Measurement and Analysis of Urban Inclusive Green Development Efficiency in the Yellow River Basin from a Water Cycle Perspective: Postprint

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Date: 2025-10-28T16:21:38+00:00

Abstract

Focusing on the water cycle perspective, the measured level of inclusive green development efficiency serves as a crucial basis for assessing ecological protection and high-quality development in the Yellow River Basin. Grounded in the connotation of inclusive green development and combined with the realistic characteristics of water resource shortage within the basin, this study innovatively incorporates the water cycle into the indicator system for measuring inclusive green development efficiency; employs the super-efficiency SBM model to construct and measure the inclusive green development efficiency of 77 cities in the basin from 2013 to 2022, and analyzes their spatiotemporal evolution characteristics; finally, while combing through the influencing factors of inclusive green development efficiency based on existing research, utilizes the Geographically and Temporally Weighted Regression (GTWR) model to analyze the spatiotemporal evolution characteristics of their impact effects. The results indicate: (1) The inclusive green development efficiency in the Yellow River Basin shows an overall upward trend year by year, and this trend becomes more pronounced after the proposal of the national major strategy of "Ecological Protection and High-Quality Development of the Yellow River Basin." (2) The spatiotemporal variation trends of inclusive green development efficiency at different regional levels within the basin exhibit significant differences. (3) The inclusive green development efficiency within the basin demonstrates positive spatial autocorrelation in its spatial distribution, showing a clustered distribution pattern of high-efficiency values centered around provincial capitals and other developed cities, yet this autocorrelation exhibits a gradually weakening trend. (4) The influencing factors of inclusive green development efficiency in the Yellow River Basin are mainly concentrated in four aspects: urban development, physical geography, institutional environment, and social development, and their spa-

tiotemporal variation characteristics of impact effects on inclusive green development efficiency differ from each other.

Full Text

Preamble

ARID LAND GEOGRAPHY Vol. 48 No. 10 Oct. 2025

Measurement and Analysis of Inclusive Green Development Efficiency in Yellow River Basin Cities from a Water Cycle Perspective

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Abstract: Measuring inclusive green development efficiency (IGDE) from a water cycle perspective provides a critical foundation for evaluating ecological protection and high-quality development in the Yellow River Basin. This study innovatively integrates water cycle indicators into an IGDE measurement framework, addressing both the conceptual underpinnings of inclusive green development and the region' s severe water scarcity. Employing a super-efficiency SBM model, we measure IGDE across 77 prefecture-level cities in the basin from 2013 to 2022 and analyze its spatiotemporal evolution. We further identify influencing factors and examine their spatiotemporal dynamics using a geographically and temporally weighted regression (GTWR) model. The results reveal: (1) IGDE exhibits a year-over-year upward trend, accelerating notably after the national strategy for "Ecological Protection and High-Quality Development of the Yellow River Basin" was introduced; (2) Significant variations exist in IGDE trajectories across different sub-regions; (3) Positive spatial autocorrelation characterizes IGDE distribution, with high-efficiency clusters concentrated around provincial capitals and developed cities, though this spatial dependence is gradually weakening; and (4) Influencing factors concentrate in four dimensions—urban development, physical geography, institutional environment, and social development—each displaying distinct spatiotemporal heterogeneity in their effects.

Keywords: water resources; inclusive green development efficiency; super-efficiency SBM model; GTWR model; Yellow River Basin

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The Yellow River Basin spans nine provinces and regions, with a permanent population of 4.2×10^{8} and a regional GDP of 3.61×10^{13} yuan (as of

2023). As a vital energy base, ecological security barrier, and socio-economic development zone in China, the basin has achieved remarkable economic progress while facing severe challenges from overdevelopment, including water shortages, environmental pollution, and ecological fragility. These issues have become major obstacles to high-quality development in the region and nationwide in the new era. Since the 18th Party Congress, General Secretary Xi Jinping has paid close attention to the basin's ecological protection and high-quality development, conducting multiple inspection tours and hosting three thematic symposiums in 2019, 2021, and 2024. The discourse evolved from "in-depth promotion" to "comprehensive promotion" of ecological protection and high-quality development, elevating the strategy to a national priority. This progression reflects the basin' s transition from green transformation to inclusive green development—a higher-level paradigm prioritizing resource conservation, environmental protection, economic growth, and social inclusivity. Given that water resources constitute the most critical constraint in the Yellow River Basin—accounting for only 2% of national water resources while supporting 12% of the population and 15% of GDP—water conservation and recycling standards must be central to any inclusive green development framework.

Existing research on IGDE measurement exhibits three main characteristics. First, early studies predominantly employed entropy weight methods, which introduce subjectivity through manual weight assignment. Recent scholarship has shifted toward data envelopment analysis (DEA) and its derivatives, including SBM and super-efficiency models. Second, conventional indicator frameworks typically select capital, labor, and resources as inputs; GDP as desirable outputs; and pollutants as undesirable outputs. Third, research has evolved from static analyses of regional disparities to dynamic investigations of driving mechanisms, focusing on economic development, environmental regulation, and industrial structure.

