

## Article

# Rainfall Pressure, Stormwater Pipe Network Scale, and Urban Flood Disaster Occurrence in Guangdong Province

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## Abstract

Urban flood resilience depends not only on the scale of infrastructure investment, but also on whether such investment can be translated into observable flood-mitigation outcomes. Focusing on the transformation from infrastructure response to flood outcomes, this study uses panel data for 21 prefecture-level cities in Guangdong Province from 2016 to 2022. Annual maximum monthly precipitation is used to represent rainfall pressure, stormwater pipe density to represent infrastructure scale, and the number of reported flood events to represent the outcome variable. A two-way fixed-effects Poisson pseudo-maximum likelihood (PPML) model is employed. The results show that, in the full sample, rainfall pressure is positively, but not significantly, associated with reported flood occurrence, while stormwater pipe density does not exhibit a stable negative moderating effect. The main conclusion remains broadly unchanged when alternative outcome and precipitation indicators are used, when pipe density is lagged by one period, and when a conservative sample is adopted. Extended analysis provides only limited weak negative evidence for Pearl River Delta cities, and this evidence is not robust across alternative specifications. The findings indicate that pipe length per unit of built-up area primarily reflects the scale of infrastructure provision and cannot be directly equated with the operational performance of the drainage system. By separating response inputs from outcome performance, this study reveals the conditional nature of the transformation from infrastructure scale to operational performance in urban flood resilience research and provides empirical support for a shift from infrastructure expansion toward performance-oriented and integrated governance in high-density coastal cities.

**Keywords:** urban flood resilience; infrastructure scale; operational performance; rainfall pressure; stormwater pipe network



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## 1. Introduction

Under the combined effects of climate change and rapid urbanization, extreme precipitation and the concentration of populations and assets are continuously increasing urban flood risk [1]. Flood governance has consequently shifted from a narrow emphasis on engineering protection toward a broader concern with cities' capacities to absorb, adapt to, and recover from disturbances. In the context of urban flood resilience, infrastructure investment is not an outcome in itself [2]. Investment is converted into resilience performance only when engineering responses—such as drainage networks, pumping stations, and detention facilities—reduce flood occurrence, losses, or recovery costs [3]. Therefore, the transformation between “how much infrastructure has been built” and “whether mitigation outcomes have been achieved” is central to understanding urban flood resilience [4,5].

Existing studies mainly evaluate regional flood resilience through composite indicator systems or simulate precipitation, runoff generation, and inundation processes using hydrological models and disaster data [6]. Composite evaluations can characterize differences in resilience across regions, but they often directly incorporate response indicators such as drainage infrastructure, fiscal investment, and governance capacity into overall scores [7,8]. When the same indicators are subsequently used to explain resilience levels, circular reasoning can arise. Moreover, greater response investment does not necessarily lead to simultaneous improvements in flood outcomes [9]. As a result, the question of how response inputs are transformed into outcome improvements remains a relatively closed black box.

This study adopts urban flood resilience as its theoretical framework and examines a key link in the resilience formation process: whether the stormwater pipe network, as an infrastructure response, can weaken the translation of rainfall pressure into reported flood outcomes under a given precipitation disturbance. By measuring external pressure, infrastructure response, and outcome performance separately, the study does not assess the overall level of urban resilience; instead, it investigates whether infrastructure scale produces observable flood-mitigation outcomes.

This transformation is not automatic. Different precipitation-runoff generation mechanisms alter the process through which rainfall becomes surface runoff [10]. Land subsidence may weaken existing drainage gradients and reduce effective infrastructure capacity, while pipeline siltation, network connectivity, and operation and maintenance can create discrepancies between nominal infrastructure scale and actual drainage performance [11]. At the same time, the configuration of green-gray infrastructure, monitoring and early warning, and residents' adaptive behavior jointly constitute external conditions under which engineering responses operate [12,13]. Accordingly, the evaluation of infrastructure effects must move beyond asking whether infrastructure exists to asking under what conditions it generates performance.

Guangdong Province has long been exposed to intense rainfall, typhoons, and urban waterlogging, while also experiencing rapid urban expansion, a high concentration of population and assets, and substantial infrastructure investment [14,15]. More importantly, cities within Guangdong differ markedly in their economic foundations, urban scale, drainage conditions, and levels of regional coordination [16]. City-level panel data from Guangdong therefore provide an appropriate case for examining the regional conditionality of infrastructure effects. Similar combinations of high pressure, high investment, and internal heterogeneity are also common in monsoon-affected coastal regions, delta urban agglomerations, and rapidly expanding metropolitan areas.

Against this background, this study uses panel data for 21 prefecture-level cities in Guangdong Province from 2016 to 2022. Rainfall pressure, stormwater pipe network scale, and reported flood outcomes are measured separately to test whether infrastructure scale weakens the relationship between rainfall pressure and reported flood occurrence, and to further examine regional differences between Pearl River Delta (PRD) and non-PRD cities. The study makes three main contributions. First, it uses a city-level pressure-response-outcome analysis to reduce scale-related bias. Second, it separates infrastructure response from flood outcomes, thereby avoiding the use of response indicators to explain a composite resilience index that already contains those indicators. Third, it opens the "input-performance" black box in flood resilience research and demonstrates that the transformation from infrastructure scale to operational performance is conditional, thereby providing theoretical and empirical support for performance-oriented urban flood governance.

## 2. Literature Review and Theoretical Analysis

### 2.1. Flood Resilience Assessment

Existing research on urban flood resilience mainly uses two approaches: composite indicator assessment and hydrological process simulation. The former compares regional resilience levels by integrating indicators related to the natural environment, infrastructure, socioeconomic conditions, and governance capacity [17], whereas the latter focuses on precipitation, runoff generation, drainage, and inundation processes [18,19]. These approaches are well suited to macro-level comparison and physical-process interpretation, respectively, but direct tests of whether specific governance responses improve flood outcomes remain relatively limited. Composite resilience indices are particularly likely to obscure the transformation from response inputs to outcome performance. When variables such as drainage infrastructure and fiscal investment are both components of a resilience index and subsequently used to explain that index, the observed relationship may partly reflect index construction rather than the actual effect of infrastructure response on flood outcomes. Resilience research therefore needs to distinguish between “how many response resources a city possesses” and “whether those resources improve outcomes,” and to measure pressure, response, and outcome separately.

