

Article

An Augmented Indicator Framework for Hydrologic Alteration Assessment in Tidal River Networks: A Case Study of the Pearl River Delta, China

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Abstract

River networks influenced by tides represent dynamic, hydrologically complex systems where fluvial inflows interact with oceanic tidal forcing. Conventional flow-based indicators of hydrologic alteration (IHA) inadequately capture tidal-driven dynamics, including diurnal water level fluctuations, flow reversals, and tidal asymmetry. This study develops an augmented IHA (AIHA) framework comprising 96 indicators derived from hourly-resolution hydrodynamic simulations (1960–2019) in the Pearl River Delta (PRD), China. The AIHA extracts four daily series—ebb-peak flow and residual, highest, and lowest water levels—supplemented by tidal characteristic metrics. A moving *t*-test identified 1991 as the significant regime shift, enabling comparison of reference (1960–1991) and altered (1992–2019) periods. Three-dimensional alteration was assessed as follows: deviation from the range of variability (RVA), shift in central tendency (RCM), and change in dispersion (RCD). Indicator importance was integrated via CRITIC weighting and multi-site Borda scoring. Results show that range shifts and central-tendency shifts were generally dominated by low-intensity alteration, accounting for 58.3–71.9% and more than 85% of the indicators, respectively, whereas dispersion shifts were more pronounced, with medium- and high-alteration indicators accounting for an average of 42.4%. Water level indicators exhibited substantially greater alteration sensitivity than flow indicators, particularly in estuarine zones where the alteration degrees of some indicators exceeded 90%. Among hydrological elements, ebb-peak flow indicators responded more strongly in range shifts, with an average comprehensive alteration degree of 29.6%, while water level indicators showed more pronounced changes in central tendency and dispersion; the lowest water level indicators were especially sensitive, with average comprehensive alteration degrees of 19.6% and 77.3%, respectively. Spatially, center-of-distribution shifts (RCM) diverged: positive in western/northern tributaries (increased flows) versus negative in the eastern PRD (decreased flows). Integrated Borda scoring identified low-flow extremes during dry seasons, event timing, and tidal modulation as the most sensitive responses to hydrological stress. The AIHA framework demonstrates that tidal river alteration is characterized by intensified low-flow volatility and amplified tidal influence, with water level metrics providing a superior detection capacity than achieved by discharge alone. This process-integrated approach offers robust quantitative support for ecological flow management and estuarine restoration in tidal environments globally.



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1. Introduction

Rivers are intrinsically linked to the development of human civilization, with their natural flow regimes essential for maintaining biodiversity and ecosystem integrity [1]. However, their hydrological conditions have been profoundly altered by external drivers such as large-scale climate change and intensive human activities [2], whose effects are often coupled [3], leading to significant modifications in runoff processes, flood–dry patterns, and the frequency and duration of extreme hydrological events [4,5]. The hydrological regime serves as a critical nexus between hydrological processes and ecological responses. Alterations in this regime can propagate to the ecosystem level through pathways such as habitat area/connectivity, nutrient transport, fish migration, and reproductive phenology, ultimately impacting riverine ecosystem functions [6]. Consequently, quantitatively identifying and assessing the degree of hydrological alteration has become a fundamental task for integrated water resource management and ecological flow research [7].

Numerous parametric systems have been developed to characterize flow regimes, with some systems encompassing over 170 individual metrics, each designed to represent specific hydrological and ecological attributes or management objectives [8,9]. Existing hydrologic alteration assessments generally rely on three metric- or statistics-based approaches: indicator-based methods, including IHA and other ecohydrological metrics, to characterize changes in flow magnitude, timing, frequency, duration, and rate of change [10–13]; range-based methods, particularly RVA and its modified forms, including distribution-based extensions, to quantify departures from natural or reference variability ranges and classify alteration degrees [14–17]; and statistical comparison/change-detection methods to examine shifts in central tendency, variability, extremes, abrupt changes, and long-term trends [18–21]. Among these methods, the IHA system remains one of the most widely applied frameworks because it provides a standardized, quantitative, and ecologically meaningful tool to evaluate human impacts on natural flow regimes [10,11]. It systematically quantifies various facets of both baseline and altered flow patterns and has evolved into a structured framework of 33 key indicators grouped into five categories. Owing to its clear ecological relevance, structural integrity, and ease of application, the IHA has been extensively used to identify flow alterations, analyze ecological responses, and assess environmental flows across diverse climatic zones and disturbance scenarios [7,12,13,22]. Nevertheless, these approaches remain limited by metric redundancy, scale dependence, reference-period selection, attribution uncertainty, and weak links between hydrological metrics and ecological responses [23]. These limitations are amplified in complex riverine or estuarine systems, where strong spatial heterogeneity and rapidly varying flow–water level dynamics often require process-based hydrological or hydrodynamic modeling to complement conventional indicators and interpret hydrologic alteration patterns [24–27].

Tidal river networks, situated within the transitional zone where freshwater and marine environments interact, are subject to pronounced periodic water level fluctuations and flow reversals, unlike unidirectional fluvial rivers [28,29]. The interplay between freshwater inflows and oceanic tides governs complex hydrodynamics that control sediment transport and salinity intrusion patterns and profoundly influence nutrient cycling and the structure and function of estuarine ecosystems [30]. Early research on hydrologic alteration in these regions has primarily relied on qualitative descriptions from water level and flow observations and has progressively evolved toward multi-factor analysis

and process-based investigation [24]. The current literature emphasizes the simultaneous influences of tidal dynamics, upstream inflow variability, geomorphic changes, human activities, and climate change [25,26,31], with research increasingly addressing ecological conservation and flood-tide risk [32]. Meanwhile, advances in hydrological resilience, estuarine adaptation, ecological flow, and data-driven detection highlight the need for operational indicators tailored to high-frequency tidal dynamics in river networks [33], a research gap addressed by the augmented AIHA framework proposed in this study. As a leading framework, the IHA has been employed in tidal-influenced river network studies to assess impacts from engineering regulation and human activities [34–36]. However, the conventional IHA, based largely on daily, monthly, or annual flow statistics, is primarily designed for runoff-dominated riverine systems [37]. Its fixed statistical windows and single-scale nature struggle to capture the high-frequency dynamics (e.g., semi-diurnal water level variation, flow direction reversals) central to tidal environments [38].

In response to these limitations, recent international studies in major river basins and tidal systems (e.g., Pearl River, Yangtze River, Mekong Delta) have developed specialized hydrologic indicators for regime alteration assessment, dam-impact attribution, ecological-effect linkage, and estuarine network characterization [39–42]. Some IHA/RVA studies have replaced flow-based metrics with water level alternatives (e.g., mean monthly maximum/minimum water level, annual extreme water levels and their timing) to assess engineered impacts on water level regimes [43]. Further refinements incorporate tidal parameters like tidal range, seasonal variations in tidal range, and duration asymmetry to characterize tidal waveform changes from channel modifications or sea-level rise [44–47]. For the downstream reaches subject to significant saltwater intrusion, indicators like extreme water levels near salinity interfaces and their frequency have also been adopted to assess combined impacts on flood risk and habitat suitability [48–50]. Overall, these studies show a shift from flow-centered metrics to process-specific indicators for capturing water level variability, tidal dynamics, and compound estuarine influences. Despite these advances in metric augmentation at the indicator level, comprehensive assessments at the river network scale—particularly those derived from high-resolution hydrodynamic modeling to elucidate spatiotemporal patterns—remain relatively scarce. Addressing this gap necessitates a systematically extended IHA framework tailored to tidal settings.

Therefore, this study aims to develop an augmented indicators of hydrologic alteration (AIHA) framework for tidal river networks. Leveraging hourly-resolution outputs from a coupled hydrodynamic model, we derive four high-temporal-scale hydrological time series: daily ebb-peak flow (EPF), daily residual water level (RWL), daily highest water level (HWL), and daily lowest water level (LWL). These form the basis of the augmented IHA, with the addition of tidal regime indicators. We apply this framework to the Pearl River Delta (PRD), China, using the range of variability approach (RVA), relative change of the median (RCM), and relative change of dispersion (RCD) to quantify the spatiotemporal patterns of hydrological alteration. We integrate the results via CRITIC weighting and Borda count methods to identify key indicators driving changes in the tidal hydrologic regime. This integrated approach facilitates a multi-dimensional and non-redundant assessment of hydrological changes, while capturing the uniqueness of tidal-influenced river systems.

2. Study Area and Data

2.1. Study Area

The Pearl River Delta (PRD) in southern China, located in a humid subtropical climate zone, is formed by the confluence and interaction of three major rivers—the Xijiang, Beijiang, and Dongjiang waterways—and is among the world's most human-impacted and intensely developed delta systems [51–53]. Hydrologically, the region is dominated by

seasonal monsoon-driven precipitation, with significant intra- and inter-annual variability in upstream inflows, strongly influencing downstream flood events and saltwater intrusion dynamics [54]. Concurrently, oceanic tides from the South China Sea propagate upstream through a complex branched channel network, creating time-varying water levels and tidal ranges that vary spatially across the delta [46]. Since the commencement of China's economic reforms in the late 1970s, intense land reclamation, large-scale channel dredging for navigation, and rapid urbanization have significantly altered regional hydrodynamics and sediment transport, thereby impacting flood risk, saltwater intrusion patterns, and the health of estuarine wetlands and floodplain habitats [55].

This study focuses on the tidal river networks of the PRD fed by the Xijiang, Beijiang, and Dongjiang waterways and which encompasses eight major outlets (Figure 1). The Xijiang waterway, the dominant contributor of flow and sediment to the delta, is the primary channel for flood conveyance and seasonal runoff distribution [56,57]. The Beijiang waterways enter the mid-upper delta network from the north, playing a key role in supplying the northwestern distributaries and influencing flood propagation [58]. The Dongjiang waterways transition into the tidal reaches and are vital for water supply security for the eastern cities of Guangdong, Hong Kong, and the Macao Greater Bay Area, given their sensitivity to saltwater intrusion [59]. To represent these three subsystems, twelve representative stations (S1–S12) were selected from upstream to estuarine locations: Gaoyao (S1), Makou (S2), Tianhe (S3), and Denglongshan (S4) in the Xijiang Waterway Zone; Shijiao (S5), Sanshui (S6), Sanduo (S7), and Sanshakou (S8) in the Beijiang Waterway Zone; and Boluo (S9), Shilong (S10), Dasheng (S11), and Sishengwei (S12) in the Dongjiang Waterway Zone.

