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ARTICLE

Research on Flood Impact Assessment of Mountainous Small Watersheds Based on AI Technology

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ABSTRACT

This article focuses on improving the accuracy and systematic approach of flash flood disaster prevention in the central urban area of Tongren. This study is based on hydrological and water resources theory along with a disaster risk assessment framework. The study covers a 758.3 km^2 area in Bijiang and Wanshan Districts. It integrates hydrological, meteorological, topographic and socio-economic data from 1951 to 2021. The results show that flash floods in the central urban area are characterized by "strong destructive power of rainstorms, rapid confluence response, and spatial concentration of risks." 82% of riverside villages have flood control capabilities below the 20-year return period standard. The Xieqiao River (drainage area 198 km^2) and Sanzhai River (drainage area 45 km^2) are high-risk core areas, with design peak flows of 894 m^3/s and 345 m^3/s respectively for a 100-year return period. Among the 39 danger zones classified by risk level, extremely high-risk zones (recurrence period <5 years) account for 30.8%, concentrated in densely populated areas such as the Heping resettlement area and Xiaohaha Commercial City. The critical rainfall warning index range for 1–24 h is 34–204 mm, requiring differentiated response thresholds for different risk zones (69 mm for immediate evacuation in high-risk zones and 41 mm in low-risk zones). The research findings can provide theoretical support and a technical paradigm for risk management and precise early warning of urban flood disasters in southwestern mountainous areas.

Keywords: Tongren Central Urban Area; Flash Flood Disaster; Design Flood; Danger Zone Delineation; Critical Early Warning Indicators; Geographic Information Systems (GIS) Spatial Analysis; Risk Assessment

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1. Introduction

Flash floods are one of the most devastating natural disasters in mountainous urban areas, especially in an era of climate change and urbanization [1]. Over the past few decades, the rise in frequency and intensity of extreme precipitation events has exacerbated flood hazards, seriously affecting human lives, property and regional socio-economic development [2]. Urban areas in hilly regions are particularly vulnerable due to their topography, steep slopes, and highly responsive catchments, which allow for the rapid concentration of runoff, sudden flood peaks, and short warning times [3]. This poses a challenge for risk assessment and early warning systems.

The central urban area of Tongren is located in the middle reaches of the Wuling Mountains in northeastern Guizhou Province, and is in the mid-subtropical monsoon humid climate zone. Orographic uplift and monsoonal circulation make rainstorms "short, heavy and sudden," with an average of 5–7 days of rainstorms each year and a 24-h maximum rainfall of 373 mm (July 2016). The five major rivers in the region, such as the Sanzhai River, Longtian River and Xieqiao River, are typical rain-fed mountain rivers with drainage areas of 12.58–198 km^2 and an average slope of 6.9‰–37‰. They have a hydrologic feature of "fast convergence, sharp rise and fall of flood peaks, and intricate flood pathways", which is easily prone to river breakage and flooding, and secondary geological hazards [4].

Over the past few years, as global warming has intensified, extreme rainstorms have become more frequent. For instance, on July 3–4, 2016, there was torrential rain in the central urban area, which led to the swelling of the Xieqiao River and Longdong River, causing 15 communities to be inundated, 23 roads to be blocked, more than 2,800 people to be evacuated, and direct economic losses of more than 1.8 billion yuan. During the 2024 flood season, flash floods occurred on the Sanzhai River due to short-term heavy rainfall, affecting 1,169 people in the Xiaohaha Commercial City area. These events have revealed issues such as low accuracy in disaster risk assessment and delays in early warning. So, systematic investigation and assessment of flood disasters, and establishment of a scientific early warning index system, are important to enhance the flood disaster prevention capacity of mountainous cities and protect people's lives and property [5].

Existing research has made significant advances in flood risk assessment through hydrologic simulations, Geographic Information Systems (GIS)-based hazard mapping, and vulnerability analysis [6]. But traditional methods typically address individual aspects of the disaster process and do not provide a holistic framework that integrates data collection, hydrologic simulation, spatial risk mapping, and the development of early warning indicators. Moreover, traditional early warning models tend to adopt a uniform rainfall threshold, which fails to account for the spatial variability of topography, hydrologic response, and flood control measures in mountainous urban environments and thus cannot be effectively applied in practice.

