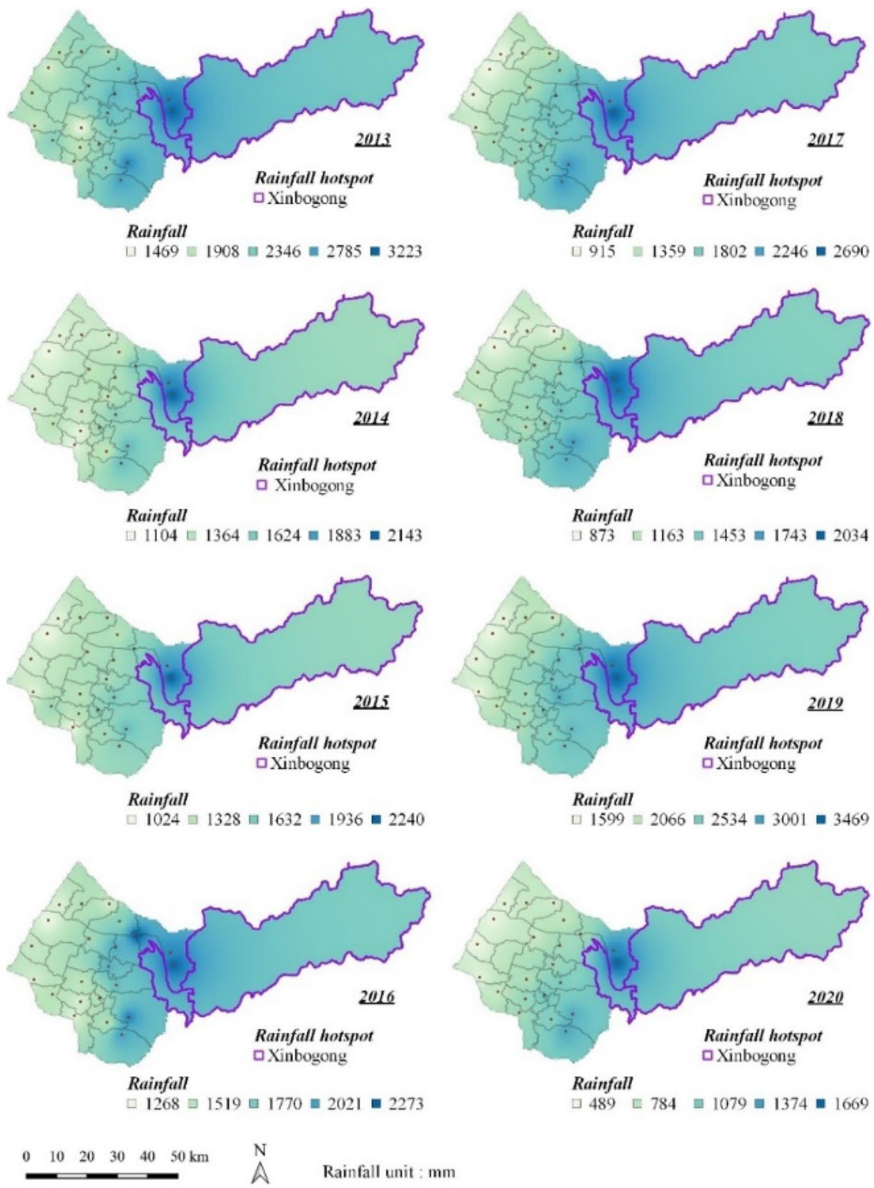


Fig. 3 Rainfall distribution at stations below 500 m

Rainfall distribution at stations below 100 m

According to the above rainfall distribution, the distribution in the areas below 100 m could be further observed. These are the areas of major urban development in the city, and such low elevation areas often generate the accumulation of water and flooding during heavy rainfall events, which leads to inconvenience and damages for residents. Therefore, this study compared the stations below the elevation of 100 m from May to August, where the most rainfall and the highest number of rainfall events occur, as shown in Fig. 4.

Analysis of regional rainfall hotspots

The Taichung, Dali, and Dajia rainfall stations are located at elevations below 100 m and are the regions where the heaviest rainfall occurs most often during rainfall events. Figure 4 shows that when rainfall events took place in low elevation areas below 100 m, the heaviest rainfall occurred four times in the old city center of Taichung, followed by three times in the Dali district and one time in the Dajia district in 2016, and the maximum rainfall in low elevation areas below 100 m ranged from 1120 to 2508 mm.

