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Stormwater Runoff Allocation and Basin-Wide Flood Mitigation Mechanism From the Perspectives of Efficiency and Equity

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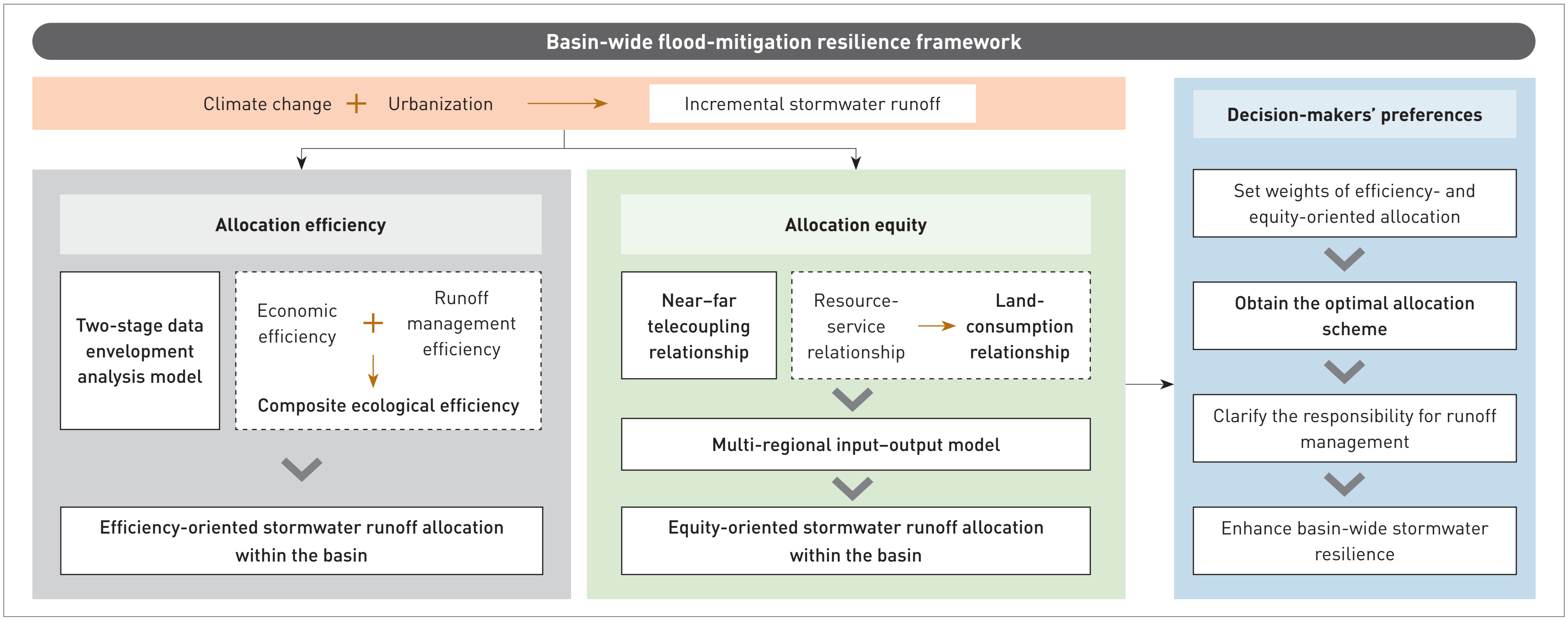
GRAPHICAL ABSTRACT



ABSTRACT

Watershed flood management requires a systematic assessment of disaster-related risks and the application of resilience-oriented design to reduce exposure and vulnerability. However, how to enhance basin resilience by integrating land use planning for stormwater regulation, while balancing the interests of upstream, midstream, and downstream regions, remains a key challenge. To address this issue, this study constructs a basin-wide flood-mitigation resilience framework considering allocation efficiency and equity. First, a two-stage data envelopment analysis model is established to evaluate the economic efficiency and runoff management efficiency, forming an efficiency-oriented stormwater allocation method. Second, near–far telecoupling relationships are identified and a multi-regional input–output model is used to examine regional development imbalances, thereby developing an equity-oriented method. Finally, the allocation proportions are adjusted according to decision-makers' preferences. The results show that: 1) under the efficiency-oriented scheme, the upstream region is required to undertake 88.80% of stormwater runoff; 2) under the equity-oriented scheme, the downstream bears 78.25% of the rainstorm runoff; and 3) when the decision makers' preference is set to 0.2 (i.e., indicating greater emphasis on equity), inter-regional allocation disparities within the basin are minimized. This study responses to the challenges of spatial runoff allocation and cross-regional compensation, providing a practical and instructive approach for improving basin-wide flood-mitigation resilience.

KEYWORDS

Flood Mitigation Resilience; Runoff Allocation; Stormwater Management; Efficiency; Equity; Basin-Wide Framework

HIGHLIGHTS

- Develops a basin-wide flood-mitigation resilience framework that incorporates efficiency and equity
- Clarifies the runoff compensation mechanism, enhancing the basin's overall flood prevention resilience
- Addresses key technical challenges of spatial runoff allocation in water–land integrated basin planning

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1 Introduction

In recent years, rapid urbanization has led to a sharp increase in the amount of impervious surfaces. Meanwhile, climate change has further intensified the severity of stormwater runoff in terms of its magnitude, intensity, and frequency[1], resulting in an annual increase in flood disasters triggered by typhoons and heavy rainfall worldwide. As the impacts of stormwater runoff on cities and basins become more pronounced, enhancing the resilience of these systems to future environmental challenges has become ever more critical[2–3]. With the growing recognition of the resilience concept, the Rockefeller Foundation launched the "100 Resilient Cities" initiative[4], while Europe and the USA subsequently advanced the notion of "Planning for Resilient Cities and Regions"[5], aiming to strengthen cities' adaptive capacity to acute shocks and chronic stresses[6]. Accordingly, resilient city building and basin-wide risk management urgently require systemic approaches to assessing disaster risks, coupled with design-oriented measures to reduce disaster exposure and lower the vulnerability of both cities and basins.

The flood risk induced by changes in stormwater runoff is characterized by significant uncertainty. Despite substantial investment, the structural efficiency and environmental impacts of traditional flood control projects are increasingly questioned. For example, the elevation of upstream levees may generate negative externalities for downstream areas. Since disaster losses often become apparent only ex post, controlling risks at the source has become a crucial pathway for reducing potential losses[7].

At present, basin governance is shifting toward a resilience-oriented paradigm that emphasizes the coordination between hydraulic engineering and spatial planning. International practice in this field has exhibited multi-dimensional innovations. For example, the USA has adopted low impact development (LID) techniques to replace conventional pipe networks with small-scale water treatment facilities[8]; Australia promotes water sensitive urban design (WSUD) to integrate urban water–land systems and to optimize flood detention[9]; the sponge city program in Chinese mainland focuses on multi-scale stormwater management[10] and the "runoff sharing–outflow control" strategy in Taiwan, China regulates land development and reserve flood storage space[11]. Although these policy frameworks have established a dual framework compromising macro-scale total runoff control and micro-scale construction codes, two major gaps remain at the meso-scale within the cross-subcatchment runoff allocation mechanism[12]: first, the lack of operational criteria to address distributive equity issues arising from unbalanced regional development; and second, the insufficient use of land-use planning to effectively balance disaster-prevention needs with development rights. In response to these challenges, an incremental stormwater runoff allocation mechanism can be established to realize in-situ risk control. By clearly defining runoff quotas for each subarea and setting up a compensation scheme for stormwater runoff management, this mechanism can provide quantitative guidance for engineering measures such as the construction of flood detention basins, thereby enhancing disaster-prevention resilience across the entire basin. Among these tasks, accurately determining the runoff quota for each subarea is not only a prerequisite for implementing stormwater management measures, but also a critical foundation for constructing a systemic flood control regime.

The core of establishing an incremental stormwater runoff allocation mechanism lies in integrating spatial planning and water resource management concepts to develop a resilience-oriented, water–land integrated risk prevention and control model. However, commonly applied approaches to water–land integrated runoff allocation still face several limitations. For example, the cost–benefit analysis (CBA) method is highly subjective in evaluation, requires the unification of indicator dimensions, and has difficulty in specifying concrete allocation schemes[13]. Hydrological–hydrodynamic modelling methods are mainly employed to simulate the spatial distribution of stormwater runoff and to reveal rainfall–runoff processes and flood routing characteristics in river channels, but they overlook economic and social factors, which may lead to inequitable runoff allocation and insufficient incentives for governance[14]. By contrast, the data envelopment analysis (DEA) method overcomes the shortcomings of CBA and can serve as an alternative tool to evaluate the efficiency of water–land integrated runoff allocation; the near–far coupling approach helps clarify land-use transformation relationships among different areas within a basin, thereby explaining inequities in stormwater runoff allocation; meanwhile, multi-regional input–output (MRIO) models can further quantify the coupling between urbanization and the ecological environment, providing a quantitative basis for runoff allocation[15–16].

Ideally, stormwater runoff should be allocated by identifying its underlying causes and then assigning flow volumes to the corresponding areas. However, its allocation and the assignment of governance responsibilities within a basin are often shaped by spatially uneven development, e.g., excessive urbanization in the middle and lower reaches heightens the demand for ecosystem services provided by upstream areas. Consequently, trade-offs between efficiency and equity are difficult to avoid in the allocation process[17]. Given the complexity of basin governance, allocation approaches that emphasize only one aspect are overly reductive and hard to effectively balance the interests of all subareas across the entire basin.