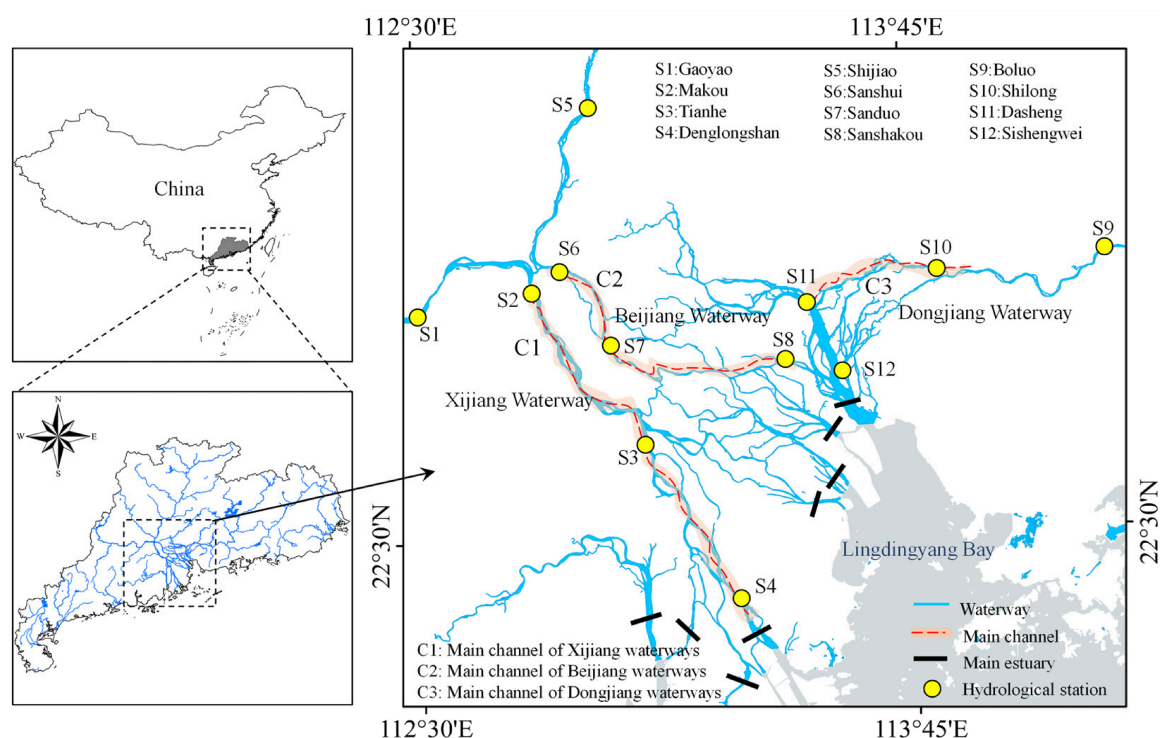


Figure 1. Location of the study area and main channels and gauging stations.

2.2. Dataset

The data employed in this study are primarily for the construction and validation of the hydrodynamic model. Required datasets include river channel geometry and topographic data for the river network and adjacent coastal sea; hourly runoff data at upstream boundary control stations (1960–2019); and hourly tide level data at open sea boundaries derived

from the DTU10 global tide model with a spatial resolution of 0.125° , which may introduce limited nearshore uncertainties but which was adopted due to the lack of observed tidal data along the open sea boundaries. For model calibration and validation, field observations collected during two representative hydrological periods were utilized: 21–30 June 2005, representing the flood period, and 1–21 December 2019, representing the dry period. The observations included hourly flow data at Makou (S2) and Sanshui (S6) and hourly water level data at Makou (S2), Tianhe (S3), Denglongshan (S4), Sanduo (S7), Shilong (S10), and Sishengwei (S12).

3. Methodology

3.1. River Network Hydrodynamic Modeling

The hydrodynamic simulations were implemented using MIKE ZERO 2014 developed by the Danish Hydraulic Institute (DHI Water & Environment, Hørsholm, DK) and comprising multiple numerical modules. Specifically, the MIKE 11 module was used for the one-dimensional river network, while the MIKE 21 flow model (FM) module was used for the two-dimensional estuarine and coastal domains. To accurately simulate the hydrodynamic characteristics of both the tidal river network and the estuarine coastal waters, a coupled 1D–2D hydrodynamic model was established. The river network zone was simulated using 1D Saint–Venant equations to describe unsteady flow along the channel direction [60,61], while the estuary and adjacent coastal waters were simulated using 2D depth-averaged shallow water equations to model planar flow movement [62]. The control equations for the 1D river network include the continuity equation and momentum equation, as follows:

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q \quad (1)$$

$$\frac{\partial Q}{\partial t} + gA \frac{\partial z}{\partial x} + \frac{\partial \left(\alpha \frac{Q^2}{A} \right)}{\partial x} + g \frac{Q|Q|}{C^2 AR} = 0 \quad (2)$$

where Q is discharge (m^3/s); z is water level (m); A is cross-sectional flow area (m^2); g is gravitational acceleration (m/s^2); q is lateral inflow per unit length ($\text{m}^3/\text{s}/\text{m}$); R is hydraulic radius (m); C is the Chézy coefficient ($\text{m}^{1/2}/\text{s}$); x and t are spatial and temporal coordinates, respectively; and α is the momentum correction coefficient.

Two-dimensional flow movement in the estuary and adjacent coastal waters is described by depth-averaged shallow water equations, with control equations as follows:

$$\frac{\partial z}{\partial t} + \frac{\partial h_u}{\partial x} + \frac{\partial h_v}{\partial y} = 0 \quad (3)$$

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + g \frac{\partial z}{\partial x} + g \frac{u \sqrt{u^2 + v^2}}{C^2 h} = \nu_t \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) \quad (4)$$

$$\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + g \frac{\partial z}{\partial y} + g \frac{v \sqrt{u^2 + v^2}}{C^2 h} = \nu_t \left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right) \quad (5)$$

where z is total water depth (m); u and v are depth-averaged flow velocities in the x and y directions (m/s), respectively; h_u and h_v are discharge per unit width in the x and y directions (m^3/s), respectively; and ν_t is the eddy viscosity coefficient.

At the coupling boundary between the 1D river network and 2D coastal waters, bidirectional information exchange between the two computational domains is achieved using water level continuity and flow conservation as the basic coupling conditions [63,64]. Specifically, flow and water level at the coupling points are the key variables exchanged between the 1D and 2D models: the 1D model calculates discharge through continuity and

momentum equations and passes it as a source term to the 2D model; the 2D model receives this flow, updates the water level through its own continuity and momentum equations, and feeds the water level back to the 1D model for the next prediction step. Through this coupling approach, the model can simultaneously reflect the river network transport processes controlled by upstream inflows and the estuarine hydrodynamic response driven by coastal tides, thereby realistically reproducing the runoff–tide interaction processes in the tidal river network system [65,66].

Model upstream boundaries were established at Gaoyao Station (S1) on the Xijiang River, Shijiao Station (S5) on the Beijiang River, and Boluo Station (S9) on the Dongjiang River. Downstream boundaries were connected to the eight outlets of the Pearl River Delta and the open sea boundary at approximately the -110 m isobath. Manning's n roughness coefficients ranged from 0.016 to 0.065, with a main channel roughness of 0.020–0.026, a floodplain roughness of 0.026–0.038, and an overall roughness for the network of 0.016–0.044 [67,68].

Calibration and validation were conducted for both flood and drought seasons to assess the model performance under contrasting hydrological conditions. The flood-season analysis was based on the “056” flood event, the largest flood event in the Pearl River Delta in 2005, with 21–24 June 2005 for calibration and 25–30 June 2005 for validation. The dry-season analysis used observed river-network data collected in December 2019, with 1–14 December 2019 for calibration and 15–21 December 2019 for validation. Model performance was evaluated using five metrics: Nash–Sutcliffe efficiency (NSE), coefficient of determination (R^2), root mean square error (RMSE), mean absolute error (MAE), Kling–Gupta efficiency (KGE), and absolute percent bias ($|PBIAS|$), covering correlation degree, overall fitting efficiency, absolute error magnitude and relative bias of simulations, as summarized in Table 1.

Table 1. Model performance metrics for flood and dry seasons. The symbol ‘-’ refers to missing observed data for the corresponding station.

Station		Flood Season						Dry Season					
		NSE	R ²	RMSE	MAE	KGE	PBIAS (%)	NSE	R ²	RMSE	MAE	KGE	PBIAS (%)
Water level	S2	0.87	0.99	0.24	0.22	0.88	2.6	0.91	0.92	0.10	0.08	0.84	5.1
	S3	0.93	0.99	0.13	0.12	0.96	2.1	0.92	0.93	0.10	0.07	0.84	1.3
	S4	0.80	0.94	0.15	0.13	0.69	5.6	0.93	0.95	0.10	0.08	0.93	8.0
	S6	0.83	0.99	0.29	0.27	0.89	3.2	0.85	0.87	0.13	0.10	0.85	4.8
	S7	0.91	0.97	0.14	0.12	0.95	2.2	0.85	0.89	0.17	0.14	0.84	11.0
	S10	-	-	-	-	-	-	0.83	0.89	0.19	0.14	0.86	5.0
	S12	0.97	0.99	0.18	0.15	0.84	10.9	-	-	-	-	-	-
Flow	S2	0.92	0.99	2728	2421	0.87	6.0	0.91	0.90	1203	924	0.94	3.2
	S3	0.95	0.99	693	609	0.85	0.2	0.86	0.88	388	276	0.87	3.4
	S6	0.90	0.97	988	878	0.78	2.8	-	-	-	-	-	-

For water level simulations: Flood-season NSE ranges from 0.80 to 0.97 with all R^2 above 0.94; RMSE and MAE stay below 0.29 m and 0.27 m. Most stations have $|PBIAS|$ below 6%, except S12 (10.9%). KGE varies between 0.69–0.96, with S3 and S7 exhibiting the best overall fit. In dry seasons, NSE rises to 0.83–0.93 and absolute errors shrink ($RMSE \leq 0.19$ m). Most stations have $|PBIAS|$ below 8%, except S7 (11%). KGE varies between 0.84–0.93. For flow simulations across S2, S3 and S6: Flood-period NSE reaches 0.90–0.95 and all R^2 exceed 0.97. Large flood flow leads to higher RMSE ($693\text{--}2728\text{ m}^3/\text{s}$) yet small relative deviation ($|PBIAS| \leq 6\%$). Dry-season baseflow reduces RMSE to $388\text{--}1203\text{ m}^3/\text{s}$ for S2 and S3, and $|PBIAS|$ reduce slightly to 3.2% and 3.4%, accompanied by mild KGE increase. All flow NSE values exceed 0.86, meeting standard calibration criteria. Note that water level (m) and flow (m^3/s) have different units, so their RMSE/MAE values cannot be directly compared. Floods produce larger absolute flow errors, whereas

dry tides mainly degrade water level fitting and relative bias. Overall, the proposed coupled 1D–2D hydrodynamic model achieves satisfactory fitting performance at most representative stations across both flood and dry periods, and can reliably reproduce the core hydrodynamic features of the complex tidal river network in the Pearl River Delta.

3.2. Augmented Indicators of Hydrologic Alteration (AIHA)

The traditional IHA indicator system uses 33 daily flow statistics to characterize intra-annual flow conditions, assessing river flow regimes from multiple aspects including magnitude, extreme events, timing, frequency, and rate of change [69,70]. This indicator system has been widely applied in the analysis of many natural rivers, and recent studies have improved the IHA indicator system by developing ecology-linked hydrological indices, modifying conventional IHA indicators and optimizing IHA parameters to reflect water quantity and fluctuation requirements [71–73]. By grouping these indicators, the IHA framework provides a structured basis for interpreting flow regimes in terms of magnitude, extremes, timing, persistence, and variability. However, for a tidal river network with significant water level fluctuations and flow reversals within a tidal day, annual characteristic indicators extracted solely from daily-scale flow processes have limitations in fully revealing short-timescale fluctuations and tidal-driven mechanisms of hydrological regimes.

In a tidal river network, hydrological changes are manifested not only in flow variations but more prominently in water level fluctuation amplitude, duration of high tidal levels, and exposure time of low water levels. For applications such as flood defense standards, navigation guarantee rates, and gate/pumping station operation rules, water level processes are often more directly meaningful than flow processes [18,74].