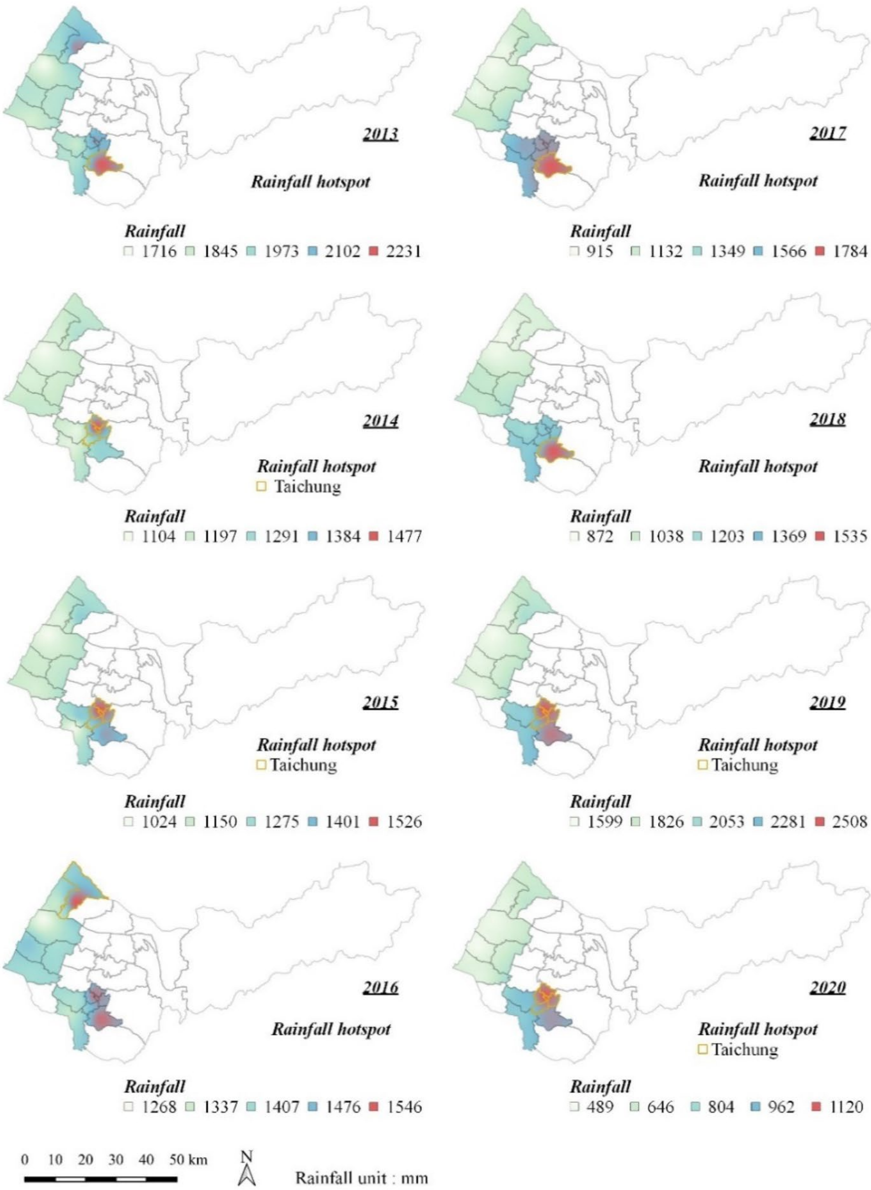


Fig. 4 Rainfall distribution at stations below 100 m

Rainfall-causing events and inundation potential areas

Figure 5 shows potential inundation areas according to the simulation of 24-h cumulative rainfalls of up to 200 mm, 350 mm, and 500 mm, considering the spatial and temporal distribution of rainfall and normal operations of reservoirs and flood control facilities, and under the conditions of no overflow of embankments and no consideration of the downstream tide level, the maximum inundation depth was calculated for each area according to the designed rainfall scenarios, hydrogeological conditions, and hydrological model (NCDR, 2020). The flood potential maps provided by the Ministry of Economic Affairs (MOEA) mainly consider the following influencing factors in the runoff rationalization Eq. 10.