### 2.2. Relationship Between Rainfall Pressure and Reported Flood Occurrence

Precipitation is a direct external disturbance contributing to urban flooding [20]. As rainfall amount or intensity increases, the volume and generation rate of surface runoff generally rise [21]. When runoff exceeds surface storage capacity and the carrying capacity of the drainage system, the likelihood of urban waterlogging and flooding increases [22,23]. Urban expansion and the growth of impervious surfaces further reduce infiltration space and amplify rainfall pressure. The translation of rainfall into flood outcomes is also affected by rainfall duration, antecedent wetness, topography, and runoff generation mechanisms [24]. Previous research has shown that different hydroclimatic zones may be characterized by saturation-excess runoff, infiltration-excess runoff, or mixed mechanisms; therefore, a single precipitation indicator cannot fully represent the runoff process [10]. Nevertheless, when other conditions are relatively stable, greater rainfall pressure imposes a larger water load on the drainage system and should increase the probability that flooding is reported. Accordingly, the following hypothesis is proposed:

**H1.** *Greater urban rainfall pressure is associated with a higher number of reported flood events.*

### 2.3. Buffering Mechanism and Operational Boundaries of Stormwater Pipe Networks

Stormwater pipe networks provide an engineering response to rainfall disturbances by collecting, conveying, and discharging surface runoff [25]. Relative to the size of the built-up area, a higher level of pipe network provision should theoretically shorten surface-flow and drainage pathways, increase runoff conveyance capacity, and reduce the likelihood that a given level of rainfall pressure is translated into urban waterlogging. The role of the pipe network may therefore be reflected not only in its direct association with flood outcomes, but also in its moderation of the effect of rainfall pressure. However, pipe length or density mainly reflects infrastructure scale and cannot fully capture pipe diameter, design standards, system connectivity, pumping and detention capacity, or operation and maintenance. Di et al. further showed that pipeline siltation changes effective conveyance capacity and affects the flood-control performance of green-gray infrastructure combinations. Whether the theoretical buffering effect of network scale can be detected in city-level statistical data thus depends on whether the infrastructure forms an effectively functioning system [12]. Based on the fundamental engineering mechanism, the following hypothesis is proposed:

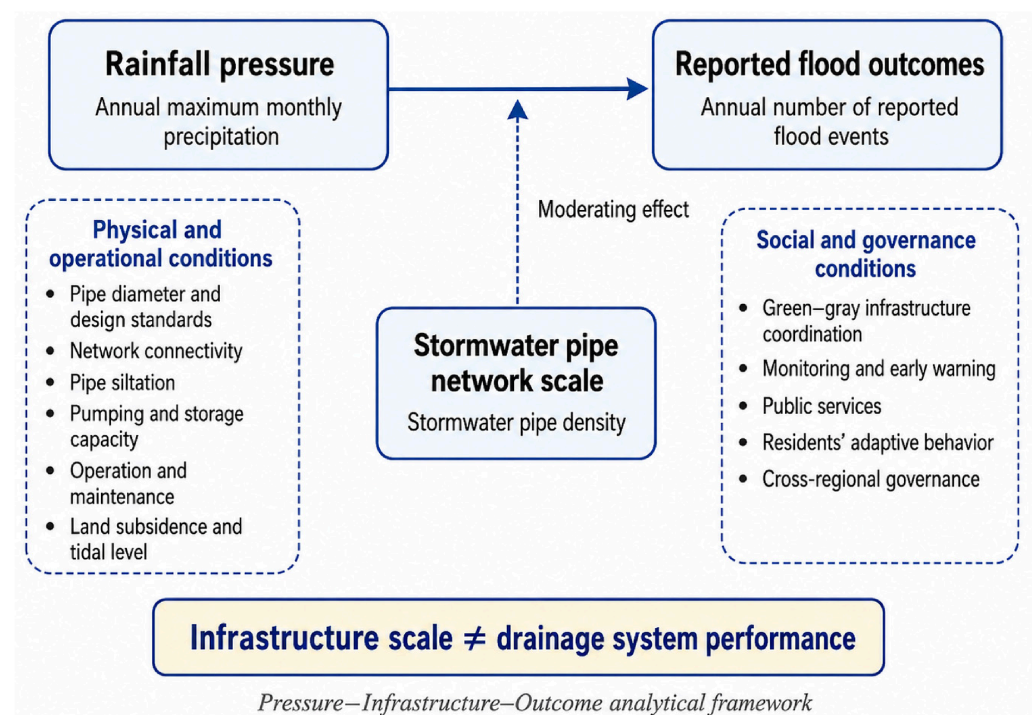
**H2.** Higher stormwater pipe density weakens the positive association between rainfall pressure and reported urban flood occurrence.

#### 2.4. Infrastructure Response

Infrastructure effects are also constrained by spatial and social conditions. In coastal and delta cities, land subsidence may reduce relative elevation and alter drainage gradients, causing the same pipe network scale to exhibit different levels of effective capacity [11]. Moreover, the extent to which engineering facilities contribute to broader flood resilience also depends on green infrastructure, spatial planning, monitoring and early warning, public services, community needs, and residents' adaptive behavior [13,26].

Cities in Guangdong differ substantially in urbanization levels, infrastructure foundations, and regional coordination. Therefore, in addition to the baseline analysis, this study compares PRD and non-PRD cities as an exploratory extension without imposing a directional hypothesis. The academic contribution is not to classify which cities are “more resilient,” but to measure stormwater pipe network scale and reported flood outcomes separately and directly test whether infrastructure scale is translated into flood-mitigation performance, thereby addressing the relationship between response inputs and outcome outputs in urban flood resilience research.