Based on this understanding, and relying on the high temporal resolution hydrological characteristic sequences (such as hourly processes) output by the hydrodynamic model, we extracted daily maximum discharge to characterize the ebb flow of a tidal river network—which, in a certain sense, corresponds to the flow characteristics of unidirectional rivers. This ebb-flow indicator reflects the drainage and flushing capacity of tidal rivers, with ecological relevance to material transport and habitat disturbance [75,76]. Recent environmental flow assessments increasingly integrate hydrological and hydraulic information to characterize ecologically relevant flow and water level conditions [77]. We further extracted daily residual water level, daily highest water level, and daily lowest water level to characterize key features within a typical daily tidal cycle. Together, these water level indicators characterize the tide-affected background water level condition, high-tide condition, and low-tide condition of the river network, with ecological relevance to inundation, exposure, and habitat connectivity [78]. Referencing the grouping and indicator structure of the classic IHA indicator system, we constructed an augmented indicators of hydrologic alteration (AIHA) system reflecting tidal characteristics (Table 2). Compared with previous tidal IHA modifications, the AIHA framework extends the indicator system more systematically by using high-temporal-resolution tidal sequences of daily ebb peak flow, residual water level, highest water level, and lowest water level across the river network.

Specifically, based on multi-year hourly hydrodynamic simulation results for tidal rivers, daily hydrological characteristic series for any given year can be obtained, including: daily ebb-peak flow (EPF, i.e., daily maximum discharge) series, $\{Q_e(i), i = 1, 2, \dots, N\}$, daily residual water level (RWL) series, $\{WL_r(i), i = 1, 2, \dots, N\}$, daily highest water level (HWL) series, $\{WL_h(i), i = 1, 2, \dots, N\}$, and daily lowest water level (LWL) series, $\{WL_l(i), i = 1, 2, \dots, N\}$, where N is the number of days in that year.

Table 2. Augmented IHA systems.

Group	Property	Indicators	Number
G1	Monthly characteristic	Monthly mean of daily ebb flow peak from January to December	1–12
		Monthly mean of daily residual water level from January to December	13–24
		Monthly mean of daily highest water level from January to December	25–36
		Monthly mean of daily lowest water level from January to December	37–48
G2	Extreme event	Annual minimum of 1 d, 3 d, and 7 d averaging for daily ebb flow peak	49–51
		Annual maximum of 1 d, 3 d, and 7 d averaging for daily ebb flow peak	52–54
		Annual minimum of 1 d, 3 d, and 7 d averaging for daily residual water level	55–57
		Annual maximum of 1 d, 3 d, and 7 d averaging for daily residual water level	58–60
		Annual maximum of 1 d, 3 d, and 7 d averaging for daily highest water level	61–63
		Annual minimum of 1 d, 3 d, and 7 d averaging for daily lowest water level	64–66
G3	Timing of extreme event	Date of annual minimum for daily ebb flow peak	67
		Date of annual maximum for daily ebb flow peak	68
		Date of annual minimum for daily residual water level	69
		Date of annual maximum for daily residual water level	70
		Date of annual maximum for daily highest water level	71
		Date of annual minimum for daily lowest water level	72
G4	Frequency and duration of high and low pulses	Count of low pulses for daily ebb flow peak	73
		Mean duration of low pulses for daily ebb flow peak	74
		Count of high pulses for daily ebb flow peak	75
		Mean duration of high pulses for daily ebb flow peak	76
		Count of low pulses for daily residual water level	77
		Mean duration of low pulses for daily residual water level	78
		Count of high pulses for daily residual water level	79
		Mean duration of high pulses for daily residual water level	80
		Count of high pulses for daily highest water level	81
		Mean duration of high pulses for daily highest water level	82
		Count of low pulses for daily lowest water level	83
		Mean duration of low pulses for daily lowest water level	84
G5	Change of daily processes	Rise rate for daily ebb flow peak	85
		Fall rate for daily ebb flow peak	86
		Count of reversals for daily ebb flow peak	87
		Rise rate for daily residual water level	88
		Fall rate for daily residual water level	89
		Count of reversals for daily residual water level	90
		Rise rate for daily highest water level	91
		Count of reversals for daily highest water level	92
		Fall rate for daily lowest water level	93
G6	Characteristics of tidal-influenced event	Count of reversals for daily lowest water level	94
G6	Characteristics of tidal-influenced event	Annual maximum of 7 d averaging for daily water level range	95
		Annual minimum of 7 d averaging ratio of ebb duration	96

Following the grouping logic of the classic IHA system, the first group of indicators, I_1–I_48, referred to as monthly characteristics, characterizes average hydrological conditions at the monthly scale. Taking the monthly average of daily ebb-peak flow for January as an example, for a given year with January daily ebb-peak flow series, $\{Q_e(i), i = 1, 2, \dots, M_1\}$, where M_1 is the number of days in January, we find the following:

$$I_1 = \frac{1}{M_1} \sum_{i=1}^{M_1} Q_e(i) \quad (6)$$

The second group of indicators, I_{49} – I_{66} , referred to as annual extreme events, characterizes annual extreme hydrological events. Taking annual minimum 7-day average ebb-peak flow, I_{51} , and annual maximum 7-day average ebb-peak flow, I_{54} , as examples, for the annual 7-day moving average series of the daily ebb-peak flow, $\{Q_e^7(i), i = 1, 2, \dots, N - 6\}$, we find the following:

$$I_{51} = \text{Min}[Q_e^7(i)] \quad (7)$$

$$I_{54} = \text{Max}[Q_e^7(i)] \quad (8)$$

The third group of indicators, I_{67} – I_{72} , referred to as timing of annual extremes, characterizes the temporal location when annual extreme values occur, i.e., the timing of annual minimum or maximum values. Taking the date of annual minimum daily ebb-peak flow, I_{67} , and annual maximum daily ebb-peak flow, I_{68} , as examples, we find the following:

$$I_{67} = \text{Argmin}[X(i)] \quad (9)$$

$$I_{68} = \text{Argmax}[X(i)] \quad (10)$$

The fourth group of indicators, I_{73} – I_{84} , referred to as frequency and duration of high and low pulses, characterizes occurrence frequency and average duration of low-pulse and high-pulse hydrological events. Low and high pulses generally refer to events below the 25th percentile and above the 75th percentile values, respectively. Note that daily highest water level only considers high-pulse events, while daily lowest water level only considers low-pulse events. Taking low-pulse event frequency, I_{73} , and mean duration for daily ebb-peak flow, I_{74} , as examples, where Q25 is the 25th percentile value of daily ebb-peak flow, and based on the Run method, the start and end times of low-pulse events below the threshold (Q25) are obtained as $\{T_s(j), j = 1, 2, \dots, L\}$ and $\{T_e(j), j = 1, 2, \dots, L\}$, respectively, with L being the number of events, and we find the following:

$$I_{73} = L \quad (11)$$

$$I_{74} = \sum_{j=1}^L [T_e(j) - T_s(j) + 1] / L \quad (12)$$

The fifth group of indicators, I_{85} – I_{94} , referred to as rate and frequency of hydrological change, characterizes hydrological process changes, including average rising rate, average falling rate, and number of reversals. Here, daily highest water level only considers average rising rate and number of reversals, while daily lowest water level only considers average falling rate and number of reversals. Taking changes in daily ebb-peak flow, I_{85} , I_{86} , I_{87} , as examples, based on monotonicity principles of flow variation, monotonically increasing and decreasing events are identified with start and end times of $\{\hat{T}_s(j), j = 1, 2, \dots, K_1\}$, $\{\hat{T}_e(j), j = 1, 2, \dots, K_1\}$, and $\{\check{T}_s(j), j = 1, 2, \dots, K_2\}$, $\{\check{T}_e(j), j = 1, 2, \dots, K_2\}$, respectively, with event counts of K_1 and K_2 , giving the following:

$$I_{85} = \sum_{j=1}^{K_1} \frac{Q_e[\hat{T}_e(j)] - Q_e[\hat{T}_s(j)]}{\hat{T}_e(j) - \hat{T}_s(j)} / K_1 \quad (13)$$

$$I_{86} = \sum_{j=1}^{K_2} \frac{Q_e[\check{T}_e(j)] - Q_e[\check{T}_s(j)]}{\check{T}_e(j) - \check{T}_s(j)} / K_2 \quad (14)$$

$$I_{87} = K_1 + K_2 - 1 \quad (15)$$

The sixth group adds indicators characterizing typical tidal features, setting annual maximum 7-day moving average daily tidal range, I_{95} , and annual minimum 7-day moving average ratio of ebb tide duration, I_{96} . Letting daily tidal range and ebb tide duration ratio be $\{R_h(i), i = 1, 2, \dots, N\}$ and $\{r_T(i), i = 1, 2, \dots, N\}$, respectively, then the 7-day moving averages for tidal range and duration ratio are $\{R_h^7(i), i = 1, 2, \dots, N - 6\}$ and $\{r_T^7(i), i = 1, 2, \dots, N - 6\}$, giving the following:

$$I_{95} = \text{Max} [R_h^7(i)] \quad (16)$$

$$I_{96} = \text{Min} [r_T^7(i)] \quad (17)$$

3.3. Abrupt Change Detection in Hydrological Processes

To identify potential abrupt changes or stepwise mean shifts that may exist in the hydrological series during the study period, the moving t -test was applied to conduct point-by-point testing of time series [14,19,79]. This method determines whether the sequence has undergone variation near a given location by comparing whether the difference between means of two sub-sequences before and after a candidate time point reaches statistical significance. In this study, this method was applied to identify change points in the 1960–2019 annual mean discharge series at the three upstream boundary stations. Moving windows of 3 or 5 years are standard for hydrological time series mutation detection; a 5-year window was selected herein considering the 60-year length of our annual dataset, as it suppresses short-term interannual noise while retaining long-term hydrological evolution signals, consistent with prior research [80,81].

For any candidate year k , the periods before and after it constitute two adjacent sub-samples, denoted by their means, $\bar{q}_1$ and $\bar{q}_2$, and variances, s_1^2 and s_2^2 , respectively. Assuming equal population variances for the two sub-samples, the pooled t -statistic can be expressed as follows:

$$t_k = \frac{\bar{q}_1 - \bar{q}_2}{s_p \sqrt{\frac{1}{n_1} + \frac{1}{n_2}}} \quad (18)$$

where n_1 and n_2 are the lengths of the two sub-samples before and after the candidate year, respectively, and s_p is the pooled standard deviation:

$$s_p = \sqrt{\frac{(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2}{n_1 + n_2 - 2}} \quad (19)$$

where statistic, t_k follows a t -distribution with degrees of freedom, $n_1 + n_2 - 2$. At a given significance level, if $|t_k| > t_{1-1/2\alpha}$, the mean difference between the two periods before and after is considered statistically significant, and this position can be regarded as a candidate change point. Considering overlapping between adjacent sliding windows, consecutive years with significant statistics usually correspond to the same variation period; therefore, the year with the maximum $|t_k|$ is further taken as the most likely change year.

3.4. Analysis of Hydrological Alteration

River hydrological regime changes can be studied from three aspects: range alteration, central tendency alteration, and dispersion alteration. Based on the AIHA indicator system [82], this study uses the range of variability approach (RVA), relative change of the median (RCM), and relative change of dispersion (RCD) methods to analyze hydrological regime changes in tidal rivers. The core concept of RVA is to use the natural variation range of hydrological indicators during the undisturbed period (usually set as the 25th–75th percentile) as a baseline. When rivers are affected by human factors such as water conservancy

projects, the hydrological indicators after disturbance are compared with the set target range to calculate the degree of hydrological alteration [15,16,20]. If the number of years in which an indicator falls within the target range decreases significantly, this indicates that the hydrological characteristic has been obviously altered. This study uses the mutation year as the boundary to divide the AIHA indicator series of tidal rivers into two stages: the pre-mutation series is used as the baseline, and the post-mutation range alteration is studied. Thus, we have the following:

$$D_1(i) = \frac{n[I_a(i)] - n[I_p(i)]}{n[I_p(i)]} \times 100\% \quad (20)$$

$$D_1 = \frac{1}{m} \sum_{i=1}^m |D_1(i)| \quad (21)$$

where $D_1(i)$ denotes the alteration degree of any AIHA indicator i , m is the number of the AIHA indicators, and $n[I_p(i)]$ and $n[I_a(i)]$ are the observed and expected number of years in which the indicator value falls within the natural variation range before and after the mutation, respectively. $D_1(i) > 0$ indicates that the frequency of falling within the target range is higher than expected and the hydrological regime tends to be stable or concentrated; $D_1(i) < 0$ indicates that the frequency of falling within the target range is lower than expected and the hydrological regime fluctuates more intensely or deviates from the natural state. Based on the comprehensive alteration degree of hydrological characteristics, D_1 , it can be judged whether the overall hydrological regime fluctuation is in a state of low ($D_1 < 33\%$), moderate ($33\% \leq D_1 < 66\%$), or high ($D_1 \geq 66\%$) alteration.