$$Q = CIA/360 \tag{10}$$

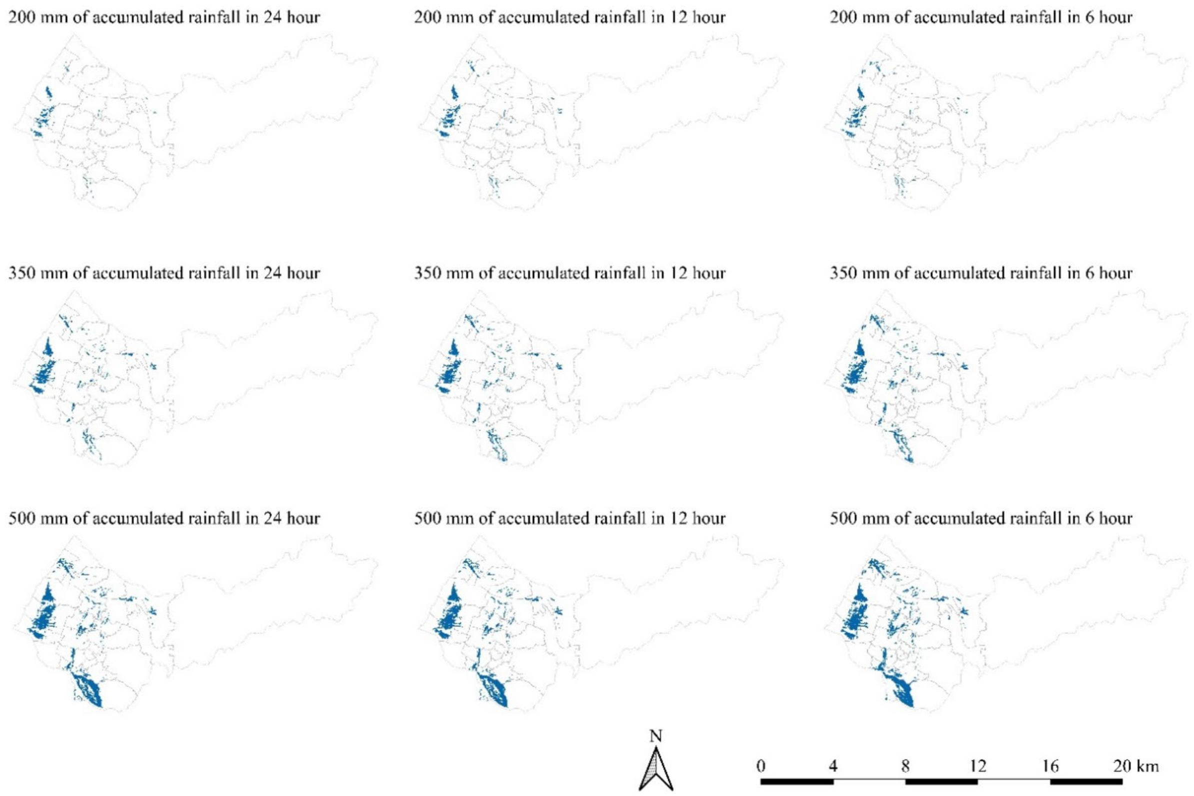


Fig. 5 Disaster potential maps

where Q is the runoff volume; C is the runoff coefficient. In Taiwan, different levels of parameters are used for different zones; I is the average rainfall rate during the rainfall duration; A is the catchment area.

In addition to the above equations, the maps consider the inferences from the hydrology of reservoirs, barrage weirs, flood diversion facilities, pumping stations, and detention ponds, and calculate the inundation conditions of the simulated areas. This flooding potential is suitable for pre-disaster mitigation and preparatory planning (Water Resources Agency, 2021).

Figure 6 shows the historical inundation data of the regions where the government surveyed and integrated the disasters caused by inundation. While this large-scale inundation survey excludes the ponding and inundation occurring on local urban roads and low-lying farmland and fish farms, it includes the inundated areas caused by typhoons and rainfall events over the past 20 years and is mainly intended as a reference for engineering effectiveness analysis.