Based on the above discussion, this study distinguishes rainfall pressure, stormwater pipe network scale, and reported flood outcomes, and treats the stormwater pipe network scale as an infrastructure response variable that may moderate the relationship between rainfall pressure and reported flood outcomes. Meanwhile, the role of infrastructure may also be conditioned by physical and operational factors as well as social and governance factors. The overall analytical framework is shown in Figure 1.

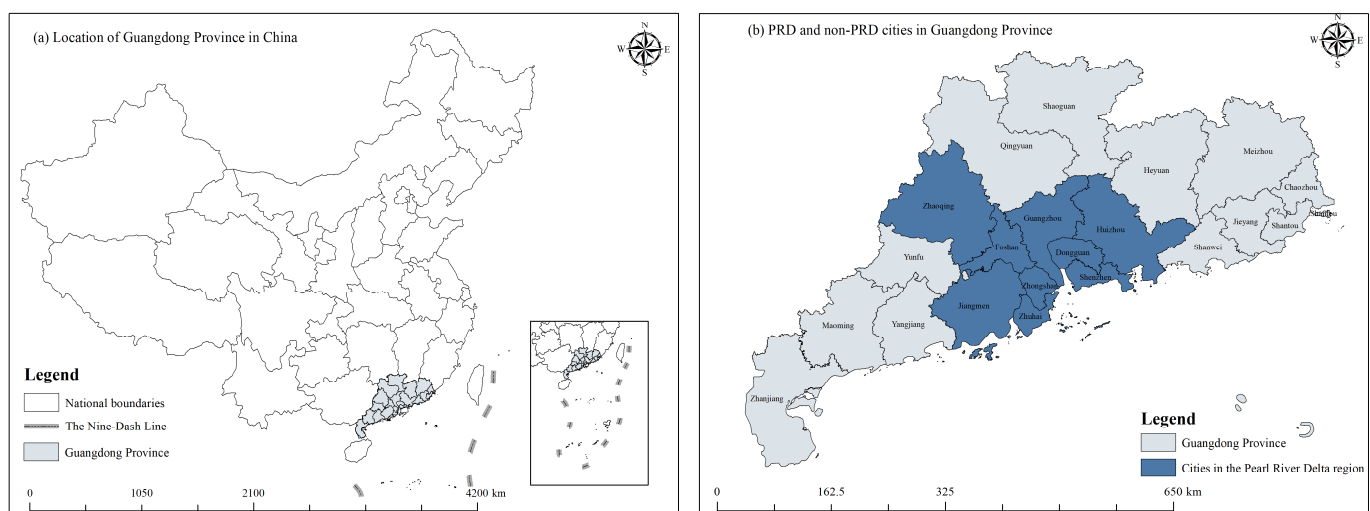


**Figure 1.** Analytical framework linking rainfall pressure, stormwater pipe network scale, and reported flood outcomes.

### 3. Data Sources and Research Methods

#### 3.1. Study Area and Data Sources

This study covers all 21 prefecture-level cities in Guangdong Province over the period 2016–2022. To examine intra-provincial heterogeneity, Guangzhou, Shenzhen, Zhuhai, Foshan, Huizhou, Dongguan, Zhongshan, Jiangmen, and Zhaoqing are classified as PRD cities, while the remaining 12 prefecture-level cities are classified as non-PRD cities. The study area and regional classification are shown in Figure 2. City-level data are used to capture differences in precipitation conditions, urban expansion, drainage infrastructure provision, and reported flood outcomes across cities, thereby avoiding the use of provincial averages to infer city-level relationships. Urban flood data are drawn from a county-level Chinese urban flood news-text dataset developed by Fu et al. [27]. Precipitation data are obtained from a 1 km monthly precipitation product for China [28]. Urban construction and drainage infrastructure data are taken from the China Urban Construction Statistical Yearbook, while economic and fiscal data are obtained from the Guangdong Statistical Yearbook, municipal statistical yearbooks, and statistical bulletins. Daily extreme-precipitation indicators used for robustness checks are derived from ERA5 reanalysis data [29]. Flood and precipitation data are aggregated according to municipal-district boundaries; owing to their special administrative structures, Dongguan and Zhongshan are treated using whole-city boundaries. Matching all datasets by city and year yields 147 city-year observations. Because Zhongshan recorded zero reported flood events throughout the study period, complete separation occurs in the city fixed-effects PPML estimation. The baseline model therefore uses 20 cities and 140 observations, while Zhongshan is retained in the full sample and descriptive analysis.



**Figure 2.** Location of Guangdong Province and PRD-non-PRD classification of the study cities.

#### 3.2. Variable Selection and Measurement

This study does not directly measure comprehensive urban flood resilience; instead, it focuses on the key link through which infrastructure response is translated into flood outcomes. To avoid circular interpretation in which response indicators both constitute and explain a composite resilience index, rainfall pressure, infrastructure scale, and reported flood outcomes are measured separately. The definitions of the main variables are presented in Table 1.

**Table 1.** Definitions and data sources of the main variables.

| Variable Type             | Variable                                       | Measurement                                                                     | Unit               | Data Source                                                        |
|---------------------------|------------------------------------------------|---------------------------------------------------------------------------------|--------------------|--------------------------------------------------------------------|
| Dependent variable        | Number of reported flood events                | Municipal-district flood records aggregated by city-year                        | Events             | Fu et al. [27], county-level Chinese urban flood news-text dataset |
| Core explanatory variable | Rainfall pressure                              | Municipal-district monthly precipitation aggregated and annual maximum selected | mm                 | 1 km monthly precipitation product for China [28]                  |
| Moderating variable       | Stormwater pipe density                        | Stormwater pipe length/built-up area                                            | km/km <sup>2</sup> | China Urban Construction Statistical Yearbook and related sources  |
| Interaction term          | Rainfall pressure × stormwater pipe density    | Product of the two mean-centered variables                                      | —                  | Calculated from the underlying variables                           |
| Control variable          | Built-up area                                  | Natural logarithm of built-up area                                              | —                  | China Urban Construction Statistical Yearbook and related sources  |
| Control variable          | Economic development                           | Natural logarithm of GDP per capita                                             | —                  | Guangdong and municipal statistical yearbooks                      |
| Control variable          | Fiscal expenditure intensity                   | General public budget expenditure/GDP                                           | %                  | Guangdong and municipal statistical yearbooks                      |
| Robustness variables      | Alternative flood and precipitation indicators | Alternative outcomes and precipitation indicators at different temporal scales  | —                  | Flood database, monthly precipitation data, and ERA5 [29]          |

### 3.2.1. Dependent Variable

The dependent variable is the annual number of reported flood events in each city. It is derived from the county-level Chinese urban flood news-text database by selecting municipal-district flood records in Guangdong Province for 2016–2022 and aggregating them by city and year. Owing to their special administrative structures, Dongguan and Zhongshan are treated using whole-city boundaries.