Relative change of the median (RCM) defines hydrological regime change as the relative change rate of the indicator median value in the study period (e.g., the period after the mutation) relative to the baseline period (e.g., the period before the mutation) [21,83], which can reflect the change in central tendency of indicators in the AIHA system. We find the following:

$$D_2(i) = \frac{Me[I_a(i)] - Me[I_p(i)]}{|Me[I_p(i)]|} \times 100\% \quad (22)$$

$$D_2 = \frac{1}{m} \sum_{i=1}^m |D_2(i)| \quad (23)$$

where $D_2(i)$ denotes the median alteration degree of any AIHA indicator i , D_2 is the overall alteration degree based on the median of indicators in the AIHA system, and $Me[I_p(i)]$ and $Me[I_a(i)]$ are the median values of indicator i before and after the mutation, respectively. If $D_2(i) > 0$, the hydrological indicator median increases and if $D_2(i) < 0$, the hydrological indicator median decreases. Based on the comprehensive alteration degree of hydrological characteristics, D_2 , it can be judged whether the overall hydrological characteristic central tendency is in a state of low ($D_2 < 33\%$), moderate ($33\% \leq D_2 < 66\%$), or high ($D_2 \geq 66\%$) alteration.

Relative change of the dispersion (RCD) defines hydrological regime change as the relative change rate of the indicator coefficient of variation in the study period (e.g., the period after the mutation) relative to the baseline period, which can reflect the dispersion alteration of indicators in the AIHA system. We have the following:

$$D_3(i) = \frac{Cv[I_a(i)] - Cv[I_p(i)]}{Cv[I_p(i)]} \times 100\% \quad (24)$$

$$D_3 = \frac{1}{m} \sum_{i=1}^m |D_3(i)| \quad (25)$$

where $D_3(i)$ denotes the dispersion alteration degree of any AIHA indicator i , D_3 is the overall alteration degree based on the coefficient of variation of indicators in the AIHA system, and $Cv[I_p(i)]$ and $Cv[I_a(i)]$ are the coefficients of variation of indicator i before and after the mutation, respectively. If $D_3(i) > 0$, the hydrological indicator dispersion increases and if $D_3(i) < 0$, the hydrological indicator dispersion decreases. Based on the comprehensive alteration degree of hydrological characteristics, D_3 , it can be judged whether the overall dispersion degree of hydrological characteristics is in a state of low ($D_3 < 33\%$), moderate ($33\% \leq D_3 < 66\%$), or high ($D_3 \geq 66\%$) alteration.

3.5. Importance Assessment of AIHA Indicators

As there is generally a certain degree of correlation among various AIHA indicators, the alteration degrees assessed by different methods may show significant differences or convergence. Criteria importance through intercriteria correlation (CRITIC) is an objective weighting method used to determine the weights of evaluation indicators in multi-criteria decision analysis. Its core idea is to measure information quantity based on the contrast intensity and conflict of indicators [84,85]. The CRITIC weighting method was selected in preference to alternative objective weighting tools because the AIHA framework integrates multiple indicators across different alteration dimensions, which may involve overlapping information. Thus, CRITIC helps reduce redundancy without relying on subjective preference assumptions. Based on the analysis of range alteration, central tendency alteration, and dispersion alteration of the river hydrological regime, the CRITIC method can be used to evaluate the relative importance of AIHA indicator alteration degrees. Given the hydrological alteration degrees $D_j(i)$, $i = 1, 2, \dots, m; j = 1, 2, 3$, the information content of each alteration degree, C_j , is calculated by the product of standard deviation and conflict, and normalized to obtain the following weight:

$$C_j = \sigma(D_j) \sum_{k=1}^3 [1 - \rho(D_j, D_k)] \quad (26)$$

$$\omega_j = C_j / \sum_{j=1}^3 C_j \quad (27)$$

where $\sigma(D_j)$ is the standard deviation of the j -th alteration degree of the AIHA indicator system and $\rho(D_j, D_k)$ is the correlation coefficient between the j -th and k -th alteration degrees in the AIHA system. The comprehensive alteration degree of AIHA indicators, $D(i)$, integrated by the three methods is as follows:

$$D(i) = \omega_1 |D_1(i)| + \omega_2 |D_2(i)| + \omega_3 |D_3(i)| \quad (28)$$

For tidal river networks, the Borda count method is introduced to integrate weighting results from various stations, constructing a multi-site consistency comprehensive score. At each station, all AIHA indicators are ranked in descending order according to their CRITIC-weighted comprehensive alteration degree, $D(i)$, obtained from Equation (28), with larger $D(i)$ values indicating stronger hydrological alterations. The station-level ranks are then converted into Borda scores and summed across all stations to obtain the total Borda score for each indicator, which is further normalized as a percentage score to facilitate comparison. If the number of stations in the study area river network is N_s and the rank of any AIHA indicator, $D(i)$, at the k -th station is $R(i, k)$, then the Borda score $B(i)$ and percentage score $S(i)$ of the indicator are, respectively, as follows:

$$B(i) = \sum_{k=1}^{N_s} [m - R(i, k)] \quad (29)$$

$$S(i) = \frac{B(i)}{\sum_{i=1}^m B(i)} \times 100 \quad (30)$$

The relative importance of indicators in AIHA system in a river network area can be comprehensively reflected based on the weight of multi category change degree and the score of multi-sites.

4. Results and Discussion

4.1. Detection of Abrupt Change Points

Moving t -tests ($\alpha = 0.05$, 5-year window) applied to the 1960–2019 annual flow series at the three major inflow boundaries identified several statistically significant change points (Figure 2). At Gaoyao (S1) on the Xinjiang River, significant mean shifts were detected in 1986, 1991, 1992, and 2002; at Shijiao (S5) on the Beijing River in 1964, 1984, 1985, 1986, 1991, and 1992; and at Boluo (S9) on the Dongjiang River in 1973, 1974, 1985, 1986, and 1991. Notably, for Gaoyao and Shijiao—the two stations contributing the majority of freshwater input to the delta—the strongest statistical signals occurred in 1991, with t -values reaching 4.7 and 4.5 respectively, indicating robust upward shifts in mean discharge. Boluo station exhibited its most significant mean decline in 1985 ($t = -4.8$), though 1991 also registered a significant positive shift ($t = 2.5$).

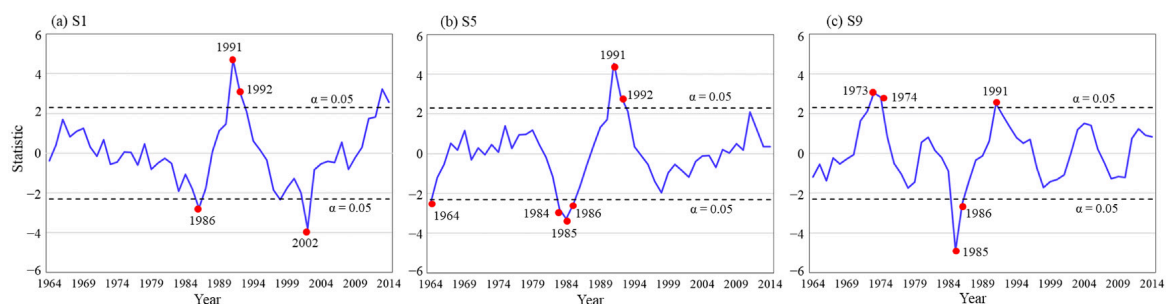


Figure 2. Change point detection of upstream streamflow based on moving t -test: (a) Gaoyao station (S1), (b) Shijiao station (S5), and (c) Boluo station (S9). Blue lines, red dots, and dashed lines indicate moving t -statistics, significant change points, and $\alpha = 0.05$ thresholds, respectively.

The year 1991 showed collective and regionally consistent significance across all three major inflow boundaries and coincided with intensified anthropogenic intervention in the Pearl River Basin around the early 1990s. During this period, large hydraulic infrastructure projects, rapid urbanization, increasing river-flow regulation, and substantially increased water withdrawal demands became prominent in the PRD [46,52,86]. Based on this statistical consistency and anthropogenic background, 1991 was adopted as a representative hydrological change point for the PRD study. Consequently, the period 1960–1991 was defined as the reference (pre-disturbance) period, while 1992–2019 represents the altered (post-disturbance) period for all subsequent analyses.

Discussion: Our detection of 1991 as a regional tipping point supports previous findings by Zhang et al. [40] who identified the early 1990s as a transition period for the Pearl River hydrological regime, though their analysis focused primarily on the Xijiang River. The divergence between the Xijiang and Beijiang Rivers (positive mean shift) and the Dongjiang River (negative mean shift in 1985, weaker positive in 1991) reflects differing basin characteristics: the Dongjiang River watershed is smaller, and subject to higher water abstraction pressures for municipal supply to the eastern PRD megacities, potentially explaining its earlier and more pronounced anthropogenic signal [87]. Therefore, the 1991 breakpoint was used as a representative regional threshold to provide a consistent basis for comparative analyses, while complementary change-point methods, such as the Pettitt test, may provide additional support in future analyses.

4.2. Spatiotemporal Patterns of Hydrologic Alteration

Based on the river network hydrodynamic simulation and hydrological alteration index calculation formulas, annual series of AIHA were obtained for the 12 representative stations in the study area, followed by quantitative assessments using the RVA, RCM, and RCD methods.

4.2.1. Individual and Overall Alteration for the AIHAs

The classification heatmaps of alteration degrees for individual AIHA indicators are shown in Figure 3, with distributions of negative/positive alterations and proportions at various levels presented in Tables 3 and 4.