This study used the government inundation potential map and data concerning the disaster events caused by previous rainfalls, which were combined with the map overlay analysis of rainfall hotspots of stations at the elevations below 100 m, and the results are presented in Fig. 7. The blue area is the area with flooding risk; the red area is the area with a high risk of flooding, which is also the area that the government currently focuses on; the yellow line is the area with low risk of flooding; while the yellow area is the hotspot area for rainfall analysis in this study, the government data platform does not show the area in the center of old Taichung City as having a high risk of flooding. Thus, this study further investigated the spatial characteristics of the old city center of Taichung and the surrounding regions.

Risk area adaptation and spatial characteristics

The geographical environment of Dali is similar to the mountainous area (Fig. 8) and is located at the

Fig. 6 Range of rainfall disaster from 2000 to 2020

confluence of two rivers. As shown on the map, many tributaries from the mountainous area converge here, which causes a large amount of river water to indirectly affect the Wuri district. When coupled with the direct rainfall in this area, the rainfall flowing from the high mountains may cause the land to be overloaded.

The Taichung station is located in the old city center of Taichung and covers the east, west, south, north, and central districts, which is the region with the most frequent occurrence of maximum rainfall during rainfall events. This study analyzed the rainfall capacity of green areas and the amount of rainfall that can be accommodated during rainfall events in this area. In the map overlay image (Fig. 9), it can be observed that buildings occupy the most area, indicating a large area of human development, while rivers have the least area; while there is a wide river on the east side, all rivers in this area are tributaries. The area taken by roads is more than that of the green space, which suggests a prosperous urban area with convenient transportation despite the small amount of green space. However, in Taiwan, where rainfall is high, the natural infiltration capacity of this area may be insufficient due to the lack of green space, which increases the risks of ponding and flooding.

