Computational Methods for Comprehensive Evaluation of Development Quality in the Yellow River Basin

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Abstract

This study adopts a systems thinking perspective, utilizing information entropy and dissipative structure theory to compute the Basin Development Index (BDI), and preliminarily establishes a scientific comprehensive assessment methodology system for watershed development quality, thereby conducting a comprehensive evaluation and analysis of the evolution of the Yellow River Basin complex system over the past four decades. Entropy weight analysis of the indicators reveals that the ratio of basin per capita GDP to the national average and the total sediment accumulation in the lower Yellow River have consistently occupied the highest weights, exerting relatively substantial influence on basin development across different historical periods. Throughout the 40-year period, BDI values ranged from 50.5 points in 1996 to 66.6 points in 2019, following an overall trajectory of initial decline followed by subsequent increase. The evolution pattern of the Yellow River Basin' s BDI corresponds with the basin' s overall development trajectory and demonstrates significant correlation with major events impacting basin development. This research methodology is generalizable to domains such as regional governance; compared with evaluation models predominantly based on economic indicators, this approach exhibits greater systematicity and scientific rigor, thereby better serving scientific decision-making.

Full Text

Research on Calculation Method for Comprehensive Evaluation of Development Quality of the Yellow River Basin

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Abstract

From a systematic thinking perspective, this study employs information entropy and dissipative structure theory to comprehensively evaluate and analyze the evolution of the Yellow River Basin' s complex system over the past 40 years. By introducing the concept of "Basin Development Index (BDI)," a preliminary scientific framework for comprehensive assessment of basin development quality has been established. Entropy weight analysis of indicators reveals that the ratio of per capita GDP in the basin to the national average and the total sedimentation volume in the lower Yellow River have consistently held the greatest weight, exerting relatively significant influence on basin development across different historical periods. Over the entire 40-year period, BDI values have ranged from 50.5 points in 1996 to 66.6 points in 2019, following a general trend of initial decline followed by subsequent increase. The evolution pattern of the Yellow River Basin' s BDI aligns with the basin' s overall development trajectory and demonstrates substantial correlation with major events affecting basin development. This methodology can be extended to regional governance and other domains. Compared with evaluation models primarily based on economic indicators, this approach offers greater systematicity and scientific rigor, thereby providing more robust support for scientific decision-making.

Keywords: Information Entropy; Dissipative Structure; Complex System; Systematic Governance; Yellow River Basin; Basin Development Index; High-quality Development

1 Overview of Basin Development Quality Assessment Methods

Historically, the Yellow River has experienced frequent flooding disasters. From Yu the Great' s flood diversion to Pan Jixun' s sediment flushing strategy, and into modern river management, Yellow River governance has focused primarily on flood control and disaster mitigation, with evaluation of management effectiveness based mainly on disaster frequency and loss assessment [?, ?]. Since the implementation of comprehensive Yellow River management, large-scale protection efforts have been undertaken under the strategies of "upstream detention and downstream discharge with flood diversion on both banks" for flood control and "detention, regulation, discharge, release, and excavation"for comprehensive sediment management. Traditional approaches have primarily utilized measured data analysis, mathematical modeling, and physical model experiments, evaluating protection effectiveness from limited perspectives such as flood control and sediment reduction using a restricted set of indicators. Currently, Yellow River governance is transitioning from traditional flood control-centered management toward comprehensive and systematic management.

From a systematic perspective, the Yellow River Basin constitutes a complex giant system within which river dynamics, socio-economics, and ecological environment continuously interact and compete, waxing and waning throughout the evolution process. Evidently, conventional methods employing limited indicators from flood control or sediment reduction perspectives cannot comprehensively or systematically assess overall basin development quality. Some scholars have attempted to evaluate Yellow River governance from a systems theory perspective. For instance, Huang Yanfen et al. [**?**] conducted qualitative analysis of the Yellow River Basin governance status, drawing inspiration from collaborative governance in the Rhine River Basin. Liu Jianhua et al. [**?**] quantitatively assessed the coordination between ecological protection and high-quality development in the Yellow River Basin using a "single-indicator quantification–multi-indicator synthesis–multi-criteria integration" approach. Peng Xiang [**?**] proposed qualitative recommendations for systematic governance approaches, emphasizing the importance of water-sediment relationships and water resource utilization. Xu Guobin [**?**] and Ai Nanshan et al. [**?**] analyzed Yellow River channel evolution using entropy theory and dissipative structure theory. Chang Jianxia et al. [**?**] employed dissipative structure and entropy theories to determine the evolution direction of water resource complex systems. Overall, these studies remain predominantly qualitative with limited evaluation dimensions, failing to encompass the complete spectrum of river dynamics, socio-economics, and ecological environment.