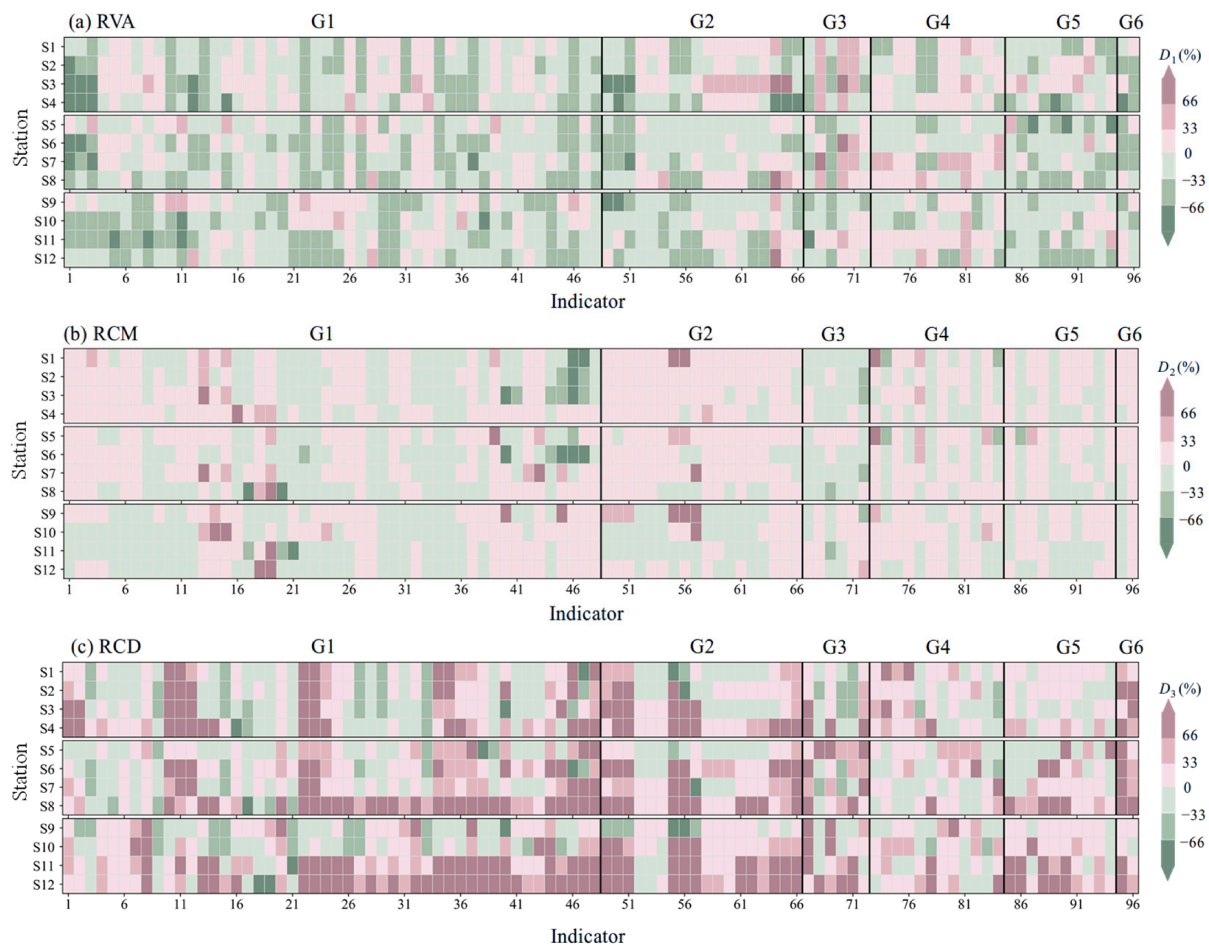


Figure 3. Heatmaps of station-specific hydrologic alteration levels based on (a) RVA, (b) RCM, and (c) RCD.

RVA-based assessment: Across the entire river network, the proportion of indicators showing negative alteration was substantial. Specifically, negative alteration ratios ranged from 46.9–66.7% in the Xijiang Waterway Zone, 63.5–77.1% in the Beijiang Waterway Zone, and 62.5–78.1% in the Dongjiang Waterway Zone. These results indicate that during the study period, the frequency of various hydrological indicators falling within the natural variability range was generally lower than expected based on the reference period, with many indicators in the river network deviating from their normal ranges.

Table 3. Count and ratio of indicators of hydrological alteration for various levels.

Waterway	Station	RVA						RCM						RCD					
		Negative		Positive		None		Negative		Positive		None		Negative		Positive		None	
		Count	Ratio	Count	Ratio	Count	Ratio	Count	Ratio	Count	Ratio	Count	Ratio	Count	Ratio	Count	Ratio	Count	Ratio
Xijiang	S1	57	59.4	22	22.9	17	17.7	40	41.7	50	52.1	6	6.3	40	41.7	55	57.3	1	1.0
	S2	62	64.6	24	25.0	10	10.4	39	40.6	52	54.2	5	5.2	39	40.6	57	59.4	0	0.0
	S3	45	46.9	44	45.8	7	7.3	40	41.7	50	52.1	6	6.3	47	49.0	49	51.0	0	0.0
	S4	64	66.7	15	15.6	17	17.7	31	32.3	61	63.5	4	4.2	26	27.1	70	72.9	0	0.0
Beijiang	S5	70	72.9	19	19.8	7	7.3	30	31.3	61	63.5	5	5.2	46	47.9	49	51.0	1	1.0
	S6	74	77.1	17	17.7	5	5.2	46	47.9	50	52.1	0	0.0	31	32.3	65	67.7	0	0.0
	S7	62	64.6	27	28.1	7	7.3	33	34.4	57	59.4	6	6.3	35	36.5	61	63.5	0	0.0
	S8	61	63.5	29	30.2	6	6.3	49	51.0	41	42.7	6	6.3	15	15.6	81	84.4	0	0.0
Dongjiang	S9	66	68.8	24	25.0	6	6.3	41	42.7	51	53.1	4	4.2	42	43.8	53	55.2	1	1.0
	S10	71	74.0	18	18.8	7	7.3	44	45.8	45	46.9	7	7.3	35	36.5	61	63.5	0	0.0
	S11	60	62.5	23	24.0	13	13.5	55	57.3	35	36.5	6	6.3	18	18.8	78	81.3	0	0.0
	S12	75	78.1	15	15.6	6	6.3	49	51.0	43	44.8	4	4.2	13	13.5	83	86.5	0	0.0

Table 4. Integrated single-dimension alteration degree in term of all indicators.

Waterway	Station	D_1 (%)	Ratio for D_1 (%)			D_2 (%)	Ratio for D_2 (%)			D_3 (%)	Ratio for D_3 (%)		
			Low	Moderate	High		Low	Moderate	High		Low	Moderate	High
Xijiang	S1	22.8	70.8	29.2	0.0	17.9	87.5	7.3	5.2	33.6	67.7	19.8	12.5
	S2	25.0	68.8	30.2	1.0	13.0	94.8	4.2	1.0	61.9	64.6	19.8	15.6
	S3	29.2	58.3	31.3	10.4	18.8	89.6	7.3	3.1	39.6	62.5	18.8	18.8
	S4	29.5	63.5	25.0	11.5	9.2	95.8	3.1	1.0	65.1	52.1	17.7	30.2
Beijiang	S5	23.7	71.9	25.0	3.1	17.0	86.5	11.5	2.1	32.7	64.6	25.0	10.4
	S6	28.1	65.6	31.3	3.1	17.9	92.7	3.1	4.2	49.6	52.1	24.0	24.0
	S7	27.5	60.4	34.4	5.2	12.6	91.7	5.2	3.1	34.7	65.6	19.8	14.6
	S8	28.7	59.4	39.6	1.0	11.6	94.8	2.1	3.1	90.6	34.4	18.8	46.9
Dongjiang	S9	25.5	68.8	29.2	2.1	20.0	88.5	6.3	5.2	30.2	68.8	20.8	10.4
	S10	25.8	69.8	28.1	2.1	10.0	93.8	3.1	3.1	51.9	57.3	30.2	12.5
	S11	27.2	62.5	33.3	4.2	6.8	94.8	3.1	2.1	90.5	43.8	14.6	41.7
	S12	26.6	60.4	38.5	1.0	6.7	96.9	1.0	2.1	117.1	29.2	18.8	52.1

However, although most AIHA indicators have deviated from the reference period state, the overall pattern was dominated by low-intensity alteration. The negative alteration ratio reflects how many indicators deviated in the negative direction, while D_1 represents the magnitude of deviation; thus, widespread negative alteration does not necessarily imply severe alteration intensity. The proportions of low-alteration indicators were 58.3–70.8% in the Xijiang Waterway Zone, 59.4–71.9% in the Beijiang Waterway Zone, and 60.4–69.8% in the Dongjiang Waterway Zone. Notably, at the downstream-to-estuary sections of the Xijiang Waterway (S3, S4), the proportion of high-alteration indicators was noticeably higher than in upstream reaches, with approximately 10.4–11.5% classified as high alteration, concentrated primarily in January–March ebb flow and annual extreme low-flow/low-water conditions.

The integrated alteration degree of AIHA (D_1) across the entire river network remained in the low alteration category, though spatial heterogeneity was evident. The Xijiang Waterway Zone showed the most pronounced station-to-station variation, ranging from 22.8% to 29.5%—the widest fluctuation range among the three waterways. Specifically, the upstream boundary inflow station (S1, Gaoyao) exhibited the lowest integrated alteration degree in the entire network at 22.8%, while the estuarine outlet (S4, Denglongshan) reached 29.5%, the highest in the network, demonstrating a clear pattern of increasing hydrological alteration from upstream to estuary along the Xinjiang Waterway. The Beijiang Waterway Zone and the Dongjiang Waterway Zone showed relatively smaller fluctuations in integrated alteration degrees, with ranges of 23.7–28.7% and 25.5–27.2%, respectively.

RCM-based assessment: The Xijiang Waterway Zone exhibited higher proportions of positive alteration indicators (52.1–63.5%) than negative alteration (32.3–41.7%), indicating a general shift in indicator central tendency toward higher values. Similarly, the Beijiang Waterway Zone showed higher positive alteration proportions (42.7–63.5%) compared with negative alteration (31.3–51.0%). Notably, at the upstream inflow boundary (S5, Shijiao), the positive alteration ratio of 63.5% was significantly higher than the negative ratio of 31.3%; however, at the estuarine outlet (S8, Sanshakou), the negative alteration ratio (51.0%) exceeded the positive ratio (42.7%), suggesting that except for this estuarine location, most hydrological indicators in this zone shifted toward higher central values. In contrast, the Dongjiang Waterway Zone showed a marked increase in negatively altered indicators, with their proportion being comparable to that of positively altered indicators in the upper and middle reaches (42.7–45.8%), but exceeding it in the estuarine area (51.0–57.3%), indicating a general shift in central tendency toward lower values in this zone.

Regarding alteration level classifications, low alteration dominated absolutely across all three zones: Xijiang Waterway 87.5–95.8%, Beijiang Waterway 86.5–94.8%, and Dongjiang Waterway 88.5–96.9%, indicating generally modest shifts in central tendency. However, for moderate and high alteration levels, all three zones exhibited a differentiation pattern where upstream locations showed higher alteration than estuarine sites. For example, in the Xijiang Waterway Zone, the upstream Gaoyao station (S1) showed moderate and high alteration ratios of 7.3% and 5.2%, respectively—significantly higher than the estuarine Denglongshan (S4) values of 3.1% and 1.0%—suggesting that upstream cross-sections experienced stronger disturbance in central tendency when compared with estuarine areas. Indicators with large central tendency changes were concentrated primarily in the dry-season lowest water level indicators at monthly scales (AIHA 46–48) in the Xijiang Waterway Zone and the Beijiang Waterway Zone.

The integrated alteration degrees of AIHA (D_2) across the entire network were all in the low alteration category, ranging from 9.2–18.8% (Xijiang Waterway), 11.6–17.9% (Beijiang Waterway), and 6.7–20.0% (Dongjiang Waterway). The Dongjiang Waterway Zone showed the most significant station-to-station differences, representing the widest

fluctuation range among the three zones: the upstream boundary (S9, Boluo) reached 20.0% (highest in the entire network), while the estuarine outlet (S12, Sishengwei) was only 6.7% (lowest in the network). The Xijiang Waterway Zone showed the next largest variation, with 17.9% at the upstream boundary (S1) versus 9.2% at the estuary (S4). The Beijiang Waterway Zone exhibited relatively smaller fluctuations, ranging from 11.6% to 17.9%.

RCD-based assessment: Across all three zones, the positive alteration ratios (51–86.5%) exceeded the negative alteration ratios (13.5–49%), indicating an overall enhancement in the dispersion degree of various hydrological indicators. Further comparison revealed that, when compared with upstream and midstream sections, positive alteration was more pronounced at estuarine outlets: the Xijiang Waterway estuary showed 72.9% positive alteration, the Beijiang Waterway estuary 84.4%, and the Dongjiang Waterway estuary 86.5%—highlighting particularly prominent volatility enhancement in estuarine areas.