Thus, this study aims to construct a basin-wide flood-mitigation resilience framework with quantifiable flood-mitigation targets by integrating allocation efficiency and equity considerations and incorporating decision-makers' preferences in adjusting allocation ratios. This framework addresses the issues of allocation and compensation in basin-wide flood mitigation.

2 Allocation Efficiency and Equity

Over the long term, economic development has relied heavily on intensive ecological resource inputs, which has not only placed tremendous pressure on resource supply but also caused severe environmental degradation. Existing studies have attempted to apply ecological efficiency to measure the degree of coordination between economic development and environmental protection, thereby alleviating the conflict between human development and the environment[18]. This study seeks to employ the DEA model for calculating ecological efficiency to explore uneven development within the basin[19]. Then, it takes the results as the basis for allocating stormwater runoff, aiming to enhance the basin's regulatory resilience to floods. Related research has applied DEA to integrate the economic and environmental governance dimensions of ecological efficiency. Specifically, economic efficiency refers to the economic output generated per unit of resource input in economic activities (e.g., land use, economic resource allocation) of a basin; whereas environmental governance efficiency denotes the effectiveness of environmental governance per unit of environmental resource consumption (e.g., occupation of ecological space, increase in runoff volume)[20–21]. Building on this approach, this study takes the economic production and runoff governance efficiency of a basin as the basis for runoff allocation (Fig. 1), according to factors such as land-use patterns, current economic conditions, expected runoff increments, and disaster losses in upstream and downstream sub-catchments. Areas exhibiting lower efficiency imply that resources have not been fully utilized and therefore possess greater potential to undertake flood-mitigation responsibilities.

However, allocation schemes based solely on efficiency tend to overlook distributive inequities arising from spatially uneven development. To achieve allocation equity, it is first necessary

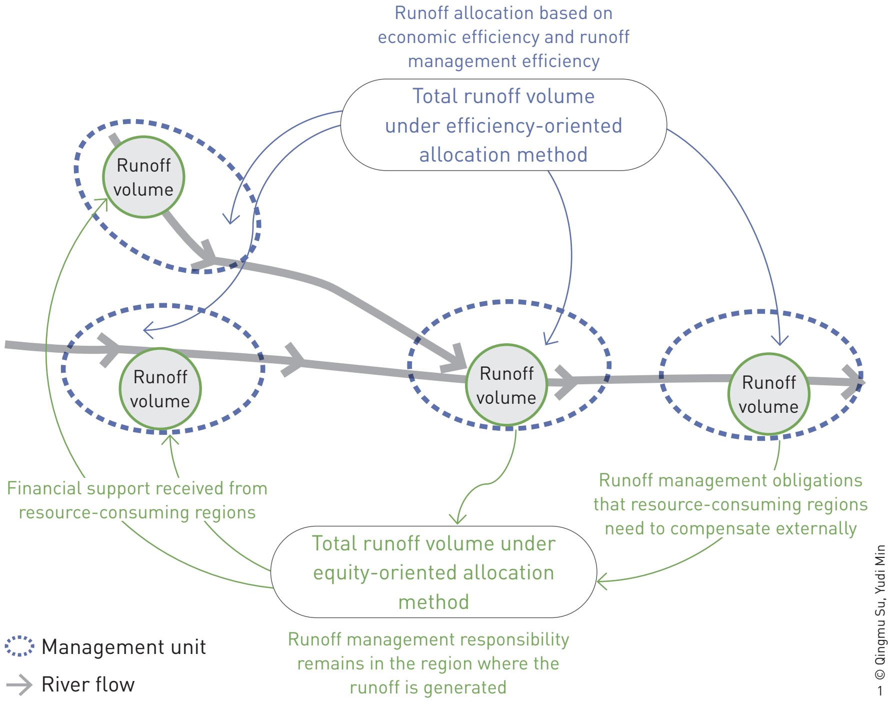


Fig. 1 Schematic diagram of the allocation efficiency and equity of stormwater runoff.

to clarify the mechanisms through which various elements within the basin interact with and to identify the root causes of inequity[15]. For instance, the middle and lower reaches depend on upstream areas for the supply of water, food, forest products, and other resources, while upstream areas, by obtaining industrial goods and daily necessities produced in the middle and lower reaches, can alleviate the pressure on the exploitation of their own resources[16]. Accordingly, this study employs MRIO–based telecoupling relationships to capture the direct and indirect environmental impacts induced by land resource consumption embedded in production processes[22]. This uncovers intra-basin development imbalances and provides a basis for stormwater runoff allocation (Fig. 1). Under this equity-oriented allocation approach, the governance responsibility for stormwater runoff will not shift away from its area of generation: resource-consuming areas are required to compensate resource-supplying areas, so as to balance development needs and, in turn, promote equity in basin governance.

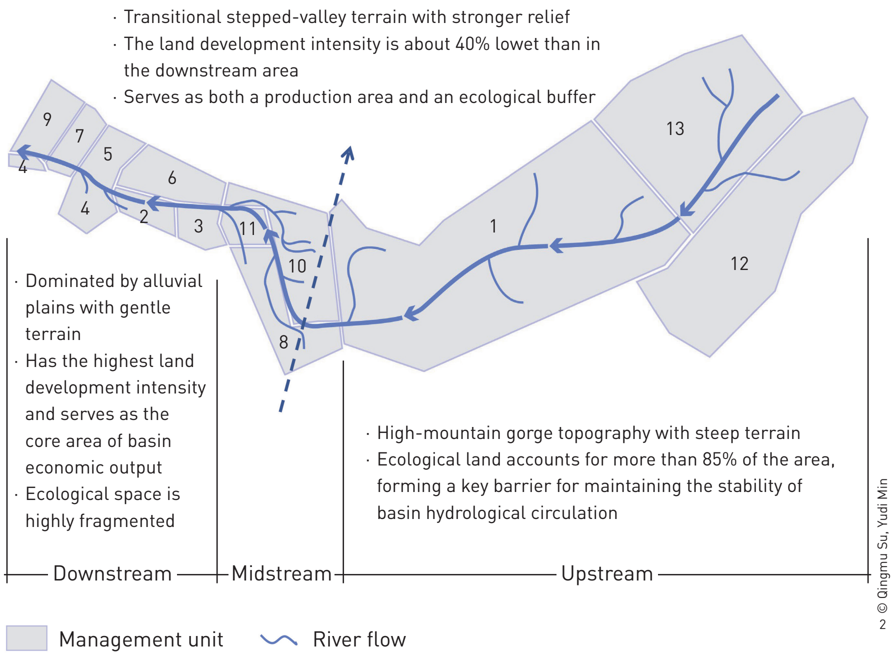
Overall, the efficiency-oriented allocation approach distributes runoff according to the actual efficiency of economic production and runoff management in each region, resulting in a shift of treatment responsibility away from the locations where the runoff is generated. In contrast, the equity-oriented allocation approach enables runoff to be handled locally through a compensation mechanism, without shifting the management responsibility away from the generating location.

3 Methodology

3.1 Study Area and Data Sources

According to the *Comprehensive Governance Master Plan for the Dajia River Basin*, the Dajia River Basin is located in the central–western part of Taiwan, China, with a drainage area of 1,244 km^2 and a main channel length of 124 km. Land development is primarily concentrated in the middle and lower reaches. The basin has an average channel gradient of 1/60 and is classified as a steep, high-energy river. The Dajia River Basin passes through 13 management units and, based on geographical conditions and governance boundaries, can be divided into upstream, midstream, and downstream (Fig. 2). The data used in this study were derived from the following sources: 1) temperature and precipitation data for 2018 obtained from the CODiS climate observation data inquiry service; 2) land use data for 2008 and 2018 taken from the Current Land Use Survey of Taiwan, China ; 3) records of flood disaster losses compiled from the *White Paper on Disaster Prevention and Protection* (2015–2019); and 4) other socio-economic indicators (i.e., labor force, energy use, changes in investment, GDP, and governance financial inputs) extracted from the 2018 Statistical Bulletin of each unit.

Fig. 2 Reaches of the study area.