Entropy theory is considered one of the greatest discoveries of the 20th century, with applications across diverse systems in various fields. As an important branch of complexity science, dissipative structure theory represents a new stage in system science development, providing a solid theoretical foundation for numerous interdisciplinary studies [**?**]. In many complex problem investigations, entropy theory and dissipative structure theory are often applied comprehensively and discussed simultaneously. To scientifically assess basin development status and evolution trends and support basin management and protection decision-making, this study integrates thermodynamic entropy, information entropy, and dissipative structure theory to systematically analyze the development and evolution patterns of the Yellow River Basin system over the past 40 years, establishing a comprehensive evaluation index system and methodology for basin development quality that provides scientifically complete decision-making tools for systematic basin governance and high-quality development.

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2 Methodology

2.1 Overall Approach

The Yellow River represents a complex giant system whose development quality can be defined and evaluated from multiple perspectives. This study considers the river’ s natural, social, and ecological attributes, employing information entropy and dissipative structure theory to conduct comprehensive evaluation of basin development quality. The specific approach involves: first establishing a comprehensive evaluation index system for basin development quality; then calculating information entropy for different evaluation indicators using possibility functions; and finally conducting comprehensive evaluation of basin development status using dissipative structure theory to propose the Basin Development Index. The overall research framework is illustrated in Figure 1 [Figure 1: see original paper].

2.2 Basin Evaluation Framework Based on Development State Analysis

Within the basin giant system, countless evolution processes at different levels and scales occur continuously. To enable macro-level quantification and analysis, this study employs mathematical induction to categorize all internal evolution processes into two types—positive entropy change and negative entropy change [?]. These two categories exhibit complex synergy and competition, jointly influencing the development trajectory and state changes of the giant system. Based on the definition of the Yellow River Basin complex giant system and the established basin development quality index evaluation system, all indicators are classified into positive and negative entropy change categories, serving as the foundation for dissipative structure state analysis.

2.3 Information Entropy Calculation Method for the Evaluation Index System

To quantitatively analyze positive and negative entropy effects within the system, it is necessary to calculate the information entropy evolution of each indicator. Evaluation indicator data represent numerical values with uncertain information, also known as gray numbers. According to gray system theory [?], possibility functions can describe the “likelihood” of indicators falling within different numerical ranges, fully extracting information contained in indicator values. In this study, based on national standards, technical specifications, internationally recognized criteria, and latest findings from similar research, each indicator’ s development quality is classified into four grades—excellent, good, medium, and poor—with corresponding thresholds established. Based on these standard intervals, possibility functions can be calculated to quantify the development status of each factor indicator. This study employs an improved version of the typical possibility function—the exponential possibility function [?]. Due to space limitations, computational details of the function are not elaborated herein; the possibility function is denoted as f_k in subsequent sections.

The information entropy calculation method based on possibility functions has been widely applied across multiple fields. Hu Hanmei et al. [?] introduced information entropy and entropy weight method into traditional gray clustering analysis, constructing trapezoidal whitening functions to analyze and identify transformer fault types. Liu Li [?] similarly incorporated information entropy into gray clustering, constructing typical exponential whitening weight functions to eliminate the "zero weight" problem in traditional gray clustering and establishing a flood disaster identification method based on gray information entropy clustering. Yang Tengteng [?] evaluated listed company performance using entropy method and whitening weight function clustering analysis, overcoming the absolute ranking limitation of traditional evaluation methods and obtaining a comprehensive evaluation approach based on objective information. In this study, information entropy values based on possibility functions are calculated using the following formulas:

$$11(ln)lnnkkkSppn == -$$

$$1kkniifpf ==$$

In formulas (1) and (2), n represents the number of indicator value standard intervals, and p_k represents the proportion of each standard possibility function value among all values. It is evident that when values are relatively large or small and deviate from the central standard region, the possibility function values corresponding to several indicator grades evolve toward greater concentration, directly leading to decreased entropy values. Based on this observation and considering the beneficial nature of entropy reduction for the system, combined with the property of indicators being either "larger-is-better" or "larger-is-worse," this study proposes a new information entropy calculation method that modifies the entropy calculation process according to indicator polarity. For larger-is-better indicators, the entropy calculation process corresponding to indicator values smaller than the boundary between "good" and "medium" standards can be modified, as shown in formula (3). For negative-polarity indicators, a similar method is applied by flipping the larger-value (right-side) interval accordingly, resulting in a generally monotonically increasing corrected entropy curve. Applying this correction uniformly to all entropy values does not affect our ability to use entropy variation patterns to measure system development quality.

$$'2*/2midSSS = -$$

In formula (3), S represents the original entropy value of an indicator, S' represents the corrected entropy value, and S_{mid} represents the entropy value corresponding to the boundary between "good" and "medium" standards for that indicator. The corrected entropy curve is generally monotonically decreasing, as shown by the circled curve in Figure 2 [Figure 2: see original paper].