This indicator reflects flooding identified and recorded in the news-text database. It does not represent all flood events that actually occurred, nor does it directly measure economic losses, inundation extent, or disaster severity. Accordingly, the term “number of reported flood events” is used consistently throughout the study.

### 3.2.2. Core Variables and Interaction Term

First, rainfall pressure. Monthly precipitation for the municipal districts under each city is aggregated to the city-month level, and the maximum value among the 12 months of each year is selected to construct annual maximum monthly precipitation. This indicator captures relatively strong monthly-scale rainfall disturbances within a year, but it is not equivalent to maximum daily precipitation or short-duration extreme rainfall.

Second, stormwater pipe density. To account for differences in built-up area across cities, the level of pipe network provision is measured as the ratio of stormwater pipe length to built-up area:

$$D_{it} = \frac{L_{it}}{A_{it}}$$

where  $D_{it}$  denotes stormwater pipe density,  $L_{it}$  denotes stormwater pipe length, and  $A_{it}$  denotes built-up area for city  $i$  in year  $t$ . The unit is km/km<sup>2</sup>. This indicator serves as a proxy for drainage infrastructure scale rather than actual drainage capacity and does not

capture pipe diameter, design standards, network connectivity, pipeline siltation, pumping and detention capacity, or operation and maintenance.

To test whether stormwater pipe density changes the relationship between rainfall pressure and reported flood occurrence, an interaction term is constructed. Rainfall pressure and stormwater pipe density are mean-centered before the interaction term is calculated. A significantly negative interaction term would indicate that pipe density may weaken the effect of rainfall pressure on reported flood occurrence. Because this study uses observational panel data, the results are interpreted primarily as statistical associations rather than strict causal effects.

### 3.2.3. Control Variables

The analysis controls for built-up area, economic development, and fiscal expenditure intensity. Built-up area is measured by the natural logarithm of built-up area; economic development is measured by the natural logarithm of GDP per capita; and fiscal expenditure intensity is measured as the ratio of local general public budget expenditure to GDP:

$$F_{it} = \frac{E_{it}}{GPT_{it}} \times 100\%$$

where  $F_{it}$  denotes fiscal expenditure intensity,  $E_{it}$  denotes local general public budget expenditure, and  $GPT_{it}$  denotes gross domestic product for city  $i$  in year  $t$ . In the regression analysis,  $F_{it}$  is divided by 10, so its coefficient represents the association with the number of reported flood events for a 10-percentage-point change in fiscal expenditure intensity. This indicator reflects overall local fiscal expenditure rather than dedicated flood-control or drainage investment.

### 3.2.4. Variables for Robustness and Extended Analyses

The number of municipal districts with reported flooding and a binary indicator of whether a city had any reported flooding in a given year are used as alternative dependent variables. Alternative precipitation variables include annual total precipitation, precipitation during the April–September flood season, maximum precipitation over three consecutive months, and ERA5 annual maximum daily precipitation. The analysis also uses one-period-lagged stormwater pipe density and a conservative sample obtained by excluding observations with large annual changes in urban construction indicators. The extended analysis adds interactions with a PRD indicator to identify differences within Guangdong and further includes the squared rainfall-pressure term and its interaction with pipe density to test whether the baseline findings omit a simple quadratic nonlinear relationship.

## 3.3. Model Specification and Estimation Strategy

Because the annual number of reported flood events is a count variable with many zero observations, the Poisson pseudo-maximum likelihood (PPML) estimator is used with city and year fixed effects. PPML directly estimates the conditional mean under heteroskedasticity and accommodates zero outcomes, making it suitable for the count outcome used in this study [30,31]. All statistical analyses were conducted using Python. The model is specified as follows:

$$E(\text{Flood}_{it}|X_{it}) = \exp[\beta_1 R_{it} + \beta_2 D_{it} + \beta_3 (R_{it} \times D_{it}) + \gamma^T Z_{it} + \alpha_i + \delta_t]$$

where  $\text{Flood}_{it}$  denotes the number of reported flood events in city  $i$  in year  $t$ ,  $R_{it}$  denotes rainfall pressure,  $D_{it}$  denotes stormwater pipe density, and  $Z_{it}$  denotes the control variables. Rainfall pressure and stormwater pipe density are mean-centered before constructing the

interaction term.  $\alpha_i$  and  $\delta_t$  represent city and year fixed effects, respectively. The coefficient  $\beta_3$  is used to test whether stormwater pipe density moderates the relationship between rainfall pressure and reported flood occurrence.

City fixed effects control for relatively stable city characteristics such as topography, location, and long-term development foundations, while year fixed effects control for annual changes common to all cities. Standard errors are clustered at the city level.

The coefficient of primary interest is  $\beta_3$ . A significantly negative value would indicate that the association between rainfall pressure and reported flood occurrence becomes weaker as stormwater pipe density increases. Because PPML is nonlinear, the interaction is further interpreted using conditional effects.