To overcome these limitations, this study proposes an integrated approach for flood disaster investigation, assessment, and early warning in the urban centre of Tongren. This framework integrates long-term multi-source data records (1951–2021) with frequency analysis-based design storm method, rainfall-runoff modelling, spatial overlay analyses in geographic information systems (GIS), and empirical testing of historical flood events. Using this integrated approach, the study quantifies flood-hazard processes and spatial risk patterns and provides a detailed delineation of hazard-prone zones [7].

A significant innovation in this study is the development of a design storm-flood analysis framework that enables quantitative analysis of potential flood hazards across various return periods, thereby enhancing confidence in risk assessment [8]. Moreover, a fine-scale spatial framework is proposed to map hazard zones based on flood magnitude, existing flood control measures, and socio-economic vulnerability, thereby improving the spatial accuracy of risk zoning. Moreover, a multi-stage early warning mechanism is developed based on the relationship among rainfall, runoff, and emergency response, in which the warning thresholds for rainfall and water level are calculated for various time scales using interpolation and back-calculation methods [9]. This gives rise to a tiered warning system that enhances both the precision and timeliness of response. The developed approach is also tested on the 2016 flood event in the Xieqiao River basin, confirming its effectiveness and feasibility.

In summary, this research builds on previous approaches by providing a data-driven, multidimensional, and spatial framework for integrated flood risk analysis and early warning systems [10,11]. This study offers both theoretical guidance and a transferable technical approach to enhance flood disaster prevention and mitigation in urban mountainous areas.

2. Overview and Basic Survey of the Study Area

2.1. Natural and Socioeconomic Characteristics of the Study Area

The central urban area of Tongren encompasses nine subdistricts (Jinjiang, Huanbei, Hexi, Tongxing, etc.) and four townships (Huashi Township, Wanshan Town, Gaolouping Township, and Bahuang Town) in Bijiang District and Wanshan District, covering a total area of 758.3 km^2. At the end of 2022, the permanent resident population was 669,000, including 450,100 urban residents and 218,900 rural residents. The terrain is mainly low to medium-altitude mountains and hills, with higher elevations in the northwest and lower elevations in the southeast. The average elevation is 500–1,000 m, with a maximum relative elevation difference of 879 m (the highest point is located in Gaolouping Township, Wanshan District, at an elevation of 1,149.2 m; the lowest point is located at the exit of the Longxi River, at an elevation of 270 m). Karst landforms are strongly developed, with carbonate rocks accounting for over 70% of the area. The soil is mainly yellow soil and limestone soil, with a vegetation coverage of approximately 62% [12].

The five major rivers in the region have significantly different hydrological characteristics (**Table 1**). Among them, Xieqiao River is a first-level tributary on the right bank of Jinjiang River with the largest drainage area (198 km^2) and is the core control target for flood control in the central urban area. Longtian River has the smallest drainage area (12.58 km^2), but the largest river gradient (30‰) and the fastest response speed to flash floods, making it prone to local sudden disasters [4].

Table 1. Hydrological Characteristics of Major Rivers in the Central Urban Area of Tongren.

River Name	Drainage Area (km^2)	Main Channel Length (km)	Average Gradient (‰)	Annual Average Flow (m^3/s)	Runoff Depth (mm)	Main Areas It Flows through
Sanzhai River	45	16.1	20.0	1.1	760	Huashi Township, Dengta Subdistrict, and Zhengguang Subdistrict of Bijiang District
Longtian River	12.58	8.9	30.0	0.3	720	Baiyanxi Community and Longtian Community, Dengta Subdistrict, Bijiang District
Xieqiao River	198	41.7	6.9	4.8	765	Daping Township, Renshan Subdistrict, and Xieqiao Subdistrict of Wanshan District
Longdong River	31.2	16.0	21.0	0.8	800	Chadian Town, Xieqiao Subdistrict, Wanshan District
Longxi River	40.3	17.0	37.0	1.0	790	Wanshan Town, Gaolouping Township, and Jiufeng Agricultural Park in Wanshan District