This spatial pattern was also reflected in the distribution of alteration level classifications. When excluding estuarine stations the Xijiang Waterway Zone showed low/moderate/high proportions of 62.5–67.7%/18.8–19.8%/12.5–18.8%; the Beijiang Waterway Zone 52.1–65.6%/19.8–25%/10.4–24%; and the Dongjiang Waterway Zone 57.3–68.8%/20.8–30.2%/10.4–12.5%. Non-estuarine stations across all three zones were dominated by low-alteration indicators. In contrast, estuarine stations showed markedly different alteration level structures. At the four estuarine outlets (S4, S8, S11, S12), low-alteration indicators were only 52.1%, 34.4%, 43.8%, and 29.2%, respectively. Particularly at the two east river estuarine outlets (S11, S12), high-alteration indicators reached 41.7% and 52.1%, concentrated primarily in monthly average high/low water level indicators (AIHA 25–48), with some lowest water level indicators exceeding 100% alteration—indicating substantially more volatile water level conditions in these estuarine areas.

The integrated alteration degrees (D_3) across the entire network generally reached moderate-to-high alteration levels. Specifically, Xijiang Waterway Zone ranged from 33.6% to 65.1%; Beijiang Waterway Zone from 32.7% to 90.6%; and Dongjiang Waterway Zone from 30.2% to 117.1%. The Dongjiang Waterway Zone showed the most pronounced intensification of indicator volatility. All three zones exhibited consistent increasing patterns, with integrated alteration degrees gradually increasing from upstream to estuary: Xijiang Waterway increased from 33.6% at the upstream boundary (S1) to 65.1% at the estuary (S4); Beijiang Waterway from 32.7% (S5) to 90.6% (S8); and Dongjiang Waterway from 30.2% (S9) to 117.1% (S12).

Discussion: Widespread departures from natural ranges, as indicated by high negative alteration ratios, together with generally low integrated alteration degrees, suggest that the PRD hydrological regime has shifted significantly from its pre-1991 condition, but has not undergone complete system-wide disruption. This combination of evident alteration and limited overall degradation has also been reported in other large, regulated river systems, where human interventions modify flow seasonality and variability while some aspects of the original hydrological structure remain detectable [88,89]. At the same time, the marked upstream-to-estuary increase in alteration highlights a strong spatial inequality in hydrological stress, with downstream reaches likely affected by the cumulative influence of upstream regulation, local channel modification, and estuarine forcing, including sea-level rise. Therefore, the observed spatial gradient should be interpreted as the outcome of cumulative hydrological regulation and progressively stronger estuarine control, rather than as a simple downstream increase in alteration values.

The contrasting RCM trends, with rising values in the Xijiang Waterway Zone and the Beijiang Waterway Zone and falling values in the Dongjiang Waterway Zone, likely reflect differences in basin characteristics and water management contexts. Although the Dongjiang River watershed is the smallest of the three systems, it is closely associated with

some of the most densely populated and economically dynamic areas in the eastern PRD, including major cities such as Shenzhen and Dongguan [90]. The relatively low median flows observed in the Dongjiang River watershed may reflect the combined influence of reservoir regulation, inter-basin water transfers, and substantial consumptive water use for municipal supply, particularly from major reservoirs such as Xinfengjiang and Fengshuba [91]. Conversely, the Xijiang River and the Beijiang River, serving as the primary flood conveyance channels for the PRD, have experienced extensive levee construction and channelization that may have increased conveyance efficiency during normal flows, coupled with potential increases in upstream precipitation or runoff efficiency due to land-cover changes in their vast upstream catchments [92].

The dramatic amplification of RCD toward the estuaries, exceeding 100% at the Dongjiang Waterway estuary, highlights a marked deterioration of hydrological stability in the tidal zone. Rather than reflecting a single driver, this pattern more likely results from the joint influence of upstream regulation and downstream tidal forcing, which together can produce stronger variability in estuarine hydrological conditions. In the lower channels, this effect may be further reinforced by navigation-related channel deepening that enhances tidal propagation, while upstream regulation may reduce the buffering capacity of freshwater inflows [26,93]. The combined influence of these factors likely contributes to the pronounced variability observed at the estuarine stations S11 and S12, where low-water indicators exceed 100% alteration, suggesting that minimum water levels have become markedly more unstable relative to the reference period. This increased variability may in turn elevate the frequency and intensity of saline wedge intrusion during the dry season [94].

Overall, the observed spatial differentiation of hydrologic alteration is interpreted as the cumulative outcome of multiple regional anthropogenic and tidal drivers, rather than as the effect of a single dominant factor. Previous studies in the PRD have shown that upstream reservoir regulation and water resource projects can reshape seasonal runoff distribution, environmental flow conditions, and hydrological regimes, particularly in the Dongjiang River [34–36,43,90]. Meanwhile, rapid urbanization, land reclamation, and broader land-cover changes may alter catchment hydrological responses, water demand, sediment transport, and flood conveyance processes [46,51–53]. In the lower Pearl River system, extensive sand mining, channel dredging/deepening, and riverbed morphological adjustment have further modified channel geometry, enhanced tidal propagation, and affected estuarine water level dynamics [46,58,91]. Together, these regional findings support our interpretation that the detected AIHA alteration patterns, especially the amplified variability and low-water alterations in downstream estuarine zones, reflect the cumulative effects of upstream regulation, catchment-scale land-use change, and local channel adjustment.

4.2.2. Alteration for Properties of Group

The integrated hydrological alteration degrees and relative contributions by property groups are presented in Table 5.

RVA-based assessment: In the Xijiang and Beijiang Waterway Zones, Group G3 (extreme timing) reached moderate alteration levels of 35.7–52.4% and 34.5–46.4%, respectively. Additionally, Group G2 (extreme events) in the downstream Xijiang Waterway (S3, S4) reached 36.9–39.3%, and Group G6 (tidal characteristics) in the mid-upstream Beijiang Waterway main channel (S5–S7) reached 32.1–46.4%—all classified as moderate alteration. Notably, Group G6 at the Xijiang Waterway estuary (S4) reached high alteration (67.9%). The Dongjiang Waterway Zone showed generally low alteration except for Group G6 at the upstream station (S10) at 35.7% (moderate). These results indicate that extreme event

timing (G3) and tidal characteristics (G6) exhibited high alteration degrees in the Xijiang and Beijiang Waterway Zones.

RCM-based assessment: Only Group G2 at the upstream Boluo (S9) in the Dongjiang Waterway reached moderate alteration with an integrated alteration degree of 53.6%, indicating relatively obvious changes in extreme hydrological event dates. All other station groups showed low alteration. Despite limited overall alteration, certain upstream groups in each zone showed integrated alteration degrees obviously higher than the overall average: for example, Group G4 at Xijiang Waterway upstream Gaoyao (S1) and Beijiang Waterway upstream Shijiao (S5) reached 26.2% and 31.4%, respectively—again demonstrating that upstream areas experienced relatively stronger disturbance. Among the six groups, Group G1 (monthly characteristics) generally showed higher integrated alteration degrees than other types, with most stations exceeding 15%, indicating relatively obvious central deviations in monthly-scale average hydrological conditions.

RCD-based assessment: In the Xijiang Waterway Zone, Group G1 remained at moderate alteration overall, while Groups G2 and G3 gradually strengthened from upstream to downstream—with the estuary (S4) reaching 95.6% (G2) and 84.1% (G3), classified as high alteration. In the Beijiang Waterway Zone, Groups G3 and G6 showed the most prominent alteration: G3 reached 78.2% (S5) and 94.7% (S8), while G6 reached 120.5% (S6) and 98.5% (S8)—both showing significant high alteration; the estuary (S8) showed generally high alteration across all groups. In the Dongjiang Waterway Zone, excluding the upstream (S9), most indicator groups showed obvious elevation at mid-downstream and estuarine stations—particularly Group G2, reaching 122.7% (S10), 120.1% (S11), and 132.1% (S12), and Group G3, reaching 96.1% (S11) and 100.1% (S12).

Discussion: The differential sensitivity of indicator groups reveals distinct ecological and management implications. The prominence of Group G3 (timing of extreme event) and Group G6 (characteristic of tidal-influenced events) in high-alteration categories (particularly in the RVA and RCD dimensions) highlights that the timing of extreme events and tidal regime characteristics are the most vulnerable aspects of the hydrological regime in the PRD. This aligns with theoretical expectations: extreme timing controls biological phenology (fish spawning, bird migration), while tidal characteristics govern salinity intrusion and wetland inundation patterns [95]. The fact that G6 reaches high alteration levels (67.9% at S4, 120.5% at S6) confirms that channel modifications have fundamentally altered tidal propagation in the delta, with cascading effects on sediment transport and estuarine ecosystem functioning.

The divergence in dominant contributors across zones suggests zone-specific alteration mechanisms. Specifically, G2 (extreme events) dominates in the Xijiang Waterway Zone, G3/G6 in the Beijiang Waterway Zone, and G2/G3 in the Dongjiang Waterway Zone. The Xijiang Waterway Zone, characterized by high discharge volumes and an extensive floodplain, primarily exhibits alterations in extreme event magnitude (G2), likely associated with broader upstream flow regulation and catchment-scale hydrological modification. The Beijiang Waterway Zone shows greater sensitivity to extreme timing and tidal characteristics, possibly owing to their shorter channel length and stronger tidal influence. In contrast, the Dongjiang Waterway Zone exhibits a combined sensitivity to both extreme magnitudes and timing.

The contrasting spatial patterns between RCM (higher alteration upstream) and RCD (higher alteration downstream) reveal that upstream regulation primarily affects central tendencies (mean flows), while estuarine modifications amplify variability. This has management implications: restoring natural flow regimes upstream might address mean flow deviations, but managing estuarine stability requires addressing local channel modifications and their tidal amplification effects [96,97]. The moderate-to-high alteration of G1

(monthly characteristics) across all zones suggests that seasonality—the fundamental template for riverine ecosystems—has been altered throughout the delta, potentially disrupting the reproductive cues of native species adapted to pre-1991 hydrological calendars [98].

4.2.3. Alteration by Hydrological Elements

The integrated alteration degrees grouped by the four hydrological elements—ebb-peak flow (EPF), residual water level (RWL), highest water level (HWL), and lowest water level (LWL)—are presented in Table 6.

RVA-based assessment: In the Xijiang Waterway Zone, the alteration degrees for EPF, RWL, HWL, and LWL were in the ranges of 24.6–34.1%, 22.2–27.8%, 20.0–30.4%, and 24.6–35.4%, respectively; in the Beijiang Waterway Zone, they were 24.6–32.5%, 23.8–29.9%, 21.1–28.6%, and 22.9–29.6%, respectively; and in the Dongjiang Waterway Zone, they were 21.2–39.2%, 19.6–30.7%, 22.5–29.3%, and 22.9–27.1%, respectively. Overall, low alteration dominated, with EPF showing higher alteration degrees than the various water level types. Notably, EPF reached moderate alteration at downstream-to-estuary sections of the Xijiang Waterway (S3, S4), mid-upper reaches of the Beijiang Waterway (S6, S7), and middle reaches of the Dongjiang Waterway (S10, S11).