To assess robustness, the analysis replaces the flood outcome and precipitation indicators, uses one-period-lagged stormwater pipe density, and re-estimates the models after excluding observations with relatively large annual changes. To examine heterogeneity within Guangdong, a PRD dummy variable is introduced and interacted with rainfall pressure and stormwater pipe density. The PRD includes Guangzhou, Shenzhen, Zhuhai, Foshan, Huizhou, Dongguan, Zhongshan, Jiangmen, and Zhaoqing. Because Zhongshan is completely separated in the fixed-effects PPML model, the heterogeneity analysis effectively includes eight PRD cities and 12 non-PRD cities. Rainfall pressure squared and its interaction with pipe density are also included to test for nonlinear effects.

## 4. Empirical Results

### 4.1. Descriptive Statistics

Table 2 reports descriptive statistics for the main variables. The mean annual number of reported flood events is 1.11, the median is 0, and the maximum is 11. Of the 140 city-year observations, 83 have zero reported flood events, accounting for 59.29% of the sample. This distribution contains many zeros and is strongly right-skewed, supporting the use of a count-data model.

**Table 2.** Descriptive statistics of the main variables.

| Variable                                      | N   | Mean      | Std. Dev. | Min.      | Median    | Max.       |
|-----------------------------------------------|-----|-----------|-----------|-----------|-----------|------------|
| Number of reported flood events               | 140 | 1.11      | 1.83      | 0.00      | 0.00      | 11.00      |
| Annual maximum monthly precipitation (mm)     | 140 | 385.13    | 75.08     | 229.71    | 389.67    | 627.55     |
| Built-up area (km <sup>2</sup> )              | 140 | 273.98    | 368.87    | 21.60     | 126.90    | 1366.02    |
| Stormwater pipe density (km/km <sup>2</sup> ) | 140 | 5.44      | 4.82      | 0.18      | 4.29      | 26.14      |
| GDP per capita (CNY/person)                   | 140 | 70,960.38 | 45,280.00 | 24,032.00 | 51,060.00 | 203,489.00 |
| Fiscal expenditure intensity (%)              | 140 | 18.09     | 7.28      | 7.69      | 16.00     | 40.09      |

Note: Built-up area and GDP per capita are log-transformed in the regression analysis, and fiscal expenditure intensity is scaled in units of 10 percentage points.

The mean annual maximum monthly precipitation is 385.13 mm, ranging from 229.71 to 627.55 mm. Built-up area and stormwater pipe density vary substantially across cities; stormwater pipe density ranges from 0.18 to 26.14 km/km<sup>2</sup>. GDP per capita and fiscal expenditure intensity also display considerable variation, indicating strong heterogeneity among Guangdong cities in precipitation conditions, urban scale, economic foundations, and drainage infrastructure provision.

### 4.2. Baseline Regression Results

Table 3 reports the estimates from the two-way fixed-effects PPML models. Model (1) includes only rainfall pressure and city and year fixed effects. Model (2) adds stormwater pipe density and the control variables. Model (3) further includes the interaction between rainfall pressure and stormwater pipe density.

**Table 3.** Two-way fixed-effects PPML estimation results.

| Variable                                           | Model (1)        | Model (2)            | Model (3)           |
|----------------------------------------------------|------------------|----------------------|---------------------|
| Rainfall pressure                                  | 0.192<br>(0.230) | 0.121<br>(0.243)     | 0.130<br>(0.237)    |
| Stormwater pipe density                            |                  | 0.077 ***<br>(0.021) | 0.056<br>(0.038)    |
| Rainfall pressure $\times$ stormwater pipe density |                  |                      | 0.032<br>(0.050)    |
| Built-up area                                      |                  | 2.321<br>(2.302)     | 2.152<br>(2.258)    |
| GDP per capita                                     |                  | −2.218<br>(1.353)    | −2.359<br>(1.451)   |
| Fiscal expenditure intensity                       |                  | 2.111 **<br>(0.768)  | 2.080 **<br>(0.763) |
| City fixed effects                                 | Yes              | Yes                  | Yes                 |
| Year fixed effects                                 | Yes              | Yes                  | Yes                 |
| Observations                                       | 140              | 140                  | 140                 |
| Deviance-based pseudo-R <sup>2</sup>               | 0.520            | 0.567                | 0.568               |

Note: City-clustered standard errors are reported in parentheses. \*\*\*, and \*\*, indicate significance at the 1% and 5% levels, respectively. Because the number of city clusters is small, statistical significance is assessed using a finite-degrees-of-freedom adjustment and supplemented by city-cluster bootstrap tests. Rainfall pressure is expressed per 100 mm, and fiscal expenditure intensity is expressed per 10 percentage points.

In Model (1), the coefficient on rainfall pressure is positive but statistically insignificant. After infrastructure and city characteristics are added, the rainfall-pressure coefficients in Models (2) and (3) remain positive but insignificant. Thus, after controlling for time-invariant city characteristics and annual changes common to all cities, the available annual city-level data do not provide sufficient evidence that rainfall pressure consistently increases the number of reported flood events. H1 is therefore not supported.

In Model (2), stormwater pipe density is significantly and positively associated with reported flooding; however, after the interaction term is introduced, its coefficient decreases and is no longer significant. This finding should not be interpreted as evidence that pipe network construction increases flooding. One possible explanation is that cities facing greater flood pressure tend to install more drainage infrastructure, creating a reverse association between risk and infrastructure construction. In addition, pipe density reflects infrastructure quantity rather than the actual operational capacity of the drainage network.

Fiscal expenditure intensity is significantly and positively associated with reported flood occurrence in Models (2) and (3). This may indicate that cities with higher flood risk or heavier governance responsibilities have greater fiscal expenditure needs; it should not be interpreted as evidence that fiscal expenditure causes flooding.