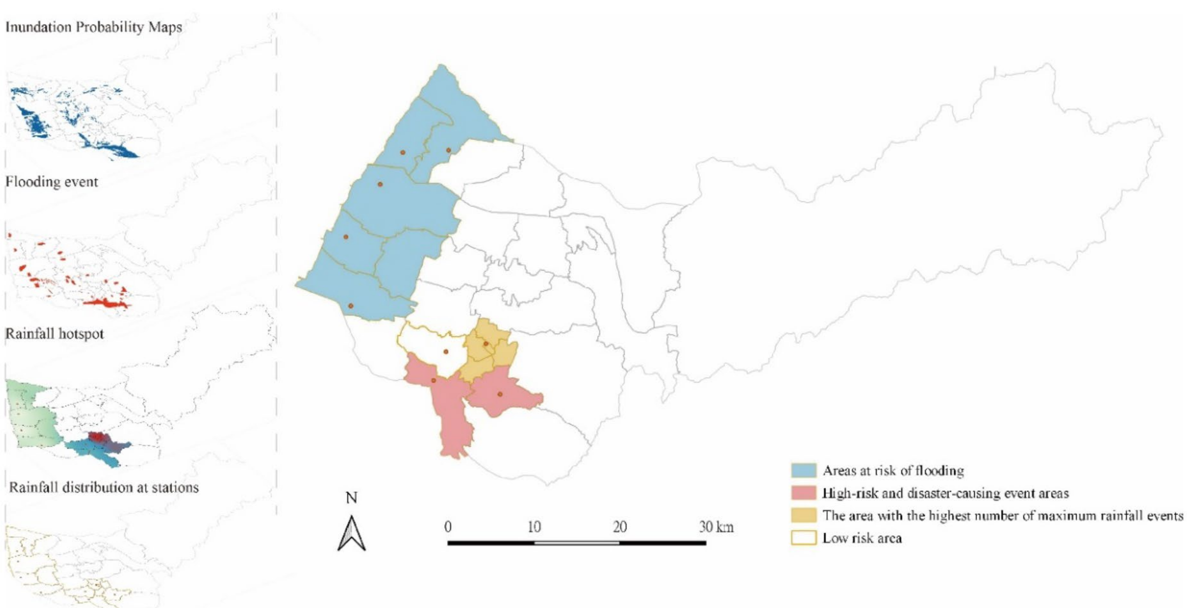


Fig. 7 Map overlay analysis result

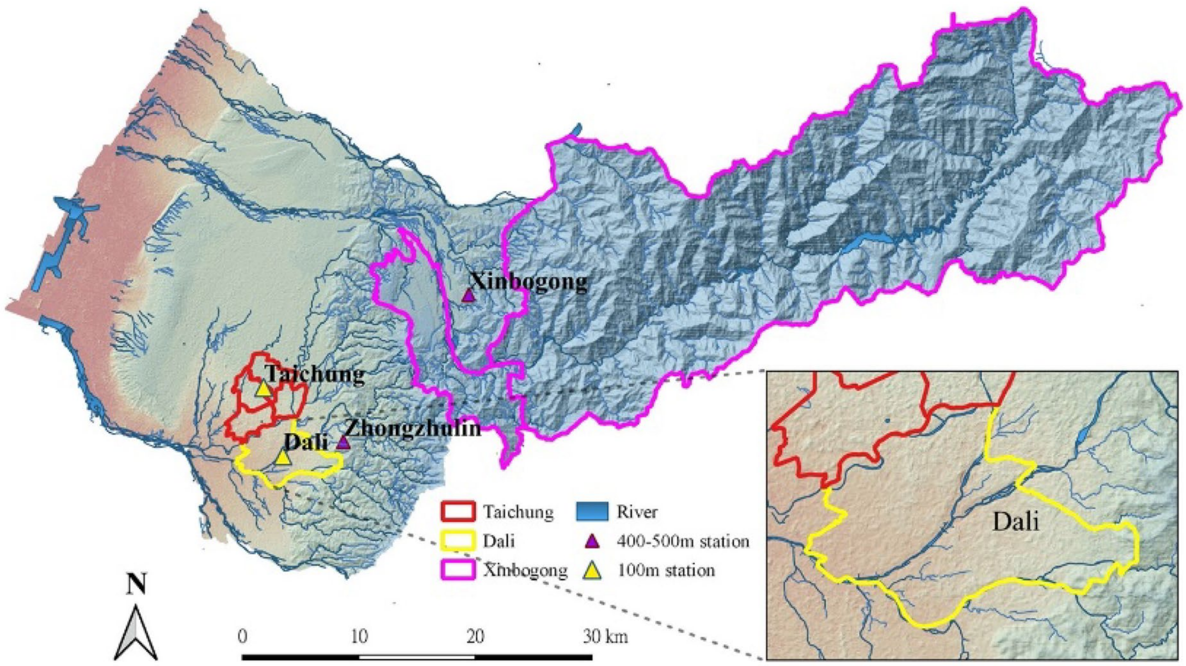


Fig. 8 Rainfall hotspot range

Data analysis of the old districts of Taichung shows that the overall area (P_a) is 29,464,357 m^2; the permeable area (P_d) is 5,349,373 m^2; the impermeable area (P_w) is 23,924,147 m^2; and the error area (D_e) is 190,835 m^2. Thus, it can be concluded that the area of the impermeable surface is greater than that of the permeable surface, with buildings constituting the largest area. According to the maps of the Taiwan Agricultural Committee, the soil quality of this area is sand shale non-calcareous alluvial soil. This study takes reference from the comparison table of the ultimate infiltration rate value in the Taiwan Green Building Evaluation Manual (Architecture and Building Research Institute, 2019) and takes 10–5 as the calculation parameter for permeable surfaces (Tsai et al., 2008).

In the old city area of Taichung, under the condition of excluding the drainage of ditches and rivers, the maximum cumulative rainfall that can be tolerated in 1 h is 6.5 mm; in 3 h is 19.6 mm; and in 24 h is 156.8 mm. The existing urban land cannot accommodate the current rainfall. This study referenced the rainfall warning level announced by the Central Weather Bureau and calculated that if the old city area of Taichung relied on the green area that could be permeated by rainwater, it could withstand the warning level of the Weather Bureau. The calculation result, as shown in Tables 1, 2, and 3 indicates that the area can only accommodate 80 mm of rainfall in 24 h, while the remaining area exceeds the warning value, and there is a risk of ponding and flooding.

On June 14, 2020, a rainfall event with 64.5 mm of precipitation within 1 h occurred in the old city center of Taichung, which resulted in ponding and flooding of the area, and was due to newly constructed interceptor ditches being too narrow; flooding also occurred in Dali (Water Resource Bureau, Taichung City Government, 2020). According to the results of this study, when the accumulated rainfall exceeds 40 mm in 1 h in the old city center of Taichung, a disaster will occur. According to the analysis on rainfall events, it can be concluded that the ways to relieve the drainage in the region are dependent on the drainage facilities and rivers, and when the drainage facilities are overloaded, it will lead to disaster in the region.