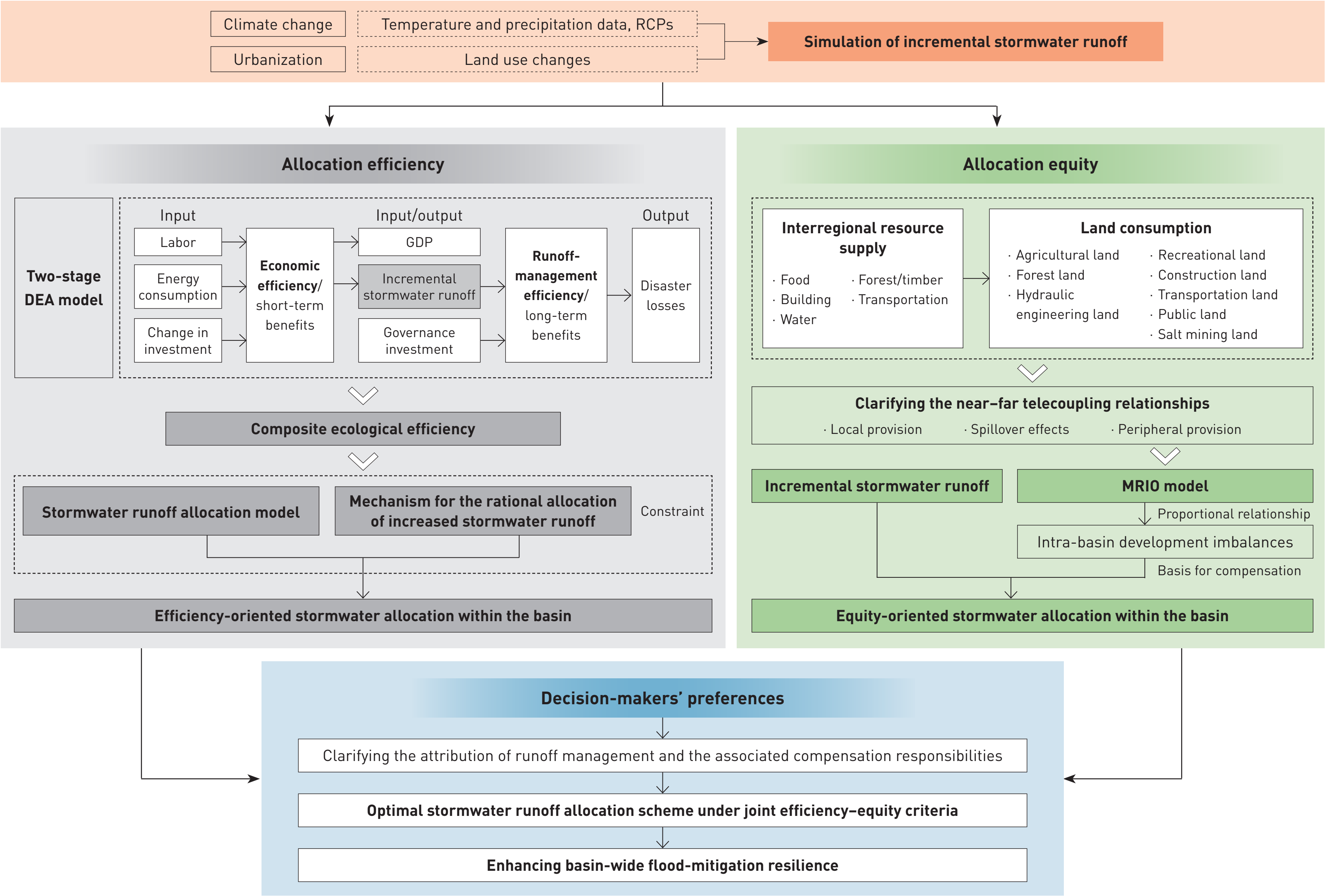
3.2 Research Framework

To address flood risk prevention and control in water–land integrated basin planning, this study develops a basin-wide flood-mitigation resilience framework that jointly considers efficiency and equity (Fig. 3). The framework consists of three main components: 1) incremental stormwater runoff simulation, 2) allocation efficiency and fairness, and 3) decision-makers' preferences.

For incremental stormwater runoff simulation, temperature and precipitation data were first processed using a downscaling method (to a grid resolution of 5 km) in conjunction with different Representative Concentration Pathways (RCPs) proposed by the Intergovernmental Panel on Climate Change (IPCC), to obtain temperature and precipitation projections for the next 200 years. Second, by comparing land use changes between 2008 and 2018, the incremental stormwater runoff induced by urbanization was estimated. Subsequently, the combined incremental stormwater runoff resulting from both climate change and urbanization was used as the basis for the subsequent model analysis.

In terms of allocation efficiency and equity, an improved two-stage DEA model was first employed to link the basin's economic efficiency with its runoff management efficiency to derive a composite ecological efficiency. On this basis, an efficiency-oriented stormwater runoff allocation model was constructed, and its results

Fig. 3 Basin-wide flood-mitigation resilience framework.



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were used to allocate the reduction in stormwater runoff. Then, after identifying near- and far-distance coupling relationships, the MRIO model was applied for quantitative analysis to obtain multi-regional inequity in ecological space. The land consumption patterns of each analytical unit generated from the MRIO analysis served as the compensation basis for promoting allocation equity.

Finally, drawing on the results of allocation efficiency and equity, the study weighed the runoff allocation volumes derived from different orientations from the perspective of decision-makers' preferences, and treated the resulting trade-offs as decision references. By further integrating the two sets of allocation results, the study clarified the attribution of runoff-management responsibilities and the associated compensation relationships, thereby informing an optimal allocation scheme for stormwater runoff that enhances regional flood-mitigation resilience.

3.3 Research Methods

3.3.1 Efficiency-Oriented Allocation Method

3.3.1.1 Two-Stage DEA Model

DEA model evaluates the relative efficiency among multiple decision-making units (DMUs), which in this study refer to the management units, under multiple inputs and outputs. This method has the advantage of being free from subjective weighting, is unaffected by correlations or multicollinearity among input and output variables. It is therefore suitable for comprehensive indicator evaluation and efficiency comparisons across decision-making units[23]. In this study, the two-stage DEA model (Fig. 3) was implemented and solved using Lingo software.

In this two-stage DEA model, the first-stage economic-efficiency subsystem and the second-stage runoff management efficiency subsystem were each specified with their own sets of input and output indicators. The incremental stormwater runoff outputted in the first stage was taken as an input indicator in the second stage. The weight assigned to this intermediate unexpected output (i.e., the incremental stormwater runoff) is kept consistent across the two stages. Imposing a unified set of weights established an internal connection within the model, preventing the overall system efficiency from being decoupled from the efficiencies of the individual subsystems. Since the economic-efficiency subsystem constitutes a prerequisite for the whole model, its efficiency scores must be held constant when solving the runoff management-efficiency subsystem, and are incorporated as constraints in the latter. The output indicators in the second stage were used to measure flood-related losses, and the corresponding efficiency scores were negatively related to resilience: when the DEA-derived efficiency value is higher, the losses increase, reflecting relatively poorer runoff management performance; conversely, when the efficiency value is lower, disaster losses decrease, indicating that the DUM exhibits stronger resilience. In the two-stage DEA efficiency analysis, this study, for the first time, introduced a division model (see supplementary material for the detailed equations).

3.3.1.2 Stormwater Runoff Allocation

Building on the two-stage DEA model, this study developed a dynamic allocation mechanism under which the temporal linkage of production technology parameters (i.e., technical parameters related to resource conversion capacity and production processes) is explicitly specified, and the first-stage technology parameters are used to characterize the efficiency frontier of the second stage[24]. Within the flood-resource allocation framework, this study assumed that the adjustment capacity of each management unit can only be adjusted through proportional scaling of its existing production level. Under the condition that unexpected inputs are freely disposable, a bi-objective optimization model was constructed: Objective 1 was to maximize desirable outputs (i.e., GDP growth, control of disaster losses), and Objective 2 was to minimize input variables (i.e., resource input, governance cost). The constraints included: 1) a total-balance constraint that ensured the full allocation of the total amount of flood reduction; and 2) unit-level equity constraints that prevented excessive allocation to specific units. A stepwise solution strategy was adopted, whereby the efficiency threshold associated with Objective 1 was achieved first, followed by the optimization of Objective 2. In this way, a resilience-oriented allocation scheme for each basin subregion was quantitatively derived (see supplementary material for the equation).

3.3.2 Equity-Oriented Allocation Method

3.3.2.1 Near–Far Coupling

Based on the resource services provided by land, this study constructed near–far coupling relationships (Fig. 4) and converted these resource-service linkages into land-consumption relationships[25]. Near coupling refers to the consumption of various land resources within a management unit by its built-up areas; far coupling denotes the situation that when a management unit's land supply cannot meet local demand, it must obtain resource services from other units within the basin; and spillover effect describes cases where certain management units possess sufficient supplies of various resources and, beyond satisfying their own development needs, are able to export resources to external systems. Drawing

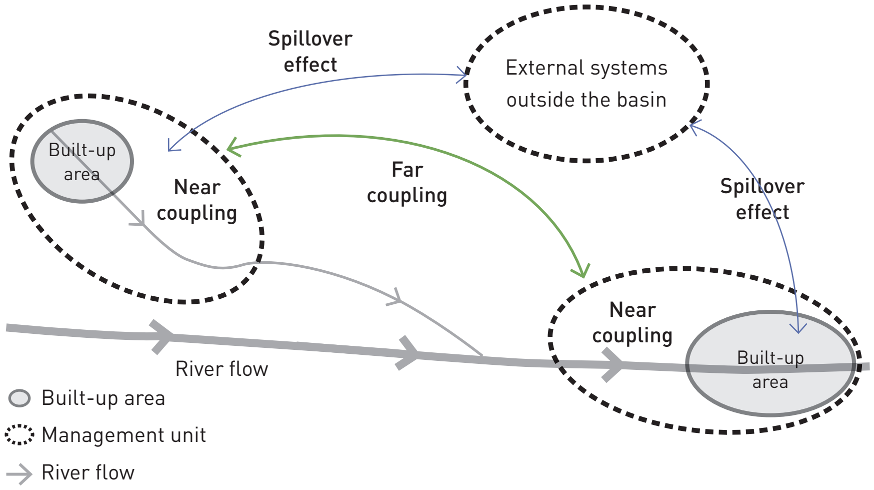

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Fig. 4 The near–far coupling relationship within the basin.

on the per capita land use conditions in Taiwan, China, this study estimated the land consumption status of each management unit within the Dajia River Basin.