After correction using the above method, the entropy value curve establishes a direct correlation between indicator value quality and its entropy increase/decrease effect on the system, regardless of whether the original indicator is larger-is-better or larger-is-worse. Excellent value ranges correspond to smaller information entropy values. Consequently, information entropy serves as an equivalent measure—a unified yardstick that standardizes the dimensions and units of all indicators within the system, directly quantifying each indicator' s impact on system development.

For each evaluation indicator, the entropy weight method can be used to calculate its information entropy weight, thereby identifying which indicator(s) contribute most to system orderliness in the basin giant system. Information entropy measures information quantity and uncertainty; indicators providing greater information have lower entropy values, lower uncertainty, and can thus be assigned greater weights. The entropy weight method avoids discrepancies arising from subjective expert weighting and, more importantly, enables real-time monitoring as indicator information entropy values change. Indicator information entropy weights are obtained using formula (4), and weighted summation of entropy values within positive and negative entropy change systems is performed using formulas (5) and (6).

$$i11iiNiSwNS = - = - , A, 1A(*)NiiAiSw ==\ \ , , 1B(*)NiBiBiSw ==$$

In formulas (4) and (5), N represents the number of corresponding indicators, S_i and w_i represent the entropy value and weight of corresponding indicators (distinguished as positive or negative entropy change), and A and B represent the total positive and negative entropy change of the system, respectively.

2.4 Quantitative Analysis of Basin Development State

Based on system information entropy calculations, this study further introduces dissipative structure theory and the "Brusselator" model to evaluate system development status. Dissipative structure theory, established by Belgian physical chemist I. Prigogine in 1969, is an emerging discipline developed from non-equilibrium thermodynamics. Prigogine [?] proposed that in the non-linear region far from equilibrium, an open thermodynamic system can generate self-organization phenomena through continuous exchange of matter and energy with its environment and internal non-linear interactions. Once system parameters reach a certain threshold, the system may evolve into an advanced ordered spatiotemporal structure—this is the "dissipative structure." Four conditions are required for dissipative structure formation: the system must be open, far from equilibrium, contain fluctuations, and involve non-linear interactions [?]. Clearly, the basin complex giant system satisfies these conditions.

The "Brusselator" model proposed by the Prigogine school quantitatively analyzes chemical cross-catalytic reaction processes to simulate the kinetic characteristics of all systems meeting dissipative structure conditions during evolution. In this model, A and B represent concentrations of two reactants, and the kinetic critical condition for the reaction system to become a dissipative structure is $|B| > 1 + A^2$. Therefore, the dissipative structure index for each time period can be calculated using formula (7):

$$2(1)DSIndexBA = -+$$

When the dissipative structure index is positive—meaning the concentrations of reactants A and B satisfy this quantitative relationship—the system transitions into a dissipative structure state. Conversely, when negative, the system remains in a non-dissipative structure (stable thermodynamic branch). When zero, the system is in a critical state between the two. As described above, for the basin giant system, A and B can represent the total positive and negative entropy changes of the system, respectively—equivalent to the concentrations of the two input reactants in the Brusselator model. Thus, kinetic analysis of chemical reaction systems can be translated into evolution analysis of the basin giant system.

The value ranges of A and B in formula (7) are in the interval [0, 1]. To make the two terms comparable within the same numerical domain, following methods employed in many studies [**?**], the negative entropy change value B is expanded by a factor of 2, resulting in a dissipative structure index range of [-2, 1]. Considering the principle of easy applicability, this study adopts a 100-point scale for the Basin Development Index. When calculating scores, the dissipative structure index range is linearly transformed to the [0, 100] interval, yielding the conversion formula in (8):

$$100 * (2)/3DSBDIIndex = +$$

In formula (8), BDI represents the Basin Development Index—a comprehensive indicator for evaluating the evolution state and development quality of the basin giant system, with detailed definitions provided in other articles in this research series; $Index_{DS}$ represents the dissipative structure index.