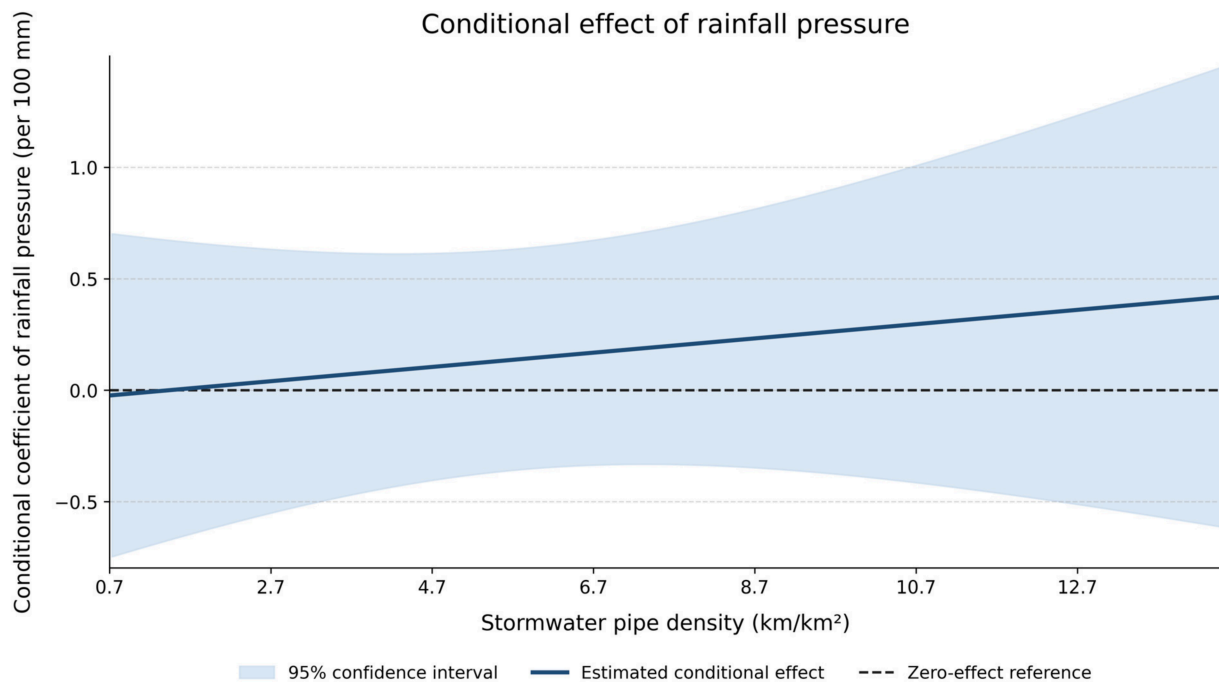
The deviance-based pseudo-R<sup>2</sup> values range from 0.520 to 0.568, indicating a reasonably strong overall fit for count-data models with city and year fixed effects. This provides additional confidence that the insignificant interaction term is unlikely to be attributable solely to poor overall model fit.

#### 4.3. Moderating Role of Stormwater Pipe Density

In Model (3), the coefficient on the interaction between rainfall pressure and stormwater pipe density is 0.032 and is statistically insignificant. The available data therefore do not show that higher stormwater pipe density consistently weakens the effect of rainfall pressure on reported flood occurrence, and H2 is not supported.

To further interpret the interaction in the nonlinear model, the conditional effect of rainfall pressure is calculated across different levels of stormwater pipe density using the full specification. As shown in Figure 3, the conditional effect of rainfall pressure increases gradually as stormwater pipe density rises, but the 95% confidence interval crosses zero

throughout the examined range of pipe density. The sample therefore provides no statistical evidence that stormwater pipe density consistently weakens the effect of rainfall pressure.



**Figure 3.** Conditional effect of rainfall pressure across different levels of stormwater pipe density.

This result does not imply that drainage infrastructure has no flood-control effect. Rather, it indicates that infrastructure quantity, measured as pipe length per unit of built-up area, does not adequately represent the actual operational performance of the drainage system. Pipe diameter, system connectivity, pumping and detention capacity, operation and maintenance, and pipeline siltation may all affect whether infrastructure is translated into flood-mitigation performance.

#### 4.4. Robustness Checks

To determine whether the baseline findings depend on specific variable definitions or sample settings, the dependent variable, precipitation indicators, and pipe network variable are replaced in turn, and the models are re-estimated using a conservative sample. The robustness results based on alternative outcomes, lagged stormwater pipe density, and the conservative sample are summarized in Table 4, while the tests using alternative precipitation indicators are reported in Table 5.

**Table 4.** Robustness-check results.

| Robustness Specification               | N   | Rainfall Pressure | Rainfall Pressure × Pipe Density |
|----------------------------------------|-----|-------------------|----------------------------------|
| Number of affected municipal districts | 140 | 0.124<br>(0.240)  | 0.039<br>(0.049)                 |
| Flood occurrence indicator             | 140 | 0.889<br>(0.692)  | 0.070<br>(0.121)                 |
| One-period-lagged pipe density         | 120 | 0.192<br>(0.259)  | 0.003<br>(0.073)                 |
| Conservative sample                    | 126 | 0.404<br>(0.287)  | 0.039<br>(0.072)                 |

Note: Standard errors are reported in parentheses. The flood occurrence indicator is estimated using a conditional fixed-effects logit model with model-based standard errors; all other specifications use two-way fixed-effects PPML with city-clustered standard errors.

**Table 5.** Tests using alternative precipitation indicators.

| Alternative Precipitation Indicator                 | Precipitation Coefficient | Interaction Coefficient |
|-----------------------------------------------------|---------------------------|-------------------------|
| Annual total precipitation                          | 0.453<br>(3.135)          | −0.203<br>(0.147)       |
| April–September flood-season precipitation          | −1.778<br>(3.155)         | −0.203 *<br>(0.115)     |
| Maximum precipitation over three consecutive months | 1.346<br>(2.459)          | 0.086<br>(0.150)        |
| ERA5 annual maximum daily precipitation             | 0.084<br>(0.426)          | 0.098<br>(0.096)        |

Note: Annual total precipitation, flood-season precipitation, and maximum precipitation over three consecutive months are expressed per 1000 mm; ERA5 annual maximum daily precipitation is expressed per 100 mm. All models control for city characteristics, city fixed effects, and year fixed effects. \* indicates significance at the 10% level.

First, when the number of municipal districts with reported flooding is used as the alternative dependent variable, neither rainfall pressure nor its interaction with stormwater pipe density is significant. The results also remain substantively unchanged when a binary indicator of whether flooding was reported in a city-year is used as the dependent variable.