2.2. Analysis of Basic Survey Results

2.2.1. Hydrological and Meteorological Characteristics

Based on measured data from 1951 to 2021, the average annual precipitation in the central urban area is 1,280 mm, with precipitation concentrated from April to September (accounting for 78% of the annual total), among which June and July have the highest frequency of rainstorms (accounting for 62% of the annual rainstorm days). The P-III type frequency curve fitting method was used to determine the statistical parameters of the rainstorms: the annual maximum 24-h average rainfall is 100 mm, with a coefficient of variation $C_v = 0.50$ and a skewness coefficient $C_s = 3.5 C_v$; the annual maximum 1-h average rainfall is 45 mm, with $C_v = 0.40$ and $C_s = 3.5 C_v$. The rainfall intensity is consistent with the characteristics of the high-value rainstorm area in eastern Guizhou Province (around Fanjingshan) [13].

Historical flood surveys show that from 1995 to 2024, the central urban area experienced six major flash floods. Among them, the Sanzhai River flood in July 1995 (70-year return period, peak flow of 243 m^3/s) and the Xieqiao River flood in July 2016 (60-year return period, peak flow of 795 m^3/s) were typical extreme events, causing river overflows, house damage, and the relocation of people, reflecting the characteristics of strong flood destructiveness and high difficulty in risk management in the region [4].

2.2.2. Current Status of Water-Related Projects and Flood Control

The existing water-related projects within the survey area include 22 bridges, 4 culverts, 1 weir, and 3 small reservoirs (Xiaoyunnan Reservoir, Liangwan Reservoir, and Maoping Reservoir). Among them, the Jinlin Peninsula Bridge and Qiujiazai Bridge on the Xieqiao River are arch bridges with insufficient flow capacity, which are prone to backwater during major floods (backwater height 0.5~1.2m); a section of the Longtian River is covered by culverts (total length approximately 3 km), resulting in a narrow flood discharge section and posing a potential risk of "using pipes instead of rivers" [14].

Regarding flood control projects, the existing flood control dikes have a total length of 8.6 km, mainly distributed in the Renshan Street section of Xieqiao River and the Dengta Street section of Sanzhai River. The dike crest elevation is designed according to the 10-20 year flood standard, but it only covers 30% of the high-risk river sections. In terms of monitoring facilities, there are currently 3 automatic rain gauge stations, 4 automatic water level stations, and 6 video monitoring stations. There are monitoring blind spots in remote areas such as Huashi Township in Bijiang District and Gaolouping Township in Wanshan District. 80% of the simple rain gauge stations and wireless broadcast early warning stations are no longer in normal operation due to disrepair over the years, and the monitoring and early warning capabilities urgently need to be improved [4].

2.2.3. Socioeconomic and Risk Exposure Characteristics

A total of 18,000 households and 67,000 people are threatened by flash floods in the central urban area, with the most affected area being the Xieqiao River (4,706 people, 70%), mainly in densely populated areas such as the Heping resettlement area and the Jinlin Peninsula community. 58 businesses and institutions are also impacted, including Tongren No. 11 Middle School (1,200 students and teachers), Xiaohaha Commercial City (52,000 m^2 of commerce), and Wanshanhong Hotel, with direct economic losses of over 5 billion yuan. In terms of risk exposure density, Dengta Street in the Bijiang District and Renshan Street of the Wanshan District are high-density exposure areas, with a population density of 1,200 people/km^2 and a building density of more than 300 buildings/km^2. These areas are likely to suffer serious casualties and losses during a flood [4].

3. Flood Disaster Analysis and Calculation

3.1. Design Rainstorm Calculation

3.1.1. Calculation Methods and Parameters

The P-III type frequency curve fitting method recommended in the "Design Flood Calculation Specification for Water Conservancy and Hydropower Projects" (SL44-2006) was adopted. Combined with the "Atlas of Contour Maps of Statistical Parameters of Short Duration Rainstorms in Guizhou Province" (2020 edition), frequency analysis was performed on the measured rainfall data from 1951 to 2021 at five stations, including Tongren and Wanshan, to determine the design rainstorm parameters (mean, Cv, Cs) for different durations (1 h, 3 h, 6 h, 12 h, 24 h). Among them, Cs was taken as 3.5 Cv according to the characteristics of rainstorms in Guizhou Province [15].