3.3.2.2 MRIO Model

On the basis of clarifying land-consumption relationships within the basin, this study employed the MRIO model for quantitative analysis. The MRIO model can capture the economic interdependencies among sectors and regions[26], and the main advantage lies in its ability to trace the direct and indirect environmental impacts caused by the final consumption of goods and services. The specific formulation is given in Eq. (1):

$$\Delta L = \sum_{r \neq s} L^{rs} - \sum_{r \neq s} L^{sr}, \tag{1}$$

where $\sum_{r \neq s} L^{rs}$ denotes the amount of land required in region r to satisfy the consumption of other regions, i.e., the outflow, and $\sum_{r \neq s} L^{sr}$ denotes the inflow. When $\triangle L > 0$, region r is characterized by a net outflow of land resources, meaning that it must provide services for other regions and bear the transferred stormwater runoff burden. Conversely, when $\triangle L < 0$, region r experiences a net inflow of land resources, indicating that it depends on other regions to support its development and should therefore assume compensatory responsibilities toward those regions. In this way, the MRIO model clarifies the runoff management responsibilities of each management unit (including both local runoff and the portion associated with external compensation), which are not reallocated among management units. This helps reduce the downstream flood management pressure and supports the enhancement of basin-wide flood-mitigation resilience under the equity-oriented allocation scheme.

3.3.3 Allocation Method Incorporating Decision-Makers' Preferences

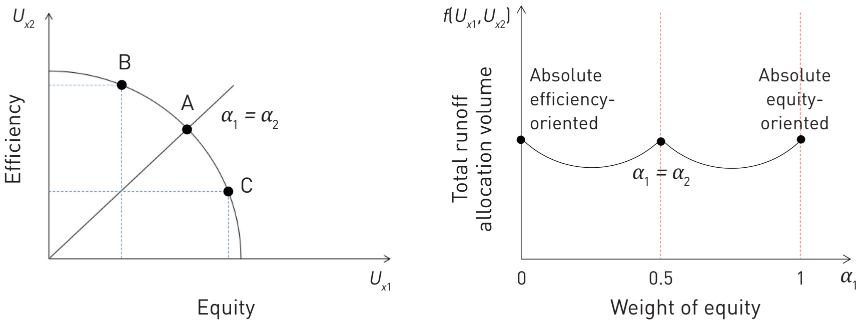
Efficiency-oriented allocation generally places greater emphasis on market-based mechanisms, whereas equity-oriented allocation reflects a stronger role of government intervention. To balance the two, this study constructed an allocation model from the perspective of decision-makers' preferences. The overall runoff allocation in the Dajia River Basin is expressed as follows:

$$f(U_{x1}, U_{x2}) = \sum(\alpha_1 U_{x1} + \alpha_2 U_{x2}), \quad x = 1,2,\ldots,n, \tag{2}$$

where α_1 and α_2 represent the weights assigned to allocation equity and allocation efficiency, respectively, with α_2 also serving as the decision-makers' preference parameter in this study, while U_{x1} and U_{x2} denote the allocation volumes derived from the equity-oriented and efficiency-oriented methods, respectively.

On the left-hand side of Fig. 5 is the utility function of decision-makers' preferences, where α_1/α_2 represents the slope of the utility curve. When $\alpha_1 < \alpha_2$ (e.g., Point B), allocation efficiency dominates; in this case, the allocation outcome may promote the development of a given region at the expense of others, thereby leading to inequitable allocation. When $\alpha_1 > \alpha_2$ (e.g., Point C), the government strengthens equity in runoff allocation, but this may come at the cost of overall basin development and result in reduced efficiency. When $\alpha_1 = \alpha_2$ (i.e., Point A), allocation efficiency and allocation equity are considered equally important. In addition, the closer the allocation point lies to $\alpha_1 = 0.5$, the smaller the divergence in runoff allocation. By adopting different settings of decision-makers' preferences, effective technical support can be provided for constructing resilient basins and cities.

Fig. 5 The utility function of decision-makers' preferences (left) and runoff allocation results under different decision-makers' preferences (right).



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4 Empirical Analysis

4.1 Quantifying Incremental Stormwater Runoff

Drawing on existing research[15], this study employed the TCCIP-AR5 model developed by the Disaster Prevention and Protection Technology Center in Taiwan, China to simulate the mean daily precipitation over the next 200 years (baseline year 2018) under different development scenarios, including RCP2.6 (mitigation scenario), RCP4.5 and RCP6.0 (stabilization scenarios), and RCP8.5 (high-emission scenario), to obtain the mean change in stormwater runoff. Subsequently, based on land use changes between 2008 and 2018, the incremental stormwater runoff induced by urbanization is further calculated[28]. The calculation is given by:

$$Q = (A_1 - A_2) \times q \times (55\% - 10\%)\ , \tag{3}$$

where Q denotes the total increase in stormwater runoff, A_1 and A_2 represent the imperviousness before and after land use change, respectively, and q denotes the runoff volume per hectare of land under natural conditions. The simulated results of incremental stormwater runoff (Table 1) show that climate change is the dominant factor driving its increase. Among the upstream areas, Unit 1, Unit 12, and Unit 13 exhibit the largest increments, whereas the midstream and downstream areas of Unit 2 and Unit 11 show relatively slighter increases. If the runoff generated in the upstream areas is not effectively managed, it is likely to concentrate in the middle and lower reaches along topographic gradients, thereby exacerbating the overall difficulty of runoff management.

Table 1: Rainstorm runoff increments across management units

Unit No.	Stormwater runoff increment		
	Increment due to climate change (10^4 m^3)	Increment due to urbanization (10^4 m^3)	Total increment (10^4 m^3)
1	2,493.7	−211.3	2,282.4
2	86.3	−14.7	71.6
3	105.3	−3.4	101.9
4	187.1	−54.1	133.0
5	115.7	2.4	118.1
6	159.6	−2.5	157.1
7	170.1	16.7	186.8
8	258.9	−0.1	258.8
9	96.6	51.8	148.4
10	328.9	−6.5	322.4
11	58.2	−1.0	57.2
12	2,950.5	−79.4	2,871.1
13	1,722.8	60.7	1,783.5

NOTE
For details of the calculation procedure, see Ref. [15].

4.2 Equity-Oriented Runoff Allocation and Compensation Mechanism

Based on the near–far coupling and MRIO analysis (Tables 2, 3), this study finds that the total land-service outflow provided by the Dajia River Basin to external systems amounts to 246,504 hm^2. Under the equity-oriented allocation assumption, the proportional shares of runoff management responsibility differ across river sections: the upstream region undertakes only 1.39%, the midstream region 4.88%, while the downstream region bears the highest share, reaching 23.44%. Overall, the Dajia River Basin functions as a net provider of land services to external systems; accordingly, external systems should compensate 70.29% of the incremental runoff, with this portion to be coordinated by the higher-level or central governments. The remaining share is allocated within the basin according to each management unit’s local responsibility and its proportion of land inflows.

4.3 Efficiency-Oriented Runoff Allocation

The DEA efficiency analysis (Table 4) shows that the mean economic efficiency is 0.890, indicating relatively high resource utilization efficiency within the basin. The mean runoff management efficiency is relatively low at 0.61, implying a low overall natural disaster risk and a comparatively safe state in the basin. The average values of composite ecological efficiency in the midstream and downstream regions are markedly higher than that in the upstream region, exhibiting an overall pattern of “midstream > downstream > upstream.” Assuming that 29.7% of the incremental stormwater runoff needs to be allocated in the second stage of the DEA model (based on the preceding equity-oriented analysis), Unit 12 bears the largest share of runoff treatment, followed by Unit 1 and Unit 13. These results indicate that the management units differ in terms of economic efficiency,

Table 2: The runoff volume across management units under the equity-oriented allocation method

Unit No.	Change in land area (hm^2)	Total runoff generated locally (10^4 m^3)	Local responsibility (10^4 m^3)	Internal exchange ratio	Intra-basin runoff management compensation (10^4 m^3)	External-system Runoff management compensation (10^4 m^3)
1	−95,413	2,383.4	40.1	—	0	2,343.3
2	6,468	96.8	96.8	2.23%	159.8	0
3	20,603	104.9	104.9	7.12%	509.2	0
4	6,272	201.5	201.5	2.17%	155.0	0
5	691	119.7	119.7	0.24%	17.1	0
6	2,695	163.4	163.4	0.93%	66.6	0
7	5,787	175.1	175.1	1.99%	142.4	0
8	−4,298	257.4	117.7	—	0	139.7
9	−107	123.1	118.7	—	0	4.5
10	−2,789	321.7	233.9	—	0	87.9
11	535	57.5	57.5	0.18%	13.2	0
12	−113,730	2,905.3	58.6	—	0	2,846.7
13	−73,218	1,754.6	21.4	—	0	1,733.2
Total	−246,504	8,664.4	1,509.3	14.9%	—	—

Table 3: The runoff volume shared by upstream, midstream, downstream, and the external system under the equity-oriented method

Region	Shared runoff volume (10^4 m^3)	Total runoff management share	Intra-basin share
External system	5,838.4	70.29%	—
Upstream	118.1	1.39%	4.75%
Midstream	422.9	4.88%	17.00%
Downstream	1,946.7	23.44%	78.25%

runoff management efficiency, and composite ecological efficiency, and therefore exhibit heterogeneous capacities in stormwater-runoff allocation.