Second, annual total precipitation, April–September flood-season precipitation, maximum precipitation over three consecutive months, and ERA5 annual maximum daily precipitation are used in place of the baseline precipitation indicator. The signs of the precipitation and interaction coefficients vary across models, but most are statistically insignificant. The interaction between flood-season precipitation and pipe density is weakly negative at the 10% level; however, this finding is not reproduced with other precipitation indicators and therefore cannot be regarded as stable evidence of a buffering effect.

Third, the interaction term remains insignificant when stormwater pipe density is lagged by one period, indicating that infrastructure construction lags do not materially alter the baseline conclusion. After observations with large annual changes in urban construction indicators are excluded, the conservative sample contains 126 observations, and the interaction term again fails to reach statistical significance.

Additional model diagnostics indicate some degree of overdispersion in the sample, but the use of city-clustered robust standard errors does not undermine the applicability of PPML. After high-influence city-year observations are removed or cities are excluded one at a time, the interaction between rainfall pressure and stormwater pipe density remains statistically non-negative. The core explanatory variables do not exhibit serious multicollinearity, indicating that the insignificant baseline interaction is not primarily driven by individual observations or collinearity.

#### 4.5. Regional Heterogeneity and Nonlinearity

Table 6 reports the extended tests of regional heterogeneity and nonlinearity. A PRD interaction is introduced to examine regional heterogeneity. In non-PRD cities, the interaction between rainfall pressure and pipe density is 0.109 and statistically insignificant. The PRD differential interaction is −0.249 and significant at the 5% level. A linear-combination test shows that the conditional interaction effect in PRD cities is −0.140 and weakly significant at the 10% level. These results suggest that the average insignificant relationship in the full sample may conceal regional differences: in PRD cities, higher pipe density is associated with a weaker relationship between rainfall and reported flooding, while no comparable pattern is observed in non-PRD cities.

**Table 6.** Extended tests of regional heterogeneity and nonlinearity.

| Variable                                                        | Regional Heterogeneity Model | Nonlinear Model |
|-----------------------------------------------------------------|------------------------------|-----------------|
| Rainfall pressure $\times$ pipe density (non-PRD)               | 0.109<br>(0.068)             | —               |
| Rainfall pressure $\times$ pipe density $\times$ PRD            | −0.249 **<br>(0.092)         | —               |
| Conditional PRD interaction effect                              | −0.140 *<br>(0.075)          | —               |
| Rainfall pressure $\times$ stormwater pipe density              | —                            | 0.107 (0.063)   |
| Rainfall pressure <sup>2</sup>                                  | —                            | −0.427 (0.331)  |
| Rainfall pressure <sup>2</sup> $\times$ stormwater pipe density | —                            | −0.093 (0.060)  |
| Observations                                                    | 140                          | 140             |

Note: City-clustered standard errors are reported in parentheses. The conditional PRD interaction effect is a linear combination of the relevant coefficients. \*\*, and \* indicate significance at the 5% and 10% levels, respectively. All models control for city characteristics, city fixed effects, and year fixed effects.

This heterogeneity result should, however, be interpreted cautiously. When annual total precipitation is used, the conditional PRD effect remains negative and approaches significance at the 10% level. Under other precipitation indicators, lagged pipe density, and the conservative sample, the regional differential mostly remains negative but does not display stable statistical significance. Therefore, this result should be viewed only as exploratory evidence that infrastructure effects may be regionally conditional and should not replace the baseline conclusion for the full sample.

After the squared rainfall-pressure term and its interaction with stormwater pipe density are added, neither the squared term nor the quadratic interaction is significant. This suggests that the baseline results are not primarily driven by the omission of a simple quadratic relationship. Given the limited sample size, multiple threshold searches are not conducted in order to avoid outcome-driven model selection.

## 5. Discussion

### 5.1. Stormwater Pipe Network Scale and Flood-Mitigation Performance

The central finding is not simply whether a particular coefficient is statistically significant, but that stormwater pipe network scale and flood-mitigation performance do not exhibit the stable correspondence that might otherwise be assumed. In the full sample, rainfall pressure is positively but insignificantly associated with reported flooding. Pipe density is positively associated with reported flooding before the interaction is introduced, but becomes insignificant in the full specification, and the rainfall-pressure-by-pipe-density interaction does not display a stable negative effect. The conclusion remains broadly unchanged after replacing the outcome and precipitation indicators, using lagged pipe density, and adjusting the sample.

These findings should not be interpreted as evidence that drainage infrastructure is ineffective, nor do they imply that adding pipe networks causes flooding. A more plausible interpretation is that pipe length per unit of built-up area reflects infrastructure stock rather than effective operational capacity under intense rainfall. In addition, high-risk cities may continuously expand pipe networks and fiscal expenditure in response to existing flood pressure, generating a reverse association between governance response and risk levels. The continued absence of a stable buffering effect when lagged pipe density is used also indicates that infrastructure quantity alone is insufficient to identify the actual role of the drainage system.

The theoretical contribution of this study is therefore to open the black box through which response inputs are transformed into outcome performance. A high response level in a composite index only indicates that a city possesses more engineering or governance re-

sources; it does not automatically mean that these resources have been converted into fewer flood events or faster recovery. Flood resilience assessment should therefore move beyond input and stock indicators to include performance indicators such as effective drainage capacity, infrastructure availability, improvement of flood-prone locations, drainage duration, and system recovery.

### 5.2. Regional Heterogeneity in Infrastructure Effects

The extended analysis shows a weakly negative conditional rainfall-pipe interaction in PRD cities and a statistically significant difference from non-PRD cities. This finding suggests that average effects may conceal the systemic conditions required for infrastructure to function effectively. In highly urbanized agglomerations with dense infrastructure networks and strong cross-regional connections, additional pipes may be more readily integrated with existing pumping stations, detention space, and management systems. In cities with different levels of infrastructure coverage, connectivity, and maintenance, the same pipe density may not represent the same effective capacity.