3.1.2. Calculation Results and Analysis

Table 2 shows the statistical results of the designed rainstorm. From the perspective of time, the rainfall intensity increases significantly with the length of time. The designed rainfall in 24 h is 2.6–2.8 times that of 1 h (for different return periods), reflecting the "long-duration cumulative effect" of rainstorms in mountainous areas. From the perspective of return period, the rainfall in the same duration increases non-linearly with the increase of return period. For example, the rainfall in 24 h with a 100-year return period (274 mm) is 2.06 times that with a 5-year return period (133 mm), reflecting the strong disaster potential of extreme rainstorms [16].

In terms of spatial distribution, the Xieqiao River Basin (with an average annual rainfall of 1,350 mm) is located on the edge of the high-value area of heavy rainfall in Fanjingshan, and its rainfall level is slightly higher than that of Sanzhai River (1,280 mm) and Longtian River (1,250 mm), so its extreme flood risk needs to be closely monitored [17].

Table 2. Design Rainstorm Statistical Results for Different Return Periods.

Duration	Mean (mm)	Cv	Cs/Cv	1% (Once in 100 Years)	2% (Once in 50 Years)	5% (Once in 20 Years)	10% (Once in 10 Years)	20% (Once in 5 Years)
1 h	45	0.40	3.5	103.95	93.60	80.10	68.85	57.60
3 h	64.1	0.41	3.5	149.60	134.60	115.10	99.20	82.60
6 h	82	0.42	3.5	196.10	176.00	149.10	127.90	106.00
12 h	84.9	0.47	3.5	222.60	198.00	164.00	138.80	111.70
24 h	100	0.50	3.5	274.00	242.00	199.00	166.00	133.00

3.2. Design Flood Calculation

3.2.1. Calculation Methods and Formulas

According to the "Practical Handbook for Calculating Rainstorm Floods in Guizhou Province," and considering the drainage area and topographic features, the design flood is calculated using the rainwater runoff method [18]. The core formula is adapted to the drainage area (F) as follows:

25 km^2 ≤ F < 300 km^2 (Xieqiao River, Sanzhai River):

$$Q_p = 0.357 r_1^{0.922} \cdot f^{0.125} \cdot J^{0.082} \cdot F^{0.834} \cdot (C_3 K_p \overline{H}_{24h})^{1.23}$$
$$(25\ km^2 \leqslant F < 300\ km^2, \theta > 30)$$

10 km^2 ≤ F < 25 km^2 (Longdong River, Longxi River):

$$Q_p = 0.\ 234 r_1^{0.848} \cdot f^{0.331} \cdot J^{0.221} \cdot F^{0.834} \cdot (C_3 K_p \overline{H}_{24h})^{1.212}$$
$$(10\ km^2 \leq F < 25\ km^2, \theta < 30)$$

F < 10 km^2 (Longtian River):

$$QP = 0.481 r_1^{0.571} \cdot f^{0.223} \cdot J^{0.149} \cdot F^{0.89} \cdot (C_1 \cdot S_P)^{1.143}\ (F < 10\ km^2)$$

In the formula: Qp is the design peak flow (m^3/s); r_1 is the confluence coefficient (taken as 0.38, suitable for mountainous area II of Guizhou Province); f is the watershed shape coefficient (f = F/L^2, where L is the main channel length); J is the average channel gradient (‰); C_1 or C_3 is the peak runoff coefficient (determined according to soil type and vegetation cover, with a value of 0.66~0.93); Kp is the modulus ratio coefficient (obtained from the P-III type frequency curve); S_P is the design rainfall intensity (mm/h) [19].

3.2.2. Calculation Results and Disaster-Causing Analysis

Table 3 shows the design flood results for each river control section. The statistical results indicate that the basin area dominates the flood peak size [20]. Xieqiao River (F = 198 km^2) has the largest designed flood peak, reaching 894 m^3/s once in 100 years, which is 5.7 times that of Longtian River (F = 12.58 km^2, 157 m^3/s), reflecting the decisive role of basin area in flood magnitude;

Table 3. Design Flood Results and Peak Flow Estimates for Key Rivers in Tongren.