From the perspective of the stormwater runoff allocation results (Table 5), there are pronounced differences in runoff management shares among the regions. The upstream region undertakes the primary management tasks, whereas the downstream region receives the smallest allocation. The main reason is that the upstream region exhibits a relatively higher efficiency value of the DEA stage 2 and greater disaster losses, indicating low performance in runoff management and more residual runoff. Consequently, it shows a higher potential for flood mitigation. Meanwhile, the incremental stormwater runoff is predominantly concentrated in the upstream region, making it the key zone for absorbing and regulating runoff.

4.4 Decision-Makers' Preferences

According to the analysis results (Table 6), the upstream region bears the majority of the efficiency-oriented share of stormwater

Table 4: DEA efficiency analysis results and the reduction of runoff across management units

Unit No.	Economic efficiency (DEA stage 1)	Runoff management efficiency (DEA stage 2)	Composite ecological efficiency (overall DEA efficiency)	stormwater runoff reduction (10^4 m^3)
1	0.981	0.1390	7.077	913.0
2	0.848	0.0311	27.640	7.2
3	0.873	1.0000	0.873	10.2
4	0.814	0.0276	29.153	13.3
5	0.800	0.0643	12.566	11.8
6	0.823	0.0201	40.960	20.5
7	0.715	0.0402	17.864	18.7
8	1.000	0.0579	17.121	103.5
9	0.824	0.0528	15.584	59.4
10	1.000	0.1121	8.938	32.2
11	0.999	0.0243	41.102	5.7
12	0.893	0.0003	2,762.823	1,148.4
13	1.000	0.5278	1.895	178.3
Average	0.890	0.1613	229.507	194.0

Table 5: The runoff volume shared by upstream, midstream, downstream, and the external system under the efficiency-oriented method

Region	Shared runoff volume (10^4 m^3)	Total runoff management share	Intra-basin share
External system	2,092.7	30.17%	—
Upstream	2,239.7	32.29%	88.80%
Midstream	141.5	22.16%	5.61%
Downstream	141.0	15.38%	5.59%

runoff, whereas the downstream region bears the majority of the equity-oriented share. The marked differences between these two allocation methods across upstream and downstream regions indicate that focusing on a single objective is insufficient for balancing the interests of all management units within the basin. As shown in Fig. 6, when the decision-makers' preference parameter α_2 ranges from 0.2 to 0.3 (i.e., when equity is given greater emphasis), the allocation disparities among management units are minimized, enabling overall optimal allocation for the entire basin. At the same time, aside from a slight decline in the standard deviation when α_2 lies between 0.1 and 0.2, the standard deviation increases with the rising weight on allocation efficiency in all other cases, implying that an excessive emphasis on efficiency exacerbates intra-basin inequity. Specifically, as α_2 increases, the runoff volume undertaken by Unit 1 and Unit 12 rises markedly, whereas that of Unit 3 and Unit 4 correspondingly decreases. Therefore, decision-makers need to flexibly adjust their strategies in light of the basin's actual development needs and the interests of different stakeholders. For example, under periods of high flood risk, efficiency-oriented allocation should be prioritized to rapidly mitigate flood peaks; during phases where ecological protection is prioritized, emphasizing equity-oriented allocation is more appropriate to safeguard upstream ecosystems.

Table 6: Efficiency- and equity-oriented runoff allocations of upstream, midstream, and downstream

Region	Efficiency-oriented		Equity-oriented		Difference (10^4 m^3)
	Allocation volume (10^4 m^3)	Share	Allocation volume (10^4 m^3)	Share	
Upstream	2,239.7	88.80%	118.1	4.75%	2,121.6
Midstream	141.5	5.61%	422.9	17.00%	−281.4
Downstream	141.0	5.59%	1,946.7	78.25%	−1,805.7

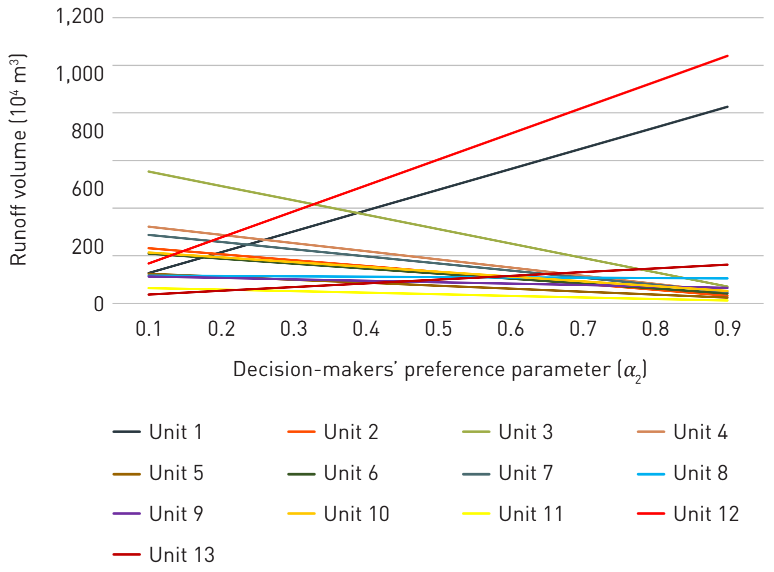

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Fig. 6 Runoff allocation among management units under different decision-makers' preferences (α_2).

5 Conclusions and Prospects

Enhancing flood-mitigation resilience is an important strategy for coping with flood risk; at its core, it aims to balance disaster-prevention capacity across regions and promote sustainable development through systematic planning and optimized allocation. Integrating the perspectives of allocation efficiency and equity, this study develops a basin-wide flood-mitigation resilience framework, to address the problem of allocating incremental stormwater runoff among upstream, midstream, and downstream regions. The framework not only clarifies runoff compensation mechanisms, but also provides an operational and quantitative basis for flood risk management, thereby contributing to the formation of more adaptive and sustainable resilience-oriented models for urban and basin governance. Considering both the efficiency and equity, this study proposes a total runoff volume control and optimized allocation method for future stormwater risk prevention. This method fills the gap in the quantitative allocation of runoff at the meso-scale and provides important support for subsequent floodplain zoning, the design of conveyance capacity for flood-control infrastructures, and the allocation of stormwater management responsibilities across various land use zones.

The conclusions are as follows: 1) Under different allocation methods, the allocation of stormwater runoff increment varies. Under the efficiency-oriented scheme, the upstream region is required to undertake 88.80% of the incremental runoff, whereas under the equity-oriented scheme, the upstream region only needs to undertake 1.39% of the total runoff volume. 2) When the decision-makers' preference parameter is set to 0.2, the standard deviation within the basin is minimized, indicating the smallest inter-regional development disparity. Overall, basin hydrological processes are complex and dynamic, and urbanization introduces additional uncertainties into the allocation of stormwater runoff. Governments and relevant institutions should strengthen the regulation of stormwater-runoff management and enhance the coordination of spatial planning. These measures play a crucial role in improving urban resilience and the capacity to cope with flooding.

The following areas could be explored in future research. First, while this study has addressed the equity issue of "who should compensate," it has not yet resolved the operational issue of "how this should be done." Follow-up research could establish a compensation negotiation mechanism among management units based on natural basin units, and translate the quantified ecological responsibility of the MRIO model into actionable fiscal transfer payments or ecological credit quotas. Second, although this study quantifies runoff allocation at the meso-scale, a substantial gap remains between this and the precise estimation of the volume to be managed. Future work could develop a dynamic resilience-based allocation model that couples climate change scenarios with land use evolution forecasts, thereby enhancing the accuracy and forward-looking nature of runoff allocation schemes. Third, subsequent research may also explore pathways for stormwater utilization. Through engineering measures such as flood detention wetlands and groundwater recharge, runoff could be converted into usable water resources, thereby improving the marginal benefits of management interventions.

ELECTRONIC SUPPLEMENTARY MATERIAL

Supplementary material is available in the online version of this article at https://doi.org/10.15302/J-LAF-0-020043.

Competing interests | The authors declare that they have no competing interests.