RCM-based assessment: In the Xijiang Waterway Zone, the alteration degree ranges for EPF, RWL, HWL, and LWL were 7.4–17.4%, 12.9–22.5%, 2.3–9.2%, and 7.8–50.8%, respectively; in the Beijiang Waterway Zone, they were 3.3–20.0%, 12.8–33.5%, 2.6–10.5%, and 3.4–42.6%, respectively; and in the Dongjiang Waterway Zone, they were 2.1–14.6%, 15.8–35.4%, 2.7–4.0%, and 2.7–24.1%, respectively. LWL showed relatively high alteration degrees, with certain stations in the Xijiang and Beijiang Waterway Zones reaching moderate alteration; in contrast, EPF showed a significant decreasing pattern from upstream to estuary across all three zones: decreasing from 17.4% upstream to 7.4% at the estuary in the Xijiang Waterway Zone, from 20.0% upstream to 3.3% at the estuary in the Beijiang Waterway Zone, and from 14.6% upstream to 2.1% at the estuary in the Dongjiang Waterway Zone.

RCD-based assessment: In the Xijiang Waterway Zone, the alteration degree ranges for EPF, RWL, HWL, and LWL were 29.2–62.9%, 30.5–106.2%, 21.6–28.6%, and 35.1–94.1%, respectively; in the Beijiang Waterway Zone, they were 18.3–40.9%, 29.8–122.1%, 19.5–87.0%, and 49.3–118.0%, respectively; and in the Dongjiang Waterway Zone, they were 27.1–57.2%, 42.1–177.9%, 19.2–92.3%, and 29.1–155.9%, respectively. RWL and LWL consistently showed higher alteration degrees than EPF and HWL, indicating that water level processes respond more dramatically to volatility changes. Spatially, all four elements exhibited a consistent longitudinal pattern of increasing alteration from upstream to estuary across all zones. In the Xijiang Waterway Zone, RWL increased from 30.5% upstream (S1) to 106.2% at the estuary (S4), while LWL increased from 48.0% to 66.9%; in the Beijiang Waterway Zone, RWL increased from 29.8% upstream (S5) to 122.1% at the estuary (S8), while LWL increased from 60.1% to 118.0%; and in the Dongjiang Waterway Zone, this trend was particularly pronounced, with RWL increasing from 42.1% upstream (S9) to 177.9% at the estuary (S12), and LWL increasing from 29.1% to 155.9%.

Discussion: These element-specific results reveal three critical mechanisms of hydrological alteration in the PRD tidal network. First, the differential sensitivity between flow and water level indicators is striking: while EPF remains manageable (mostly low-to-moderate RVA), RWL and LWL show much stronger alteration (>100% RCD at estuaries). This contrast likely reflects the different hydrodynamic controls on flow and water level in tidal river network, where flow primarily integrates upstream forcing, whereas water levels are jointly influenced by upstream conditions, downstream tidal forcing, and local channel geometry.

Table 5. Group-level integrated hydrologic alteration degree categorized by six AIHA attribute classes.

Waterway Zone	Station	D ₁ (%)						D ₂ (%)						D ₃ (%)					
		G1	G2	G3	G4	G5	G6	G1	G2	G3	G4	G5	G6	G1	G2	G3	G4	G5	G6
Xijiang	S1	19.9	18.3	35.7	32.1	27.1	14.3	18.0	20.9	5.0	26.2	13.0	0.4	39.3	35.4	24.3	32.6	10.9	29.0
	S2	25.7	19.8	39.3	23.2	20.0	46.4	16.7	8.6	10.1	11.8	8.4	1.0	59.1	136	32.9	19.3	7.3	73.8
	S3	26.5	39.3	52.4	19.6	21.4	28.6	29.0	8.0	10.5	12.9	5.1	0.3	42.2	49.0	66.1	26.6	8.6	44.2
	S4	28.6	36.9	32.1	11.3	32.9	67.9	10.7	10.0	6.1	6.6	6.8	3.5	59.5	95.6	84.1	56.3	34.3	71.6
Beijiang	S5	21.1	15.5	29.8	22.6	47.1	32.1	15.6	14.0	5.8	31.4	21.5	3.1	38.4	14.6	78.2	19.0	25.9	39.9
	S6	28.9	27.4	36.9	19.6	27.1	46.4	24.4	11.3	6.8	17.0	9.2	3.5	47.5	72.7	54.2	27.4	28.3	120
	S7	23.8	24.6	46.4	33.9	28.6	39.3	13.6	17.6	8.7	8.1	8.3	2.6	34.6	52.9	46.8	17.4	9.9	65.5
	S8	27.4	31.0	34.5	24.4	34.3	21.4	18.0	2.0	9.5	9.0	4.8	1.6	104	101	94.7	42.7	58.2	98.5
Dongjiang	S9	24.6	34.9	29.8	19.0	19.3	21.4	14.1	53.6	10.5	11.7	6.9	2.6	30.7	33.8	59.8	23.2	16.1	8.1
	S10	29.5	19.0	23.8	23.8	22.1	35.7	11.7	11.6	10.7	7.2	3.4	4.5	36.5	122	48.4	34.7	25.9	31.2
	S11	30.2	23.4	26.2	21.4	30.7	10.7	8.5	3.0	14.9	3.9	5.2	3.0	92.2	120	96.1	63.0	65.4	55.9
	S12	26.2	29.0	19.0	25.0	33.6	10.7	8.0	2.4	12.7	8.0	4.4	2.6	130	132	100	86.5	77.6	78.1

Table 6. Integrated alteration degree in terms of hydrological elements.

Waterway Zone	Station	D ₁ (%)				D ₂ (%)				D ₃ (%)			
		EPF	RWL	HWL	LWL	EPF	RWL	HWL	LWL	EPF	RWL	HWL	LWL
Xijiang	S1	24.6	22.2	20.0	24.6	17.4	22.5	9.2	22.8	32.6	30.5	25.2	48.0
	S2	24.6	25.9	23.2	23.9	9.5	12.9	6.4	25.6	29.2	96.8	25.6	94.1
	S3	33.9	27.8	30.4	23.6	7.5	16.9	6.6	50.8	62.9	32.6	21.6	35.1
	S4	34.1	23.5	21.4	35.4	7.4	17.6	2.3	7.8	49.1	106.2	28.6	66.9
Beijiang	S5	24.6	24.9	21.1	22.9	20.0	16.3	10.5	21.8	18.3	29.8	28.0	60.1
	S6	31.2	23.8	26.4	29.6	13.7	12.8	7.1	42.6	32.3	43.4	35.7	88.4
	S7	32.5	27.2	22.9	24.3	8.6	18.4	8.2	15.5	28.9	38.7	19.5	49.3
	S8	27.5	29.9	28.6	29.6	3.3	33.5	2.6	3.4	40.9	122.1	87.0	118.0
Dongjiang	S9	29.1	23.3	22.5	27.1	14.6	35.4	3.9	24.1	27.1	42.1	21.7	29.1
	S10	32.8	19.6	26.8	22.9	4.1	17.4	4.0	14.6	38.6	90.1	19.2	53.3
	S11	39.2	21.2	24.3	23.9	4.3	15.8	2.7	2.7	57.2	116.6	64.3	129.7
	S12	21.2	30.7	29.3	23.6	2.1	16.4	3.3	3.9	54.9	177.9	92.3	155.9

Second, the opposing spatial patterns between RCM and RCD carry distinct management implications. The decreasing EPF alteration from upstream to estuary (RCM) suggests that upstream regulation (reservoirs, abstractions) primarily affects flow magnitudes, with tidal buffering moderating mean changes at the estuary. However, the increasing RWL/LWL alteration toward estuaries (RCD) reveals that tidal amplification dominates variability—as channels deepen, tidal energy increases, and the superposition of regulated flows with enhanced tidal signals creates extreme water level volatility.

Third, the strong representation of LWL in the high-alteration categories (reaching 118.0% in the Beijiang Waterway Zone and 155.9% in the Dongjiang Waterway Zone) suggests that low-water conditions deserve particular attention in the PRD tidal network. Compared with HWL, which shows relatively smaller changes (maximum 92.3% RCD), LWL appears substantially more sensitive to hydrological alteration in the estuarine reaches. This contrast may imply that current management has been more effective in addressing high-water conditions than low-water variability. In this context, the inclusion of LWL in the AIHA framework is especially important, because a discharge-focused assessment alone would not fully capture this dimension of alteration.

4.3. Indicator Importance and Key Drivers

The CRITIC weighting algorithm was applied separately at each station to assign relative importance weights to the three hydrological alteration dimensions (RVA, RCM, RCD), quantifying their relative information contributions to the comprehensive characterization of hydrological alterations at each station (Figure 4).

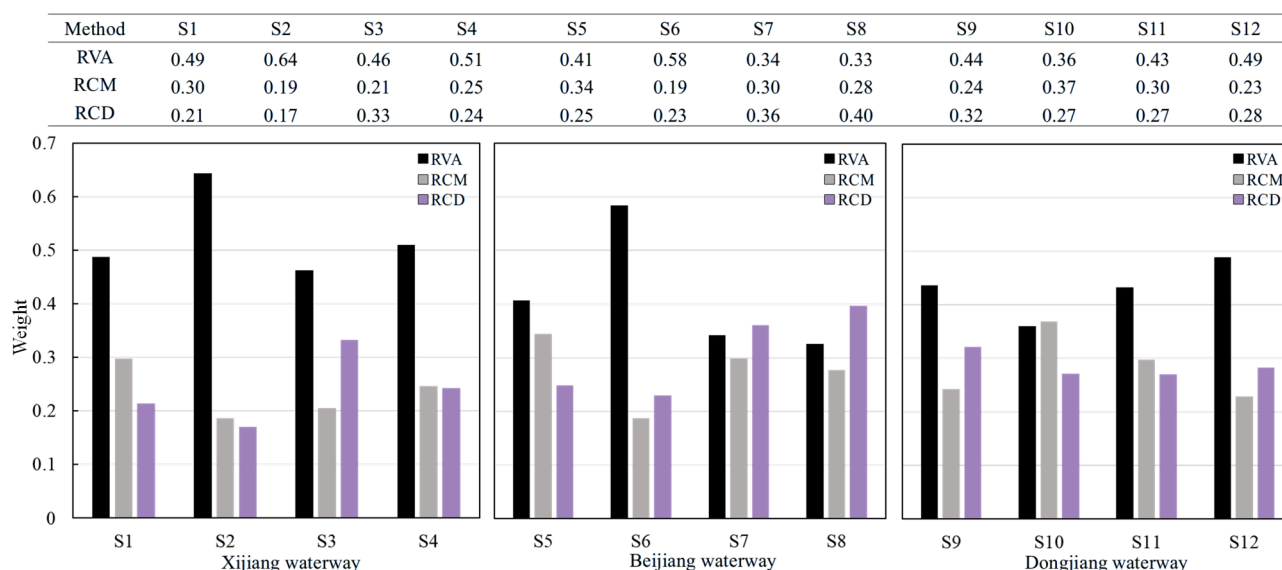


Figure 4. Weight of three methods for hydrological alteration assessment by the CRITIC.

Spatial patterns of CRITIC weights: The weight allocation results reveal spatial variations in the relative importance of the three characterization quantities. RVA exhibited weights ranging from 0.33 to 0.64, predominating at most stations and serving as the primary information source for comprehensive hydrological change characterization in the study area. RCM and RCD showed relatively lower but substantial weights, ranging from 0.19 to 0.37 and 0.17 to 0.40, respectively. In the Xijiang Waterway Zone, RVA consistently held the highest weight across all stations, reaching 0.64 at S2 (the maximum value in the entire river network), indicating that hydrological changes in this zone are predominantly manifested as deviations from the natural variability range. In the Beijiang Waterway Zone, RCD at S7 and S8 attained weights of 0.36 and 0.40, respectively, exceeding RVA, suggesting

that hydrological changes at mid-lower reaches and estuarine stations in this zone are more prominently characterized by altered dispersion features. In the Dongjiang Waterway Zone, RVA also maintained relatively high weights at all stations (0.44, 0.36, 0.43, and 0.49 at S9–S12). However, at S10, the RCM weight reached 0.37, slightly exceeding RVA's 0.36, indicating that hydrological changes at this station are somewhat more prominently manifested as shifts in the central position of indicators. Moreover, at the estuarine stations S11 and S12, RCM weights (0.30 and 0.23) were greater than or comparable to RCD (0.27 and 0.28), reflecting that center-state offset characteristics at estuarine locations also possess strong explanatory power. RCD showed relatively stable distribution in the Dongjiang Waterway Zone (0.27–0.32), maintaining consistently high information contributions despite not being dominant.