River Name	Control Section	Drainage Area (km^2)	1% (Once in 100 Years)	2% (Once in 50 Years)	5% (Once in 20 Years)	10% (Once in 10 Years)	20% (Once Every 5 Years)	Convergence Time (h)
Sanzhai River	Xiaohaha Commercial City	40.67	345	287	214	161	109	4~5
Longtian River	LT1 section	12.58	157	130	97.8	74.4	50.9	1~2
Xieqiao River	XQ1 section	198	894	747	560	418	292	6~8
Longdong River	LD1 section	31.2	208.4	176.4	133.3	100.3	70.9	3~4
Longxi River	Gaolouping Township	10.9	179	149	112	85	58.1	2~3

The gradient affects the flood response speed [21]. Longtian River (J = 30‰) and Longxi River (J = 37‰) have large river gradients and short flood confluence times (1~3 h), which can easily trigger sudden flash floods; Xieqiao River (J = 6.9‰) has a longer confluence time (6~8 h), and the flood process is relatively gentle, but the risk of overflow is higher.

The increase in extreme floods is significant. The flood peak of the same river increases exponentially with the increase in the return period [22]. For example, the 100-year flood peak (345 m^3/s) of the Sanzhai River is 3.2 times that of the 5-year flood peak (109 m^3/s). It is necessary to focus on preventing the impact of extreme floods on densely populated areas along the river.

3.3. Refined Classification of Hazardous Areas and GIS Visualization

3.3.1. Classification Standards and Technical Processes

Referring to the "Technical Specifications for Investigation and Evaluation of Mountain Flood Disasters" (SL767-2018), and considering the current flood control situation and socio-economic characteristics of the central urban area, the following standards for classifying dangerous zones are formulated [23].

Extremely high-risk areas are those where the flood recurrence period is more than once in 5 years, corresponding to the current flood control capacity being less than once in 5 years, threatened population density >800 people/km^2, and emergency evacuation measures need to be implemented first [24]. High-risk areas are those where the flood recurrence period is 5 to 20 years, the current flood control capacity is 5–10 years, the threatened population density is 400–800 people/km^2, requiring strengthened monitoring, early warning and engineering management [25]. Danger zones are those where the flood recurrence period is once every 20–100 years. The current flood control capacity is once every 10–20 years, the threatened population density is <400 people/km^2, and the daily prevention and control mechanism needs to be improved [26].

In terms of technical process, based on the ArcGIS 10.8 platform, first, topographic slope, elevation, and other elements are extracted from DEM data, and the flood range at different frequencies is simulated in combination with the design flood level; second, socio-economic data such as the distribution of settlements and houses are overlaid to count the scale of threatened population and property in each area; finally, values are assigned according to the level standards and visualized to form a spatial distribution map of danger zones [27,28].

3.3.2. Division Results and Spatial Features

A total of 39 danger zones have been designated in the central urban area, covering a total area of 7.4 km^2, affecting a population of 67,000. The distribution of core risks is shown in **Table 4**. The extremely high-risk and high-risk areas are mainly concentrated in the Renshan Street section of Xieqiao River and the Dengta Street section of Sanzhai River, accounting for 75.7% of the total risk area and 77.6% of the threatened population. Due to the dense population and insufficient flood discharge capacity of the river, this area has become the core area for risk management [4].

Table 4. Classification of Danger Zones and Flood Risk Characteristics in the Central Urban Area of Tongren.

Danger Zone Level	Quantity (Place)	Percentage (%)	Total Area (km^2)	Percentage (%)	Threatened Population (People)	Percentage (%)	Average Flood Depth (m)	Representative Area
Extremely high danger zone	12	30.8	2.1	28.4	28,000	41.8	2.2~3.0	Xieqiaohe Heping resettlement site, Longtianhe Ruili International
High-risk area	18	46.2	3.5	47.3	24,000	35.8	1.5~2.2	Sanzhaihe Xiaohaha Commercial City, Xieqiaohe Jinlin Peninsula
Danger Zone	9	23.0	1.8	24.3	15,000	22.4	0.8~1.5	Longxihe Gaolouping Township and Longdonghe Hedong Group

TDengta Street in Bijiang District (slope of 15°~25°) and Xieqiao Street in Wanshan District (slope of 20°~30°) are low-lying and steeply sloped, making them prone to flooding and having a large inundation depth (1.5~3.0 m), with a risk level significantly higher than the surrounding areas [4].