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效率与公平视角下流域雨洪径流分配与整体减洪机制

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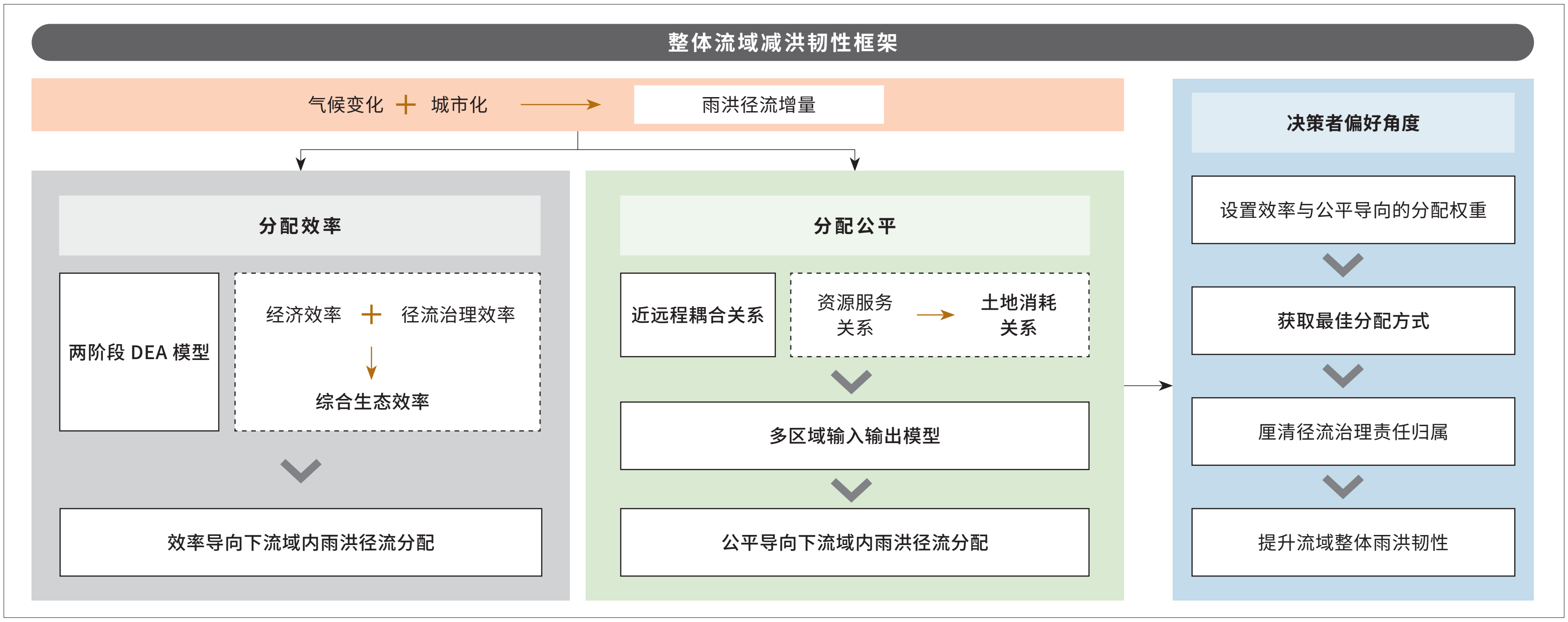
图文摘要



摘要

流域洪灾管理需要通过系统性风险评估与韧性设计手段，以降低灾害暴露度和脆弱性。然而，如何借助土地规划增强流域雨洪调控韧性，并统筹协调上游、中游和下游地区之间的权益，仍是当前亟待突破的关键问题。为此，本研究构建了一个兼顾分配效率与公平的流域整体减洪韧性分析框架。首先，采用两阶段数据包络分析模型评估流域经济效率和径流治理效率，构建效率导向的雨洪分配方法；随后，通过识别近远程耦合关系，以多区域输入输出模型分析地区发展不平衡情况，建立公平导向的雨洪分配方法；最后，结合决策者偏好调整分配比例。研究结果表明：1）在效率导向下，上游地区需要承担88.80%的雨洪径流；2）在公平导向下，下游地区需承担78.25%的雨洪径流；3）当决策者偏好为0.2时（即更加注重公平分配），流域内各区域间发展差异最小。本研究回应了流域雨洪径流的空间分配与跨区域补偿问题，为提升整体流域减洪韧性水平提供了具有指导意义的方法参考。

关键词

减洪韧性；径流分配；雨洪管理；效率；公平；整体流域框架

文章亮点

- 构建了一个兼顾效率与公平的流域整体减洪韧性框架
- 厘清了径流治理补偿机制，提升流域整体防洪韧性
- 回应了流域水土整合规划中空间径流分配的关键问题

基金项目

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- 福建省自然科学基金青创项目“基于水土整合概念推动城市耐洪规划研究”（编号：2025J08224）
- 福建省自然资源科技创新项目“基于地域分异的福建省耕地边缘空间低干预景观营建技术与可持续运维机制研究”（编号：KY-030000-04-2025-045）

编辑 高雨婷，马锡栋

1 引言

近年来，城市化进程导致不透水表面大幅增加，气候变化进一步加剧了雨洪在数量、强度和频率上的极端化趋势[1]，致使全球因台风和暴雨引发的洪涝灾害逐年增多。由于雨洪对城市和流域的影响日益显著，提升城市与流域的韧性以应对未来环境挑战变得愈发重要[2–3]。随着韧性理念的普及，洛克菲勒基金会发起了“100个韧性城市”运动[4]，部分欧美国家也相继提出“规划韧性城市和地区”的概念[5]，以增强城市在应对急性冲击与长期压力时的适应能力[6]。因此，韧性城市建设和流域风险管理亟需采用系统性方法评估灾害相关风险，并结合设计手段减少灾害暴露度、降低城市与流域的脆弱性。

雨洪径流变化引发的洪水风险具有显著不确定性。尽管投入巨大，传统防洪工程的结构效率及环境影响正面临双重质疑，例如上游堤防加高可能对下游带来负面外部效应。由于灾害损失往往在事后才显现，从源头控制风险成为减少潜在损失的关键路径[7]。

当前，流域治理正转向水利工程与空间规划协同的韧性治理范式。相关国际实践呈现多维创新：例如，美国采用低影响开发技术，以小型水处理设施替代传统管网[8]；澳大利亚通过水敏性城市设计实现城市水土整合与蓄洪优化[9]；中国大陆的海绵城市聚焦多尺度雨洪管理[10]，中国台湾则推行“径流分担－出流管制”策略，规范土地开发并设置滞洪空间[11]。既有政策虽构建了宏观尺度总量管制与微观尺度建筑规范的二元框架，但在中观尺度上，跨集水区径流分配机制仍存在双重缺口[12]。一方面，缺乏具备可操作性准则应对区域发展失衡带来的分配公平问题；另一方面，尚未通过土地规划有效平衡防灾需求与开发权益。面对上述挑战，可建立雨洪径流增量分配机制以实现风险就地管控，即通过明确各分区径流配额并设立雨洪治理补偿机制，为设置蓄洪池等工程措施提供量化依据，从而推动全流域防灾韧性的提升。其中，精准核定各分区径流配额，既是落实雨洪管理措施的先决条件，也是构建系统化防洪体系的重要基础。

建立雨洪径流增量分配机制的核心在于融合空间规划和水资源管理理念，形成水土整合的风险防控韧性模式。目前常用的水土整合径流分配方法仍存在一定局限：如成本效益分析法评价主观性强、指标需统一量纲，且难以明确具体分配方式[13]；水文水动力模拟法主要用于模拟雨洪空间分布，揭示降雨－径流过程与河道洪水传播特征，但忽略了经济、社会等影响因素，易导致雨洪分配不公和治理积极性不足等问题[14]。相比之下，数据包络分析（data envelopment analysis，DEA）方法克服了成本效益分析法的缺点，可作为衡量水土整合径流分配效率的替代方法；近远距耦合方法有助于梳理流域内不同区域的土地利用转化关系，进而解释雨洪径流分配不公现象；同时，多区域输入输出（multi-regional input-output，MRIO）模型可进一步量化城市化与生态环境的耦合关系，为径流分配提供量化基础[15–16]。

理想状态下，雨洪径流分配应通过识别其成因，将流量分配至相应区域。然而，流域内雨洪径流的分配和治理责任归属往往受空间发展不平衡的影响，比如中下游地区过度城市化会提高对上游生态服务的需求。因此，在分配过程中难以避免效率与公平之间的权衡[17]。鉴于流域治理的复杂性，仅侧重某一方面的分配方法过于片面，难以统筹兼顾全流域各区域利益。

综上，本研究旨在从效率与公平角度出发，结合决策者偏好调整分配比例，构建可量化减洪目标的流域整体减洪韧性框架，以回应流域减洪分配和补偿的问题。

2 分配效率与分配公平

长期以来，经济发展主要依赖生态资源的高投入，这不仅对资源供给造成极大压力，也对环境造成了严重破坏。既有研究尝试应用生态效率来衡量经济发展与环境保护之间的协调程度，以缓解人类发展与环境之间的冲突[18]。本研究尝试借助DEA模型计算生态效率以探索流域空间发展不平衡的现象[19]，并将其结果作为雨洪径流分配的依据，以增加流域在面对洪水时的调节韧性。相关研究应用DEA将生态效率的经济和环境治理两方面加以整合。其中，经济效率指流域在土地利用、经济资源配置等经济活动中，单位资源投入所对应的经济产出效益；环境治理效率则指单位环境资源消耗（如生态空间占用、径流量增加）所对应的环境治理效能[20–21]。基于该方法，本研究根据上下游子汇水区城市发展的土地利用、经济现状、预期径流增量与灾损程度等情况，将流域经济生产和径流治理的效率作为径流分配的依据（图1）。效率较低的地区意味着资源未得到充分利用，因此在承担减洪任务方面具有更大潜力。