On May 20, 2019, a rainfall event with 58.5 mm of precipitation in 1 h took place, and the accumulated precipitation in 3 h reached 150 mm in the old city center of Taichung. The rainfall exceeded the capacity of the land in the old city center of

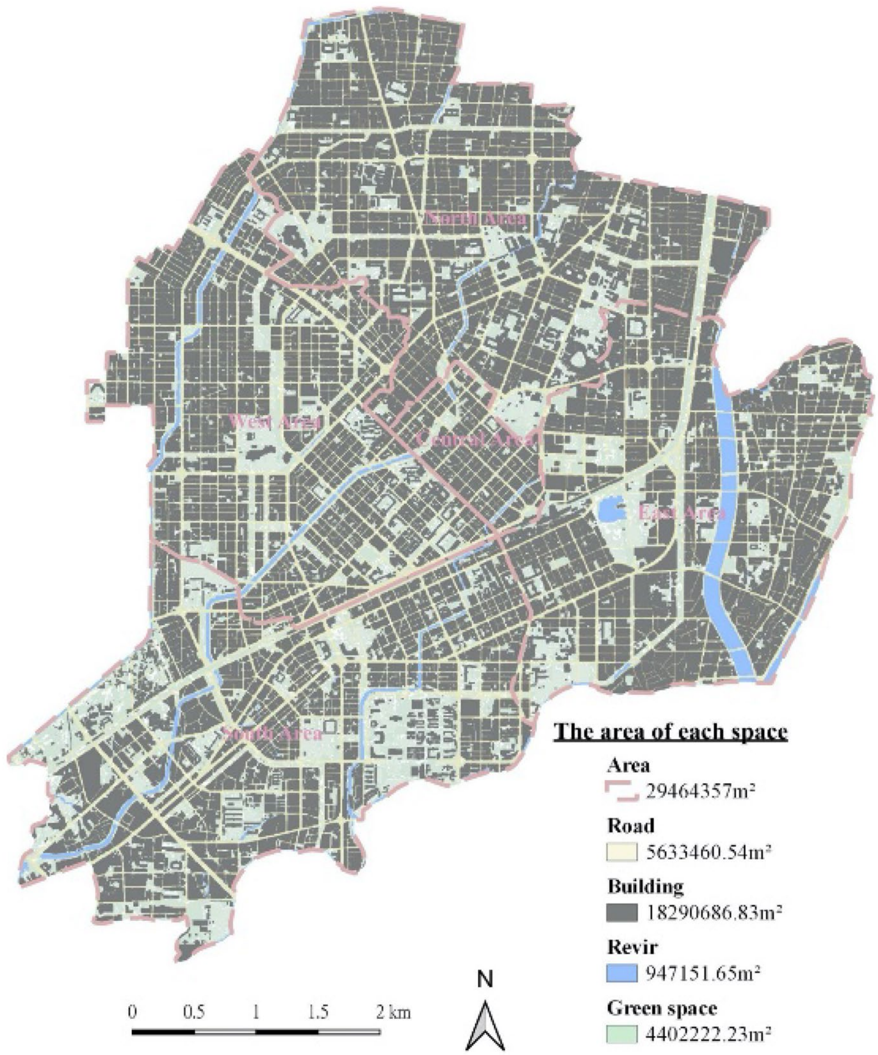


Fig. 9 The area of each space covered by the Taichung rainfall station

Taichung, which led the regional rivers to overflow and flood the surrounding area, causing anxiety and property damage to the residents. According to the results of this study, when the accumulated rainfall exceeds 40 mm in 1 h and 100 mm in 3 h in the old city center of Taichung, a disaster will occur.