The project's hidden dangers have exacerbated the risks. Due to the limited flood discharge section of the Longtian River culvert section and the Xieqiao River arch bridge section, the backwater has caused the upstream flooding area to expand by 20%–30%, and some areas have been upgraded to extremely high-risk zones [26].

3.3.3. Results Verification and Rationality Analysis

Using the measured flood of Xieqiao River in 2016 as the verification benchmark, the peak flow that year was 795 m^3/s (60-year return period). The measured inundation area included the Heping resettlement area and Jinlin Peninsula residential area, with an inundation depth of

1.8–2.5 m. Comparing the simulated 50-year return period (peak flow of 747 m^3/s) inundation area with the measured results, the overlap rate reached 85%, and the inundation depth error was <0.5 m. This verifies the rationality of the design flood calculation, inundation simulation, and hazard zone delineation, providing a reliable foundation for the subsequent construction of early warning indicators [27].

3.4. Construction of Tiered Early Warning Indicators

3.4.1. Calculation Methods and Principles

Here, two modern techniques are applied to develop accurate early warning indicators based on the "rainfall-runoff-hazard" chain reaction, which ties rainfall, runoff and hazard together. The first method used is the rainfall-runoff relationship interpolation method [29]. This approach focuses on the connection between the design storm (a theoretical model of extreme rainfall events) and the design flood (the corresponding flood generated by such rainfall). By incorporating soil moisture content—considered to be at a moderate level (around 25%–30%) typical for the central urban area during the flood season—this method interpolates the critical rainfall values for various durations. These interpolated rainfall values represent the threshold at which flooding is expected, considering how different durations of rainfall affect runoff in the local environment.

The second method applied is the water level-discharge relationship inverse calculation method [30]. This technique calculates the flow rate of the river that corresponds to the water level considered dangerous in the flood zone. Specifically, it uses the elevation of the first floor of buildings in the danger zone, which is often the first point at risk of flooding. By understanding the relationship between water level and discharge, the system can reverse-engineer the rainfall levels required to reach critical flow rates, thus setting the threshold for early warnings. This allows for a more direct and accurate prediction of when flood waters will reach hazardous levels, ensuring that responses can be triggered at the right time.

The early warning indicators are then split into two levels depending on the level of risk. The first level, "Prepare to evacuate," corresponds to a rainfall event that is expected to occur once every five years. This indicates a warning time of 1–2 h ahead, allowing enough time for authorities to make arrangements and initiate evacuation of the vulnerable population. The second level, "Immediate evacuation," is triggered by a rainfall event that is expected once every ten years. This level provides an early warning with a lead time of 30–60 min, giving authorities time to efficiently execute evacuation plans. Such a two-fold strategy gives enough time to prepare and evacuate vulnerable populations, thereby reducing the risk of loss of life and the occurrence of disaster [31].

3.4.2. Early Warning Indicator Results and Differentiated Characteristics

Table 5 shows the critical rainfall warning indicators for the key areas, from which we can observe some interesting features and trends. The time-period effect is very pronounced, with greater rainfall needed for warnings as the time period increases. For instance, the rainfall required for "immediate evacuation" over 24 h is 2.2–2.5 times more than that over 1 h. For instance, in the Qiujiazai Group of Xieqiaohe, the rainfall required for immediate evacuation over 24 h was 174 mm, 2.5 times that required for immediate evacuation over 1 h (69 mm). This is based on the fact that the longer the rainfall duration, the higher the rainfall accumulation, and hence the more serious the flood risks, which is a common feature of mountain rainstorms [32].

Another aspect is the differentiation of risk. The early warning levels for high-risk areas are much higher than those for low-risk areas. For example, the rainfall threshold for immediate evacuation (within 1 h) in the high-risk Xieqiaohe Qiujiazai Group is 69 mm, 1.7 times that of the low-risk Longtian Group of Longtianhe (41 mm). This is a good example of the "high risk, high threshold" principle, ensuring the early warning system is properly set up to reflect different flood risks [33].