然而，仅依据效率进行分配往往忽视了地区发展不平衡带来的分配不公。为实现分配公平，首先需要厘清流域系统内各类要素的影响机制，识别分配不公的根源[15]。例如，中下游地区依赖上游提供的水、粮食、森林等资源，上游地区也通过获取中下游所生产的工业产品和生活用品，减轻了对自身资源的开发压力[16]。故本研究通过分析多区域输入输出遥相关关系，捕获由生产过程背后的土地资源消耗所引发的直接和间接环境影响[22]，从而揭示流域内部的发展不均衡问题，并以此作为雨洪径流分配的依据（图1）。在公平导向的分配方法中，雨洪径流的治理责任相较于其产生区位未发生位移，资源消耗区应对资源供给区予以补偿，以平衡发展需求，进而促进流域治理的公平性。

综上，效率导向的分配方法依据各地区经济生产和径流治理的实际效率进行径流分配，径流的治理责任相较于其产生区位发生转移；而公平导向的分配方法则通过补偿机制，实现径流就近处理，径流的治理责任相较于其产生的区位不发生转移。

3 方法论

3.1 研究区域与资料来源

据《大甲溪流域整体治理纲要计划》显示，大甲溪流域位处中国台湾中西部，面积1 244 km^2，干流全长124 km，土地开发主要集中于中下游地区。该流域平均坡降为1/60，属急流河川。大甲溪流域共流经13个管理单元，依据地理条件和治理界点可划分为上、中、下游（图2）。本研究使用的数据来源如下：1）2018年气温和降雨数据来自CODiS气候观测资料查询服务；2）2008年和2018年土地利用数据来源于中国台湾国土利用现状调查；3）洪涝灾害损失资料参考《灾害防救白皮书》（2015—2019年）相关记录；4）其他社会经济指标（劳动力、能源使用、投资变化、GDP、治理资金投入）则取自流域内各单元2018年的统计公报。

3.2 研究框架

为应对流域水土整合规划中的洪灾风险防控问题，本研究构建了一个兼顾分配效率与公平的流域整体减洪韧性框架（图3）。该框架主要包括雨洪径流增量模拟、分配效率与分配公平、决策者偏好三部分。

在雨洪径流增量模拟部分，首先基于气温和降雨数据，应用降尺度方法（尺度降为5 km网格精度），结合联合国政府间气候变化专门委员会不同的排放途径（Representative Concentration Pathway，RCP）进行分析，以获得未来200年内的气温和降雨数据。其次，通过对比2008年和2018年土地利用类型变化，推估城市化所带来的雨洪径流增量。随后，将气候变化和城市化共同产生的雨洪径流增量作为后续模型分析的基础。

在分配效率与分配公平部分，首先采用改进的两阶段DEA模型，将流域的经济效率和径流治理效率关联，得出综合生态效率。其次，研究据此构建效率导向的雨洪径流分配模型，并以其结果进行雨洪减量分配。随后，在识别近远程耦合关系的基础上，利用MRIO模型进行量化分析，获取多区域生态空间不平等关系，并以MRIO模型分析所得各分析单元的土地消耗情况作为推动分配公平的补偿依据。

最后，根据分配效率与分配公平的分析结果，研究从决策者偏好角度权衡不同导向下的径流分配量，并将不同权衡结果作为决策参考。在此基础上，综合两类分配结果，厘清径流治理归属与补偿关系，从而得出雨洪径流的最佳分配方式，以增强整体地区减洪韧性水平。

3.3 研究方法

3.3.1 效率导向的分配方法

3.3.1.1 两阶段DEA模型

DEA是一种用于评价多个投入与多个产出的决策单元（本研究指各管理单元）之间相对效率的模型。该方法具有非主观加权的优点，不受投入项与产出项之间相关性或多重共线性的影响，适用于综合指标评估，便于进行决策单位间的效率比较[23]。本研究使用Lingo软件对两阶段DEA模型（图3）进行编程运算。

在该两阶段DEA模型中，第一阶段的经济效率子系统和第二阶段径流治理效率子系统分别设有各自的输出与输入指标。第一阶段输出的雨洪径流增量将被作为第二阶段的输入指标。这中间不期望产出的数量（即雨洪径流增量）与第二阶段的输入需求相匹配，其权重在两阶段保持一致。通过设置统一的权重集，在模型内部建立关联，从而避免系统整体效率独立于各子系统的效率。由于经济效率子系统是整个模型的先

决条件，在求解径流治理效率子系统时，需保持经济效率的效率值不变，并将其作为该子系统约束条件。第二阶段的输出指标用于衡量洪水灾害造成的损失，其效率值与韧性呈反向关系：当DEA输出的效率值较高时，损失程度相应增加，反映雨洪治理效益相对较差；而当效率值较低时，损失减少，表明决策单元具有更强的韧性。在两阶段DEA效率分析中，本研究首次引入了除法模型（公式见补充资料）。

3.3.1.2 雨洪径流分配

基于两阶段DEA模型，本研究构建了一套动态分配机制，其方法包括设定生产技术参数（指资源转化能力与生产流程相关技术参数）的时序关联，和采用第一阶段技术参数表征第二阶段的效率边界[24]。本研究在洪水资源分配框架下，假设各管理单元只能基于其当前生产能力按比例调整产出水平，并在允许非期望输入自由分配的条件下，构建了一个双重目标优化模型：目标一为期望输出最大化（即GDP增长、灾害损失控制）、目标二为输入变量最小化（即资源投入、治理成本）。约束条件包括：1）通过总量平衡约束确保雨洪削减总量完全分配；2）通过单元公平约束防止特定单元的超量分配。研究采用分阶段求解策略，在优先实现目标一的效率阈值后，再对目标二进行优化，最终量化各流域分区的韧性分配方案（公式见补充材料）。

3.3.2 公平导向的分配方法

3.3.2.1 近远程耦合

本研究以土地所提供的资源服务为基础，构建了近远程耦合关系（图4），并将资源服务关系转化为土地消耗关系[25]。其中，近程耦合指建成区对所在管理单元内各类土地资源的消耗；远程耦合指当某管理单元的土地供给无法满足自身需求时，需向流域其他单元索取资源服务；外溢效应则指某些管理单元的各类资源供给充足，除满足自身发展外，还可向外部系统输出资源。本研究根据中国台湾的人均土地利用情况，推算大甲溪流域内各管理单元的土地消耗状况。

3.3.2.2 MRIO模型

在厘清流域内土地消耗关系基础上，本研究采用MRIO模型进行定量分析。MRIO模型能够反映不同部门与地区之间的经济依存关系[26]，其主要优点在于可追踪由最终消费商品和服务造成的直接和间接环境影响。具体公式如下：

$$\Delta L=\sum_{r\neq s}L^{rs}-\sum_{r\neq s}L^{sr}\ , \qquad (1)$$

$\sum_{r\neq s}L^{rs}$表示区域r为满足其他区域消费所需的土地量，即流出量，$\sum_{r\neq s}L^{sr}$表示流入量。当$\triangle L>0$时，表示区域r存在土地资源净流出，即需为其他区域提供服务，并承担被转移的雨洪径流负担；而当$\triangle L<0$时，则表明区域r存在土地净流入，即需依赖其他区域支持发展，因而应承担对相关区域的补偿责任。由此，利用MRIO模型明确的各管理单元径流治理责任（包括本地与对外补偿部分）不在各管理单元之间转移，这不仅有助于缓解下游洪水治理压力，也促进了流域整体在公平导向下的减洪韧性提升。

3.3.3 决策者偏好角度的分配方法

效率导向的分配通常更注重市场分配，而公平导向的分配则体现政府干预的作用。为权衡两者关系，本研究从决策者偏好角度建立了分配模型[27]。大甲溪流域整体径流分配如下：

$$f(U_{x1},U_{x2})=\sum(\alpha_1U_{x1}+\alpha_2U_{x2}),\quad x=1,2,\dots,n\ , \qquad (2)$$

式中，α_1和α_2分别表示分配公平与分配效率的权重，其中α_2亦指代本文中的决策者偏好，U_{x1}和U_{x2}和分别代表基于公平与效率方法的分配量。

图5左侧是决策者偏好的效用函数，α_1/α_2为效用曲线的斜率，当$\alpha_1<\alpha_2$时（如B点），分配效率占主导，该分配结果可能通过牺牲其他区域利益以促进本区域发展，从而导致分配不公。当$\alpha_1>\alpha_2$时（如C点），政府在径流分配中强化了公平导向，但可能以牺牲流域发展为代价，并导致效率下降。当$\alpha_1=\alpha_2$（即A点）时，表示分配效率和分配公平具有同等重要性。此外，当分配点越靠近$\alpha_1=0.5$的位置，径流分配的分歧就越小。选择不同的决策者偏好角度，可为构建韧性流域与城市提供有效的技术支撑。

4 实证研究

4.1 量化雨洪径流增量

本研究参照既有研究[15]，采用中国台湾灾害防救科技中心开发的TCCIP-AR5模型，模拟了未来200年（基准年2018）在不同发展情景下的平均日降水量，包括RCP2.6（减缓情景）、RCP4.5和RCP6（稳定情景），以及RCP8.5（高度排放情景），以获取平均雨洪径流变化量。随后，基于2008年和2018年土地利用类型的变化，进一步计算城市化所带来的雨洪径流增量[28]。其计算公式为：

$$Q=(A_1-A_2)\times q\times(55\%-10\%)\ , \qquad (3)$$

其中，Q代表雨水径流总体增加量，A_1和A_2分别表示土地变化前后的不透水率，q代表自然情况下每公顷土地的径流量。雨洪径流增量模拟结果（表1）显示，气候变化是影响其增量的主要因素。其中，上游的单元1、单元12和单元13增量最大，而中下游的单元2和单元11增量相对较