Based on the projection pursuit clustering method [**?**], using three critical values from all indicator standard intervals, the corresponding dissipative structure index values are calculated as -0.5, -0.38, and -0.23, forming a three-level standard for system states. Including the condition for system reaching dissipative structure (dissipative structure index value of 0) constitutes a four-level standard. Considering that higher development quality is achieved when the system reaches dissipative structure, the superior three-level standard is adopted as the critical value for BDI standard intervals. The conversion table between basin system development quality and BDI scores is shown in Table 1 .

Table 1 Correspondence among Dissipative Structure Index Values, BDI Scores, and Basin Development Quality

Dissipative Structure Index ($Index_{DS}$)	BDI Score	Basin Development Quality
-2 ~ -0.38	0 ~ 54	Poor
-0.38 ~ -0.23	54 ~ 59	Medium
-0.23 ~ 0	59 ~ 67	Good
0 ~ 1	67 ~ 100	Excellent

3 Results and Discussion

Using the established calculation methodology, this study conducted a comprehensive evaluation of the Yellow River Basin' s development quality over the past 40 years.

3.1 Indicator Information Entropy Analysis

Using the aforementioned information entropy correction algorithm, the corrected information entropy values were calculated. The results demonstrate that indicator information entropy values can effectively reflect development changes. For positive-polarity indicators (larger values are better), entropy values decrease as indicator values increase. For negative-polarity indicators (smaller values are better), entropy values also decrease as indicator values decrease. As shown in Figure 3 [Figure 3: see original paper], the entropy calculation results for the typical indicator "sedimentation and erosion volume in the lower Yellow River" follow this pattern. The sedimentation/erosion volume can be positive (representing channel deposition) or negative (representing channel scour). For the system, this indicator has negative polarity (smaller values are better). Figure 3 shows that as the original sedimentation/erosion volume in the lower Yellow River decreases, the information entropy value also decreases, with consistent trend lines and inflection points. This confirms that using information entropy values to measure indicator development changes has a scientific basis.

3.2 Indicator Entropy Weight Analysis

Using the entropy weight method represented by formulas (4)-(6), the relative weight changes of 30 indicators over the 40-year history of the Yellow River Basin giant system were calculated and analyzed. Figure 4 [Figure 4: see original paper] displays the probability distribution of each indicator appearing as a relatively large weight across different years, while Table 2 details statistical results for selected high-weight indicators. For example, Indicator No. 18 (ratio of basin per capita GDP to national average) held the maximum weight in 35%

of years (14 years) over the 40-year period and ranked among the top three weights in 38% of years (15 years).

Analysis of high-weight indicators reveals that each indicator' s influence on system evolution continuously changes over time. In different development stages, inter-indicator relationships vary, with different indicators successively assuming maximum weight status and exerting significant system impacts under the effects of competition and synergy. In studies of development evolution during specific periods, analyzing the statistical patterns of maximum-weight indicators can guide scientific basin governance—prioritizing indicators with larger weights and focusing governance measures on improving these indicators.

Table 2 Partial Statistical Results of High-Weight Indicator Occurrence Probability

Indicator	Maximum Weight Probability	Top Three Weight Probability
Species richness index	3%	8%
Ratio of basin per capita GDP to national average	35%	38%
Total sedimentation/erosion volume (lower Yellow River)	25%	45%
Ecological base flow guarantee rate at key sections	13%	53%

Table 2 shows that, overall, indicators with relatively larger weights are No. 7, No. 18, No. 25, and No. 33, which originate from three different subsystems. This distribution represents the relative weight distribution among subsystems and, to some extent, demonstrates the scientific validity of the evaluation index system and subsystem classification adopted in this study. The results also reflect the mutual influence and competition among subsystems and between subsystems and the basin giant system.

3.3 Basin Development Quality Analysis

Comprehensive assessment of the basin giant system' s overall development quality requires holistic consideration of all indicators and their corresponding positive and negative entropy effects. Figure 5 [Figure 5: see original paper] and Table 3 present the 40-year evolution of the BDI index. Over the entire 40-year study period, the mean BDI value is 58.5 points, with a minimum of 50.5 points in 1996 and a maximum of 66.6 points in 2019. The BDI trajectory shows an initial decline followed by an increase. Specifically, the Yellow River Basin' s development quality experienced stages of "good-medium-poor-medium-good."