The water level-based early warning system is also very useful in areas where rainfall observation may not be adequate [34]. The disaster-causing water level and its corresponding flow are clearly defined. At Sanzhai River's Xiaohaha Commercial City, for instance, the disaster-causing water level is 310.8 m, which is equivalent to a flow of 165 m^3/s. This flow can be used as a threshold for monitoring water levels, and can compensate for the lack of rainfall data to ensure the effectiveness of early warning systems in areas where rainfall information is not readily available. **Table 5** shows the specific rainfall values for various warning levels in different regions, and the critical water level for each location, as well as the corresponding flow rate that would lead to a disaster-causing water level.

Table 5. Critical Rainfall Warning Indicators and Corresponding Disaster-Causing Water Levels for Key Areas.

Area	Warning Level	1 h (mm)	3 h (mm)	6 h (mm)	12 h (mm)	24 h (mm)	Disaster-Causing Water Levels (m)	Disaster-Causing Traffic (m^3/s)
Qiujiazhai Group, Xieqiaohe	Preparing to transfer	58	83	108	119	145	253.1	803
	Transfer immediately	69	100	130	143	174	-	-
Sanzhaihe Xiaohaha Commercial City	Preparing to transfer	49	70	91	98	118	310.8	165
	Transfer immediately	59	85	109	118	142	-	-
Longtian River Longtian Group	Preparing to transfer	34	48	62	63	74	301.3	36
	Transfer immediately	41	58	74	76	89	-	-
Longxihe Gaolouping Township	Preparing to transfer	42	64	69	73	92	754.8	51
	Transfer immediately	51	77	83	88	111	-	-

4. Conclusions and Outlook

This article synthesizes the current understanding of the interactions between eco-regulation, industrial integration, and high-quality development in the Yellow River Basin (YRB). Rather than functioning independently, eco-regulation and industrial integration operate as interdependent processes that jointly shape green transformation, industrial upgrading, regional coordination, and ecological sustainability. The literature indicates that appropriately designed eco-regulatory policies can stimulate technological innovation, cleaner production, and industrial restructuring, while industrial integration can enhance resource efficiency and regional collaboration. However, these positive outcomes remain highly dependent on regional development conditions, governance capacity, institutional coordination, and ecological constraints, resulting in considerable heterogeneity across the upstream, midstream, and downstream regions of the basin.

Despite the rapid growth of research in this field, several important limitations remain. First, much of the existing evidence is based on cross-sectional or correlational analyses, limiting the ability to establish causal relationships between eco-regulation, industrial integration, and development outcomes. Second, considerable variation exists in the indicators and evaluation systems used to measure eco-regulation, industrial integration, and high-quality development, reducing the comparability of findings across studies. Third, many empirical investigations focus on individual provinces, sectors, or policy instruments, while relatively few adopt a basin-wide perspective capable of capturing cross-regional spillover effects and governance interactions. Moreover, the dynamic feedback mechanisms among environmental regulation, industrial transformation, and regional development remain insufficiently explored, particularly under changing policy and climate conditions.

Future research should therefore move beyond descriptive assessments toward more rigorous and integrated analytical approaches. Greater attention should be devoted to longitudinal and quasi-experimental research designs that strengthen causal inference, as well as multi-scale spatial analyses capable of capturing regional heterogeneity and interregional spillover effects. Developing standardized evaluation frameworks for eco-regulation, industrial integration, and high-quality development would also improve the comparability and robustness of future studies. In addition, emerging data sources, including remote sensing, digital governance platforms, and big-data analytics, offer new opportunities to monitor environmental performance and industrial transformation more accurately. Future studies should further investigate how differentiated policy instruments, ecological compensation mechanisms, and cross-provincial governance arrangements can be coordinated to promote balanced and sustainable development throughout the Yellow River Basin.

Overall, achieving high-quality development in the

Yellow River Basin requires not only stronger environmental regulation or deeper industrial integration in isolation, but also a coordinated governance framework that aligns ecological protection with industrial transformation while accounting for regional diversity and long-term sustainability. Continued interdisciplinary research integrating environmental science, economics, geography, and public policy will be essential for supporting evidence-based decision-making and advancing sustainable development in the basin.

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