Table 1 Rainfall loads on regional lands for Taichung rainfall station

	Precipitation	P_a'	P	Flatland vigilance
Heavy rain	80 mm of accumulated rainfall in 24 h	2,357,148.56	**2,264,710.48**	Poor drainage and pockets of land are prone to flooding
	40 mm of accumulated rainfall in 1 h	1,178,574.28	−985,996.82	
Rainstorm	200 mm of accumulated rainfall in 24 h	5,892,871.4	−1,271,012.36	Highly prone to flooding
	100 mm of accumulated rainfall in 3 h	2,946,435.7	−2,368,703.32	
Torrential rain	350 mm of accumulated rainfall in 24 h	10,312,524.95	−5,690,665.91	Expanded flooding area
	80 mm of accumulated rainfall in 3 h	5,892,871.4	−5,315,139.02	
Super torrential rain	80 mm of accumulated rainfall in 24 h	14,732,178.5	−10,110,319.5	Severe flooding

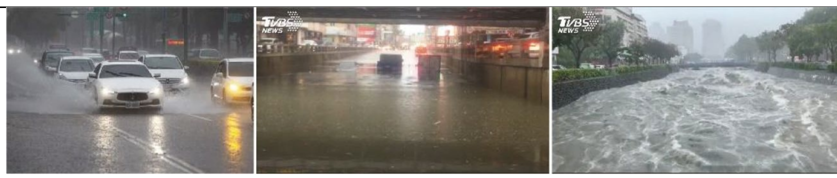
Table 2 Rainfall and disaster events in old city area of Taichung on 06/14/2020

Time	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00
Mm	-	-	64.5	32	1.5	1	-	-

Source : https://today.line.me/tw/v2/article/3wOKLo: https://gotv.ctitv.com.tw/2020/06/1307369.htm: Central Weather Bureau

Table 3 Rainfall and disaster events in the old city districts of Taichung on 05/20/2019

Time	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00
Mm	-	18	9.5	58.5	82	6	-	-



Source: https://tw.appledaily.com/life/20190520/3VYSB3WYGESZMK2NFA6CEDCFHY/ https://news.ltn.com.tw/news/life/breakingnews/2796125: Central Weather Bureau

Conclusion and discussion

The adaptation capability of resilient urban lands is important, and people are becoming increasingly aware of the significance of climate change adaptation (Haasnoot et al., 2020). Despite continuous efforts, due to the lack of urgency, low political will to take actions, and the prevalence of short-term policymaking, there is a general delay in efforts to enhance land adaptation facilities and plan for rainfall disasters. Although Taiwan has strategies and systems in place to address climate extremes, the findings of this study indicate that the ability of the region to self-adapt to rainfall and implement regional planning strategies is still inadequate.

In Taiwan, inundation areas are mainly assessed based on the simulation and deduction of influencing factors, such as the hydrological environment and runoff equations, and most priority disaster prevention areas are located in low-lying areas around rivers. The disaster prevention measures include embankments and drainage facilities. In this study, the assessment of inundation areas is based on the water retention capacity of the land, and the main consideration is given to the self-adaptation capability of urban permeable rainwater storage. The saturation of surface soil with rainwater will lead to ponding and flooding of the area; thus, the overdevelopment of cities is likely to result in a deficiency of land infiltration capacity. In Taiwan, many disaster prevention mechanisms focus on shelter and rescue functions in the event of disasters, and the drainage mechanism of the land relies mainly on drainage ditches and river relief; however, the traditional measures are not sufficient, are gradually unable to cope with extreme weather conditions, and may aggravate environmental degradation. Due to the topography and the convergence of rivers, Dali and Wuri districts are prone to ponding and flooding as a result of rainfall, and many remediation projects have been carried out in the past to allay the gravity of disasters in the districts. However, there is still a high risk of ponding and flooding.

The old city center of Taichung has few records of flooding from the past. According to this study, the intensive development of the area has reduced the ability of the land to store and infiltrate rainwater, and over-reliance on drainage facilities, together with the influence of extreme weather, may increase the risk of flooding in the future. While the results of this study are consistent with the events of the last 2 years, as the flood potential range is not recorded on the disaster-related platforms, the relevant information is mainly obtained from the civil society and the news. For this reason, this study of rainfall hotspot prediction models will continue to update data, monitor regional rainfall patterns and urban development, actively communicate and collaborate with various fields, and integrate potential flood map information from the government platform, which will speed up the improvements of environmental adaptation to rainfall. In addition, the design of green spaces and open spaces can help reduce the risk of disasters, relieve the drainage pressure on rivers and waterways, increase the storage of underground water to resist droughts, and lessen the possibility of flooding and ponding in various areas, in order to address the hazards of future climate extremes.

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Data availability The data presented in this study are available within the article.

Declarations

Conflict of interest The authors declare no competing interests.

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