During the 1980s, China was in the early stage of reform and opening up, with economic development in the basin in its initial phase and limited negative impacts of human activities on the ecological environment. Before 1985, BDI remained above the mean, indicating relatively high ecological environmental quality and overall development quality in the basin. After 1985, BDI declined with fluctuations, reaching its lowest point in 1996. During this stage, while economic development gradually improved, insufficient attention to ecological protection and maintenance of basin carrying capacity resulted in suboptimal ecological conditions. After 1996, despite continued fluctuations, the overall development trend improved due to scientific decision-making, systematic governance, and positive impacts from major projects. Particularly in the last decade, BDI volatility has decreased and gradually approached "excellent" development levels.

Table 3 Basin Development Index Calculation Results

Year	BDI Score	Development Grade
1980	62.3	Good
1996	50.5	Poor
2019	66.6	Good

Further analysis of Yellow River Basin BDI evolution in conjunction with major historical events [?] is presented in Figure 6 [Figure 6: see original paper], which illustrates the correlation between BDI evolution and several major basin events. During 1982–1984, abundant water volumes occurred in the Yellow River, particularly in August 1984 when the flood season exhibited high water flow with low sediment, resulting in relatively good water-sediment relationship coordination and favorable river health indices that positively influenced BDI. In August 1992, flooding occurred in the Wei River tributary, causing high water levels and high sediment content at Huayuankou. River drying intensified that year, with the Lijin cross-section experiencing 82 dry days. In 1995, the Yellow River dried up for 122 days total. The catastrophic "96.8" flood in August 1996 caused continuous BDI decline until reaching its minimum in 1996. After 1997, with the commissioning of the Wanjiazhai and Xiaolangdi water control projects and initial success in unified scientific water regulation, combined with gradual effectiveness of ecological projects such as Loess Plateau soil erosion control, the "Three-North" shelterbelt program, and nature reserve construction, the Yellow River Basin BDI gradually improved, peaking around 2000. Since 2000, the Yellow River has maintained continuous flow with sustained improvement, particularly after 2010. This progress closely relates to changes in national governance policies. Since the 18th Party Congress in 2012, General Secretary Xi Jinping has issued important instructions on water conservancy work, particularly proposing ecological civilization concepts in 2012. In March 2014, the "Water priority, spatial balance, systematic governance, dual efforts" water management philosophy ("16-character" water management approach) was proposed. In 2017, the battle against pollution was launched. Implementation of these scientific and robust policies has driven continuous BDI improvement. The evolution pattern of Yellow River Basin BDI shows substantial correlation with major basin events, with numerical and temporal responses existing between significant events, hydrological changes, and BDI values.

It should be specifically noted that despite continuous governance and improvement over the past two decades, the complex natural conditions and special river characteristics of the Yellow River determine the long-term, arduous, and complex nature of its management and protection. The basin system has not yet entered a dissipative structure state. Currently, flood risk remains the greatest threat, the ecological environment is fragile, water resource security faces severe challenges, and development quality requires improvement. This necessitates that river management authorities strive to reduce internal positive entropy effects while continuously enhancing external negative entropy inflow.

4 Conclusions and Outlook

This study proposes a unique and relatively complete evaluation theory and methodology for river governance and management through improvements to information entropy and dissipative structure theory. By employing the concept of information entropy from information theory, system development quality is normalized to entropy equivalents, unifying the measurement of various indicators. Combined with dissipative structure theory, a comprehensive evaluation method for basin system development quality is established from the perspectives of system development trends and endogenous evolution dynamics. The calculated evolution pattern of the Yellow River Basin' s BDI aligns with the basin' s overall development law and demonstrates substantial correlation with major basin events.

This theoretical and methodological framework breaks away from traditional linear thinking and the "treating symptoms in isolation" approach to river management. Through deep integration of natural and social sciences, it establishes scientific system models that provide decision-making foundations for strategic water resource layout and major project planning in the Yellow River Basin. Furthermore, the Basin Development Index and related theoretical methods proposed in this study can be extended to regional governance and other fields. Compared with current evaluation models primarily based on economic indicators, this approach offers greater systematicity and scientific rigor, thereby better serving scientific decision-making.

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Author Contributions

ZHANG Yuansheng, LIAN Jijian: Conceptualized research ideas and designed the study framework;
JIN Xin, CAO Zhiwei, ZHAO Yan: Conducted experiments, collected, cleaned, and analyzed data, drafted the manuscript;
LUO Qiushi, LU Jun: Revised the final version of the paper.

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Note: Figure translations are in progress. See original paper for figures.