While valuable, current literature has three notable gaps: (1) Limited focus on the Yellow River Basin as a nationally strategic region; (2) Absence of water cycle perspectives in IGDE frameworks, despite water scarcity being the basin' s defining constraint; and (3) Insufficient systematic analysis of how influencing factors and their effects vary across dimensions and spatiotemporal contexts. This study addresses these gaps by integrating water cycle indicators into an IGDE measurement framework for the Yellow River Basin, analyzing spatiotemporal evolution patterns, and examining dynamic influencing mechanisms.

1.1 Study Area

Following the methodology of Chai Guorong et al., Li Xinyue et al., and Yue Li et al., this study examines prefecture-level cities along the Yellow River. After excluding cities with severe data gaps, our sample comprises 77 cities. Based on the "Yellow River Basin Ecological Protection and High-Quality Development Plan Outline" issued by the CPC Central Committee and State Council, we divide the basin into upstream, midstream, and downstream regions (Table 1).

The spatial distribution is visualized in Figure 1.

1.2 Methodology

1.2.1 Super-Efficiency SBM Model To address the comparability limitations of traditional DEA models when multiple decision-making units (DMUs) are efficient, we employ the super-efficiency SBM model. Each prefecture-level city is treated as a DMU to calculate IGDE values. The model formula is:

$$\rho = \frac{1 + \frac{1}{m}\sum_{i=1}^{m}\frac{s_i^-}{x_{ik}}}{1 + \frac{1}{s_1+s_2}\left(\sum_{p=1}^{s_1}\frac{s_p^d}{y_{pk}^d} + \sum_{q=1}^{s_2}\frac{s_q^u}{y_{qk}^u}\right)}$$

where ρ represents IGDE; m, s_1, and s_2 denote the numbers of inputs, desirable outputs, and undesirable outputs respectively; s_i^-, s_p^d, and s_q^u are slack variables for inputs, desirable outputs, and undesirable outputs; k and j index DMUs; and x_{ik}, y_{pk}^d, y_{qk}^u represent input, desirable output, and undesirable output values for DMU k.

1.2.2 Geographically and Temporally Weighted Regression Model The GTWR model extends traditional GWR by incorporating temporal dimensions, enabling precise capture of spatiotemporal variations in parameter estimates. The model is specified as:

$$y_{it} = \beta_0(u_i, v_i, t) + \sum_{k=1}^{n}\beta_k(u_i, v_i, t)x_{ik} + \varepsilon_i$$

where y_{it} is IGDE for city i at time t; (u_i, v_i, t) represents spatiotemporal coordinates; $\beta_k(u_i, v_i, t)$ are spatiotemporally varying coefficients; and ε_i is the error term.

1.3 Indicator Selection and Data Sources

Inclusive green development seeks optimal balance among resource conservation, environmental protection, economic growth, and social inclusivity. The socio-economic water cycle—human alteration of natural water pathways through extraction, regulation, and transformation—constitutes a core element of the basin's dualistic water cycle theory and a foundation for IGDE. Building on previous frameworks and considering water resource constraints, we incorporate water cycle indicators into our measurement system.

Inputs include water resources alongside capital, labor, and energy. **Desirable outputs** comprise water reuse rates, GDP, and a comprehensive social welfare index synthesized from healthcare, education, and pension coverage indicators using an accelerated genetic algorithm projection pursuit model. **Undesirable outputs** incorporate water pollution, air pollution, urban-rural income gaps, and unemployment rates. Air pollution indices are similarly synthesized from PM2.5 and other air quality metrics. Data are primarily sourced from the *China Statistical Yearbook*, *China Urban Statistical Yearbook*, *China Urban Construction Statistical Yearbook*, provincial yearbooks, and NOAA' s National Centers for Environmental Information. Missing values are imputed using linear or geometric interpolation.

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2 Spatiotemporal Evolution of IGDE in the Yellow River Basin

2.1 Temporal Evolution

Applying the super-efficiency SBM model to our panel data reveals a consistent upward trend in basin-wide IGDE, accelerating after 2019 when the national strategy was introduced (Figure 2). The index rose from 0.68 in 2013 to 0.82 in 2019, then jumped to 0.91 by 2022, demonstrating sustained improvement since the 18th Party Congress.

Regional analysis shows distinct patterns: upstream and midstream IGDE increased continuously from 0.65 to 0.89 and 0.61 to 0.88 respectively, with midstream growth outpacing upstream despite lower initial levels. Downstream IGDE exhibited greater volatility, leading in 2013 but declining sharply by 2019 before rebounding to 0.85 by 2022—still trailing upstream and midstream levels. This pattern likely reflects: (1) easier implementation of green industries in less-developed upstream regions post-2012; (2) midstream regions' transition from traditional industry clusters; and (3) downstream' s economic contraction in 2020 and reduced water scarcity diminishing its comparative advantage after the national strategy' s implementation.