表 1：各管理单元雨洪径流增量

单元编号	雨洪径流增量		
	气候变化增量（10^4 m^3）	城市化增量（10^4 m^3）	总增量（10^4 m^3）
1	2 493.7	− 211.3	2 282.4
2	86.3	− 14.7	71.6
3	105.3	− 3.4	101.9
4	187.1	− 54.1	133.0
5	115.7	2.4	118.1
6	159.6	− 2.5	157.1
7	170.1	16.7	186.8
8	258.9	− 0.1	258.8
9	96.6	51.8	148.4
10	328.9	− 6.5	322.4
11	58.2	− 1.0	57.2
12	2 950.5	− 79.4	2 871.1
13	1 722.8	60.7	1 783.5

注

具体计算过程参考文献[15]。

表 2：公平导向的分配方法下各管理单元的径流治理分配量

单元编号	土地变化量（hm^2）	本地径流总量（10^4 m^3）	本地责任（10^4 m^3）	内部交换比例	流域内径流治理补偿量（10^4 m^3）	外部系统径流治理补偿量（10^4 m^3）
1	− 95 413	2 383.4	40.1	—	0	2 343.3
2	6 468	96.8	96.8	2.23%	159.8	0
3	20 603	104.9	104.9	7.12%	509.2	0
4	6 272	201.5	201.5	2.17%	155.0	0
5	691	119.7	119.7	0.24%	17.1	0
6	2 695	163.4	163.4	0.93%	66.6	0
7	5 787	175.1	175.1	1.99%	142.4	0
8	− 4 298	257.4	117.7	—	0	139.7
9	− 107	123.1	118.7	—	0	4.5
10	− 2 789	321.7	233.9	—	0	87.9
11	535	57.5	57.5	0.18%	13.2	0
12	− 113 730	2 905.3	58.6	—	0	2 846.7
13	− 73 218	1 754.6	21.4	—	0	1 733.2
总计	− 246 504	8 664.4	1 509.3	14.9%	—	—

表3：公平导向的上游、中游、下游及外部系统的径流分担量

区域	径流分担量（10^4 m^3）	整体径流治理分担比例	流域内分担比例
外部系统	5 838.4	70.29%	—
上游	118.1	1.39%	4.75%
中游	422.9	4.88%	17.00%
下游	1 946.7	23.44%	78.25%

少。若对上游缺乏有效管理，它们产生的径流或将沿地形变化汇集至中下游，从而加剧整体径流治理难度。

4.2 公平导向的径流分配与补偿机制

基于近远程耦合与MRIO分析（表2，3），本研究发现大甲溪流域对外部提供的土地服务总计流出246 504 hm^2。在公平导向的分配假设下，流域内各段所承担的径流处理量比例存在差异：上游地区仅承担1.39%，中游地区为4.88%，下游承担比例最高，达23.44%。总体而言，大甲溪流域整体为外部系统提供土地服务，因此外部系统需补偿其70.29%的径流增量，具体可由上级或中央政府统筹安排；余下部分则依据各管理单元的本地责任和土地流入比例在流域内部分配。

4.3 效率导向的径流分配

DEA效率分析结果（表4）显示，经济效率平均值为0.890，表明流域资源利用效率较高；径流治理效率平均值为0.161，处于较低水平，可见流域整体自然灾害风险较低，处于较安全水平。中游和下游的平均综合生态效率明显高于上游，整体呈现“中游＞下游＞上游”的特征。假

表 4：各管理单元 DEA 效率分析结果和雨洪径流减少量

单元编号	经济效率（DEA 第一阶段）	径流治理效率（DEA第二阶段）	综合生态效率（DEA 总效率）	雨洪径流削减量（$10^4\ \mathrm{m}^3$）
1	0.981	0.1390	7.077	913.0
2	0.848	0.0311	27.640	7.2
3	0.873	1.0000	0.873	10.2
4	0.814	0.0276	29.153	13.3
5	0.800	0.0643	12.566	11.8
6	0.823	0.0201	40.960	20.5
7	0.715	0.0402	17.864	18.7
8	1.000	0.0579	17.121	103.5
9	0.824	0.0528	15.584	59.4
10	1.000	0.1121	8.938	32.2
11	0.999	0.0243	41.102	5.7
12	0.893	0.0003	2 762.823	1 148.4
13	1.000	0.5278	1.895	178.3
平均值	0.890	0.1613	229.507	194.0

设DEA第二阶段需分配29.7%的雨洪径流的增量（依据前述公平分析结果），单元12的雨洪径流处理量最高，其次为单元1和单元13。结果表明，各管理单元在经济效率、径流治理效率及综合生态效率方面存在差异，因而具有不同的雨洪径流分配能力。

表5：效率导向的上游、中游和下游及外部系统的径流分担量

区域	径流分担量（$10^4\ \mathrm{m}^3$）	整体径流治理分担比例	流域内分担比例
外部系统	2 092.7	30.17%	—
上游	2 239.7	32.29%	88.80%
中游	141.5	22.16%	5.61%
下游	141.0	15.38%	5.59%

从雨洪径流分配结果来看（表5），上游、中游和下游在径流分担比例上差异显著，上游承担主要任务，下游分配比例最小。主要原因在于，上游DEA第二阶段输出效率值较高、灾害损失较大，即对雨洪径流的处理效果较低，导致更多雨洪剩余，因此表现出更高的减洪潜力。同时，雨洪径流增量主要集中于上游地区，使其成为消纳径流的关键区域。

4.4 决策者偏好角度

根据分析结果（表6），效率导向的雨洪径流分担量主要由上游承担，而公平导向的分担量则主要落在下游。两种分配模式在上下游之间差异显著，表明仅考虑单一目标难以实现流域内各管理单元的利益平衡。由图6可知，当决策者偏好为0.2～0.3时（即更注重公平导向），各管理单元之间的分配差异最小，可实现全流域整体分配最优。同时，除α_2在0.1～0.2区间标准差略有下降外，其余情况下标准差随分配效率权重上升而增加，说明过度强调效率会加剧流域内部不平等。具体来看，单元1和单元12在α_2增大时分担的径流量明显增加，而单元3和单元4则相应减少。因此，决策者需根据流域发展的实际需求与各方利益诉求灵活调整策略：如在洪水高风险时期，应优先考虑效率导向，以快速消减洪峰；在生态保护优先阶段，则宜侧重公平导向，以维护上游生态系统安全。

表6：上游、中游和下游地区在效率导向与公平导向下的径流分配差异

流域	效率导向		公平导向		差值（$10^4\ \mathrm{m}^3$）
	分配量（$10^4\ \mathrm{m}^3$）	占比	分配量（$10^4\ \mathrm{m}^3$）	占比	
上游	2 239.7	88.80%	118.1	4.75%	2 121.6
中游	141.5	5.61%	422.9	17.00%	−281.4
下游	141.0	5.59%	1 946.7	78.25%	−1 805.7

5 结论与展望

提升减洪韧性是应对洪灾风险的重要策略，其核心在于通过系统化规划与分配优化，实现区域间防灾能力平衡与可持续发展。本研究融合分配效率与公平视角，构建了面向流域整体发展的减洪韧性框架，以解决上、中、下游雨洪径流增量分配的问题。该框架不仅明确了径流补偿机制，也为洪灾风险管理提供了可操作的量化依据，有助于形成更具适应性和可持续性的韧性城市与流域管理模式。从兼顾效率与公平的视角出发，本研究提出了面向未来雨洪灾害防控的径流总量控制与优化分配方法。该方法弥补了中观尺度径流分配量化的空白，可为后续洪泛区划分、防洪设施通洪能力设计，以及基于土地分区的治理责任划分提供重要支撑。

具体结论包括：1）在不同分配导向下，雨洪径流增量分配差异较大。效率导向下，上游地区需承担88.80%的雨洪径流；而在公平导向下，上游只需分担1.39%的径流总量；2）当决策者偏好取值为0.2时，流域内标准差最低，即区域间发展差异最小。总的来说，流域水文过程具有复杂性和动态性，城市化发展也为雨洪径流分配带来更多不确定性。政府及相关机构应加强对雨洪径流治理的管控与空间规划统筹，这些措施对提升城市韧性与洪灾应对能力具有重要作用。

未来研究可进一步拓展以下方向：1）本研究验证了“谁补偿”的公平性问题，但尚未解决“如何补偿”的操作性问题，后续研究可建立基于自然流域单元的跨管理单元补偿协商机制，将MRIO模型测算的生态责任量转化为可操作的财政转移支付或生态信用额度；2）本研究在中观尺度上估算了径流分配量，但与精准核算治理径流量仍存在较大差距，后续研究可开发动态韧性分配模型，耦合气候变化情景与土地利用演变预测，增强径流分配方案的准确性和前瞻性；3）后续研究还可探索雨洪资源化路径，通过滞洪湿地、地下水回灌等工程措施，将径流转化为可利用水资源，从而提升治理措施的边际效益。

补充材料

可通过https://doi.org/10.15302/J-LAF-0-020043查看本文补充材料。

图 1. 雨洪径流分配效率与分配公平的示意图
图 2. 研究区域图示
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