Borda scoring of AIHA indicators: Upon obtaining objective weights for the three characterization quantities, the weight results for each station were substituted into Equation (28) to conduct Borda scoring for all AIHA indicators, characterizing the comprehensive performance of indicators from a relative ranking perspective (Figure 5).

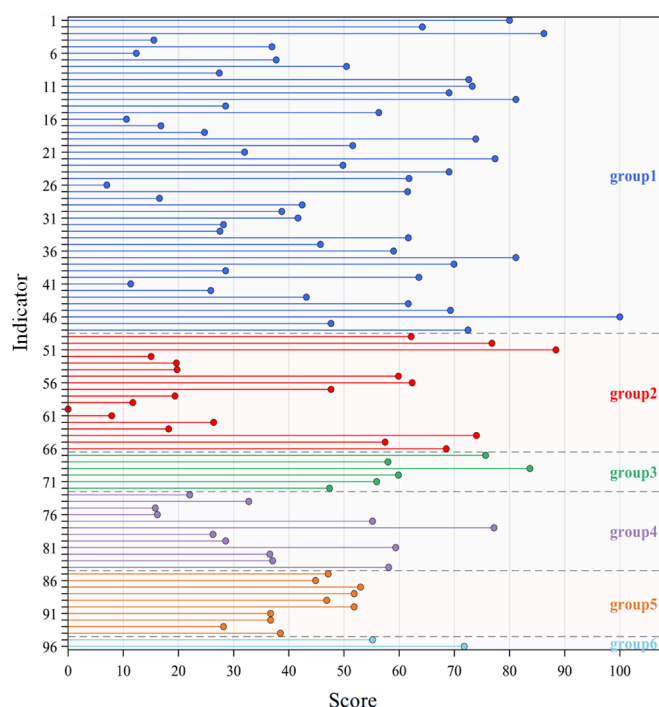


Figure 5. Individual scores of AIHA based on the Borda.

Group-level analysis: The Borda scoring results across six indicator groups revealed distinct patterns:

G1 (monthly characteristics): Mean score of 54.1, with high-scoring indicators predominantly concentrating on dry-season ebb-peak flows and low water levels. Notable high scores included October average lowest water level, January average lowest water level, January average ebb-peak flow, and March average ebb-peak flow—all exceeding 80, significantly higher than corresponding wet-season indicators.

G2 (extreme events): Mean score of 43.4, with high scores mainly concentrated on low-value extreme events. Representative indicators included annual minimum 7-day ebb-peak flow (88.4) and annual minimum 3-day ebb-peak flow (76.8), both markedly higher than corresponding high-value extreme event indicators.

G3 (timing): Mean score of 63.4, with generally high and relatively concentrated scores within the group. Changes in the occurrence dates of short-duration low-value events appeared particularly prominent.

G4 (frequency/duration): Mean score of only 38.8, the lowest among all six groups, with most indicators ranging from 15.8 to 37.1, indicating relatively limited discriminatory capacity for hydrological regime alterations.

G5 (rates): Mean score of 43.6, at a moderately low level, with flow reversal count and residual water level reversal count scoring relatively higher, suggesting certain representativeness for process adjustments.

G6 (tidal characteristics): Despite containing only two indicators, the mean score reached 63.5. Notably, the score for annual minimum 7-day flood-ebb duration ratio reached 71.8, significantly higher than annual maximum 7-day flow range at 55.2.

Element-level analysis: From the perspective of four hydrological element types, we found the following:

EPF-type indicators showed relatively high overall scores, particularly excelling in monthly-scale average conditions, extreme low-value events, and occurrence dates. Representative high-scoring indicators included March average ebb-peak flow (86.2), January average ebb-peak flow (80.0), annual minimum 7-day ebb-peak flow (88.4), and date of annual minimum 1-day ebb-peak flow (75.7). In contrast, annual maximum 1–7-day ebb-peak flow indicators scored only 15.0–19.7.

RWL-type indicators exhibited sensitivity to monthly-scale states and event timing variations, with weak responses in extreme high values. High-scoring indicators included January average residual water level (81.1), October average residual water level (77.4), and July average residual water level (73.9), whereas 1-, 3-, and 7-day annual maximum residual water level indicators all scored below 20.

HWL-type indicators showed relatively low overall scores, with particularly weak performance in the extreme events dimension. Among monthly-scale indicators, only January, March, and October average highest water level exceeded 60, while others remained at low-to-moderate levels; extreme event indicators (1-, 3-, and 7-day annual maximum highest water level) all scored below 30.

LWL-type indicators demonstrated outstanding performance in monthly-scale average conditions and extreme low-value events. Representative high-scoring indicators included October average lowest water level (100.0), January average lowest water level (81.1), December average lowest water level (72.5), Annual minimum 1-day lowest water level (74.0), and annual minimum 7-day lowest water level (68.5). Additionally, low water pulse duration (58.1) also remained at relatively high levels.

Discussion: The CRITIC weighting results reveal zone-specific dominant mechanisms of hydrological alteration across the PRD tidal network. The predominance of RVA in the Xijiang Waterway Zone indicates that hydrological changes there are primarily characterized by range deviations—the natural variability envelope has been systematically breached, likely due to upstream reservoir regulation altering the amplitude of seasonal variations. The elevation of RCD above RVA in the Beijiang Waterway Zone (S7, S8) suggests that variability amplification rather than mean deviation dominates at these locations, possibly reflecting intensified tidal modulation following channel modifications. The near-equal weighting of RVA and RCM at S10, coupled with elevated RCM weights at estuarine stations (S11, S12), indicates that central tendency shifts become increasingly important toward the estuary, where the balance between flow and tidal forcing creates persistent regime shifts.

The Borda scoring results provide critical guidance for indicator selection in monitoring network design. The stark contrast between G3's high scores (63.4) and G4's low scores (38.8) offers quantitative evidence that timing indicators (particularly low-flow event timing) are far more informative than frequency/duration indicators for capturing hydro-

logical alteration in tidal network. This has practical implications: monitoring programs should prioritize precise detection of extreme event timing.

The element-level scoring patterns reveal a significant asymmetry in hydrological sensitivity: low-value indicators consistently outscore high-value counterparts across all elements. The score for the annual minimum 7-day daily ebb flow is 88.4, whereas the score for the annual maximum 7-day daily ebb flow is only 19.4. This asymmetry suggests that ecological impacts of hydrological alteration in the PRD are likely concentrated in low-flow stress rather than high-flow disturbance regimes, as low-flow and low-water-level conditions correspond to periods when freshwater buffering is weakest and tidal forcing, saltwater intrusion, and water-use pressure become most influential.

High scores for some RWL and LWL indicators (e.g., 100, 81.1, and 77.4) highlight the importance of water level metrics in assessing hydrological alteration in tidal effect. Because water levels respond jointly to upstream discharge regulation, tidal propagation, channel morphology, and sea-level effects, they can complement flow-based indicators and capture alteration signals that may not be fully represented by flow metrics alone. These findings suggest that water level considerations should be included, together with flow-based metrics, in the ecological assessment and management of tidal river network.

4.4. Management Implications and Future Directions

The AIHA-based assessment provides several actionable insights for water resources management in the PRD:

First, prioritize low-flow maintenance and monitoring. The prominence of low-flow and extreme-low indicators in the alteration assessment suggests that ecological flow prescriptions should place particular emphasis on sustaining minimum flows and water levels during the dry season, especially in the Dongjiang Waterway Zone, where hydrological alteration is most pronounced. Although current management appears to focus primarily on flood control, our results indicate that comparable attention is also needed for dry-season low-flow protection.

Second, adopt water level-based management targets. Given that water levels showed higher alteration sensitivity than flows, and given the direct relevance of water levels to saltwater intrusion, navigation, and wetland health, management agencies should supplement traditional flow-based targets with explicit water level criteria. The AIHA framework provides ready-made indicators (LWL, RWL metrics) for such targets.

Third, address compound variability in estuarine zones. The very high RCD values observed at estuarine stations (up to 117%) suggest that these reaches may be especially sensitive to the combined influence of tidal forcing and local channel conditions. From a management perspective, future channel modifications should therefore consider their potential effects on hydrological variability, rather than focusing solely on conveyance capacity.

Limitations and future research: While the AIHA framework advances beyond traditional IHA by incorporating tidal dynamics, it remains fundamentally a hydrological assessment. Future work should link these hydrological indicators to specific ecological response variables (e.g., fish recruitment success, mangrove health indices, saltwater intrusion frequency) to establish quantitative flow–ecology relationships. Additionally, incorporating climate change projections—particularly sea-level rise scenarios—into the AIHA framework would enable assessment of future alteration trajectories and climate adaptation strategies. In addition, although the AIHA framework was developed based on standard IHA/RVA settings and objective CRITIC–Borda integration, its robustness under alternative methodological configurations remains to be further examined in future applications.

5. Conclusions

This study developed an augmented indicators of hydrologic alteration (AIHA) framework specifically tailored for tidal river network. Building upon the classic IHA structure, the AIHA utilizes four high-temporal-resolution hydrological series—daily ebb-peak flow, daily residual water level, daily highest water level, and daily lowest water level—derived from coupled hydrodynamic model outputs, augmented with tidal-specific metrics. By extending conventional flow-focused IHA indicators into high-spatiotemporal-resolution metrics derived from hydrodynamic processes, the AIHA framework provides a more process-relevant characterization of the complex dynamics of tidal river networks. Applied to the Pearl River Delta using data from 1960–2019, with 1991 identified as the critical transition year, the framework reveals distinct spatiotemporal patterns of hydrological change with important management implications.

Three key findings emerge: (1) While hydrologic indicators have generally deviated from natural reference ranges, alteration degrees are typically low-to-moderate with localized intensity increases toward estuaries; (2) a notable spatial dichotomy exists in central tendency shifts—increases in the Xijiang waterways and Beijiang waterways versus decreases in the Dongjiang waterways—reflecting divergent basin management strategies; and (3) hydrological variability increases dramatically toward estuaries, particularly for water level elements (RCD exceeding 100% at some stations), indicating compound effects of regulated inflows, sea-level rise, and channel modifications.

The CRITIC–Borda integration identified low-flow processes, extreme low water events, and tidal asymmetry characteristics as the most sensitive indicators of alteration in tidal river networks. This suggests that ecological flow prescriptions and water resources management in such environments must prioritize low-flow maintenance and tidal regime monitoring rather than focusing solely on flood peaks, as the ecological risks in tidal river networks may be strongly associated with dry-season freshwater buffering capacity, saltwater intrusion pressure, and altered river–tide interactions.

The proposed AIHA framework delivers a process-integrated quantitative tool for tidal hydrologic alteration assessment and is transferable to other tide-flow coupled delta systems subject to similar data and hydrodynamic constraints. Future extensions of the AIHA framework should incorporate comprehensive sensitivity analyses examining uncertainties introduced by indicator percentile thresholds, input temporal resolution and alternative objective weighting algorithms. Further integration of ecological response models and climate projection scenarios will advance tidal ecological flow standards for delta conservation and sustainable water management.

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