Kernel density analysis (Figure 3) shows the distribution flattening over time, with peaks decreasing and ranges widening, indicating emerging polarization. The Dagum Gini coefficient decomposition reveals that inter-regional disparities contribute most to overall inequality, though this contribution is declining. Upstream and midstream intra-regional disparities are decreasing, while downstream shows slight divergence, likely due to capital and talent concentration in Qingdao and Jinan.

2.2 Spatial Evolution

Spatial distribution maps (Figure 4) demonstrate that IGDE clusters around provincial capitals and economically advanced cities, forming contiguous high-efficiency zones. Global Moran' s I values are significantly positive but declining (Table 3), indicating weakening spatial autocorrelation—possibly reflecting policy diffusion and enhanced regional coordination.

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3 Factor Analysis of IGDE

3.1 Factor Selection and Model Validation

Drawing on existing literature and basin characteristics, we select factors across four dimensions:

Urban Development: Polycentric structure, spatial compactness, and urbanization level. Polycentricity is measured using nighttime light data; compactness via geometric properties of urban land use; urbanization by urban population share.

Physical Geography: Wind speed, temperature, and precipitation.

Institutional Environment: Environmental regulation (frequency of green terms in government documents) and fiscal support (general budget/GDP ratio).

Social Development: Industrial structure (tertiary/primary+secondary ratio), openness (trade/GDP), and technological progress (log of patent grants).

Variance inflation factors (VIFs) all fall below 5 (Table 6), indicating no severe multicollinearity. GTWR model comparison shows superior fit ($R^2 = 0.892$) versus OLS ($R^2 = 0.721$) and lower residual sum of squares, validating our approach.

3.2 GTWR Results

Urban Development: Polycentric structure coefficients are positive and increasing, expanding from downstream to upstream, reflecting policy-driven functional dispersion and resource optimization. Spatial compactness coefficients also increase while maintaining a stable downstream > midstream > upstream pattern, showing sustained benefits from intensive development, particularly in water-scarce areas. Urbanization coefficients remain positive but decline over time, with high-value zones shifting eastward, suggesting diminishing returns as population exceeds ecological carrying capacity.

Physical Geography: Wind speed coefficients shift from negative to positive, indicating successful wind energy utilization. Temperature coefficients turn from positive to negative, showing climate vulnerability—warming harms IGDE, especially in midstream/downstream. Precipitation coefficients remain negative but weakening, likely due to improved irrigation and industrial water efficiency.

Institutional Environment: Environmental regulation coefficients are positive but declining, with stronger effects upstream where ecosystems are more fragile. Fiscal support coefficients are consistently negative, suggesting traditional infrastructure investment crowds out ecological spending.

Social Development: Industrial structure coefficients are positive and rising, reflecting enhanced upstream-downstream synergies. Openness coefficients are negative and strengthening, as foreign investment favors energy-intensive manufacturing. Technology coefficients are also negative, as innovation widens income gaps and encourages water-intensive industries.

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4 Discussion

This study advances sustainability science by integrating water cycle dynamics into IGDE metrics, addressing conventional assessment limitations. Methodologically, it establishes a novel spatiotemporal framework combining efficiency measurement, spatial econometrics, and regression modeling. Practically, findings inform resource allocation optimization, cross-regional governance enhancement, and adaptive policy formulation. However, IGDE encompasses broad dimensions; future research should explore additional influencing factors and quantitatively identify improvement strategies.

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5 Conclusions and Recommendations

5.1 Conclusions

(1) **Temporal Patterns**: Basin-wide IGDE shows sustained upward growth, accelerating post-2019. Upstream and midstream regions exhibit continuous improvement, while downstream shows volatility. City-level polarization is emerging.

(2) **Spatial Patterns**: Positive spatial autocorrelation exists but is weakening. High-efficiency clusters center on capitals. Inter-regional disparities dominate overall inequality, though intra-regional gaps are narrowing in upstream/midstream while diverging downstream.

(3) **Driving Factors**: Four dimensions shape IGDE with distinct spatiotemporal heterogeneity. Polycentric structure, spatial compactness, urbanization, environmental regulation, and industrial structure promote IGDE; openness, technological progress, precipitation, and fiscal support inhibit it; wind speed and temperature effects shift direction over time.

5.2 Recommendations

(1) **Holistic Governance**: Strengthen policy coordination across the basin to prevent further IGDE divergence.

(2) **Differentiated Strategies**: Upstream regions should accelerate green transformation of agriculture and manufacturing; downstream regions should stabilize IGDE growth while cultivating new productive forces.

(3) **Dynamic Optimization**: Leverage polycentric structures and compact development; control polluting industries through strict green entry standards; adapt industrial thresholds and ecological compensation mecha-

nisms based on wind, temperature, and other natural endowments to create nature-based IGDE enhancement mechanisms.

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