However, the regional difference is not stable across alternative precipitation indicators, lagged variables, and the conservative sample, and therefore cannot be interpreted as a definitive PRD mechanism. It is more appropriately viewed as a conditional signal: infrastructure effects depend on the physical environment, system maturity, and governance coordination of a city rather than on the quantity of a single facility alone. Future research should use longer time series, event-scale precipitation, and detailed urban drainage-system data to further test this difference.

### 5.3. Boundaries of Infrastructure Effects

The finding that “infrastructure scale does not equal operational performance” directly echoes Di et al. [12]. Using flood simulation and multi-objective optimization, Di et al. [12] showed that pipeline siltation reduces effective conveyance capacity and changes the performance of green-gray infrastructure combinations [12]. This city-level panel analysis likewise finds no stable average buffering effect of nominal pipe density. Together, these two forms of evidence indicate that resilience assessment cannot stop at pipe length or infrastructure quantity; it should also consider pipe diameter, connectivity, siltation, pumping capacity, maintenance status, and coordination among facilities.

The instability of the rainfall coefficient can also be interpreted in light of differences in runoff generation mechanisms [10]. Differences in rainfall duration, antecedent wetness, and underlying surface conditions can cause the same cumulative rainfall to generate different runoff outcomes, making an annual monthly-scale indicator unable to fully capture event-scale rainfall-runoff relationships. He et al. (2025) further showed that land subsidence can alter relative elevation and drainage gradients, thereby reducing the effective capacity of existing flood-control infrastructure [11]. Although this study does not directly test runoff generation types or land subsidence, these studies show that the average effect of infrastructure scale must be understood within specific hydrological and spatial conditions.

Jiang and Chen (2026) extend this discussion from physical systems to socio-physical resilience [13]. Engineering facilities can be translated into lower losses and faster recovery only when they are integrated with community needs, public services, early warning and response, and residents’ adaptive behavior. The number of reported flood events used in this study captures only one part of the transformation from infrastructure response to outcome performance and cannot encompass comprehensive social resilience. Nevertheless, the absence of stable buffering evidence for pipe quantity reinforces the argument that urban flood resilience cannot be reduced to a single engineering stock and should instead

be evaluated within an integrated framework of physical infrastructure, ecological storage, and social adaptation. These studies are used to define the theoretical implications and operational boundaries of the findings from this study; they do not imply that pipeline siltation, land subsidence, or community behavior has been empirically identified in this analysis.

#### *5.4. Limitations and Future Research*

This study has several limitations. First, the number of reported flood events is derived from news texts and may be affected by differences in media attention and information disclosure; it cannot fully represent actual flood occurrence, inundation extent, or economic losses. Media coverage of flooding may also be systematically more intensive in larger or more economically developed cities. Although the models control for built-up area, GDP per capita, and city and year fixed effects, these controls may only partially mitigate such reporting heterogeneity, and residual reporting bias may remain if media attention or disclosure practices change over time within cities. Second, annual maximum monthly precipitation cannot capture short-duration rainstorms or peak rainfall processes, and ERA5 daily indicators cannot substitute for high-resolution urban precipitation data and inundation simulations. Future research should match flood-event timing with hourly or daily precipitation as closely as possible and incorporate outcomes such as waterlogging locations, inundation depth, drainage duration, and disaster losses. Third, stormwater pipe density captures only infrastructure scale and cannot measure pipe diameter, design standards, system connectivity, siltation, pumping capacity, or operation and maintenance. Future work could combine pipe network topology, facility inspections, green infrastructure, impervious-surface data, land subsidence, topography, and tidal levels to directly identify effective infrastructure capacity and its boundary conditions. Fourth, the sample period covers only seven years, and the regional heterogeneity findings are not stable across alternative specifications. Although city and year fixed effects control for some unobserved differences, reverse causality and omitted variables cannot be fully excluded. The findings should therefore be interpreted as city-level statistical associations rather than strict causal effects.

## **6. Conclusions and Policy Implications**

### *6.1. Main Conclusions*

Using panel data for 21 prefecture-level cities in Guangdong Province from 2016 to 2022, this study measures rainfall pressure, stormwater pipe network scale, and reported flood outcomes separately and tests whether infrastructure scale weakens the relationship between rainfall pressure and reported flood occurrence. In the full sample, rainfall pressure is positively but insignificantly associated with reported flooding, and the negative moderating effect of stormwater pipe density is not robustly supported. The main findings remain broadly unchanged when alternative outcome and precipitation indicators, lagged pipe density, and a conservative sample are used. The PRD extension provides limited weak negative evidence, but this evidence is unstable across specifications.

The central conclusion is not that drainage infrastructure is ineffective, but that infrastructure scale, represented by pipe length per unit of built-up area, cannot be directly equated with drainage-system operational performance. Whether infrastructure investment is translated into flood-mitigation performance is clearly conditional, and urban flood resilience assessment needs to separate infrastructure stock from actual outcomes.

## 6.2. Policy Implications

First, urban drainage governance should shift from evaluating infrastructure quantity to managing operational performance. While continuing to improve pipe network coverage, cities should prioritize the monitoring of system connectivity, pipeline desilting, and the availability of pumping and detention facilities, and should incorporate improvements at flood-prone locations, drainage duration, and operational stability under extreme rainfall into performance assessment.

Second, differentiated coordination of green and gray infrastructure should be advanced according to local urban conditions. High-density cities should strengthen the integration, renewal, and maintenance of existing pipe networks, pumping stations, and detention spaces. Cities with relatively weak infrastructure should address coverage gaps while improving basic operational monitoring and maintenance, and should incorporate topography, subsidence, tidal levels, and underlying surface conditions into planning.

Third, socio-physical integrated governance should be strengthened. Drainage engineering should be coordinated with monitoring and early warning, public services, community emergency response, and residents' adaptive capacity so that engineering investment is genuinely translated into risk reduction and enhanced recovery capacity. These principles may also inform other rapidly urbanizing coastal regions and delta urban agglomerations.

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