

Article

Hydrological Observations of a Two-Stage Flood Dynamics and Implications for Ecological River Regulation in the Cai Nha Trang River Basin, Vietnam

Phan Minh-Thu ^{1,*}, Nguyen Quoc Huan ², Hoang Xuan Ben ¹, Tran Van Chung ¹,
Tran Cong Thinh ¹, Dang Tran Tu Tram ¹, Dinh Truong An ¹, Nguyen Huu Huan ¹
and Ho Dinh Duan ³

¹ Institute of Oceanography, Vietnam Academy of Science and Technology, Nha Trang 650000, Vietnam; hxuanben2908@gmail.com (H.X.B.); tvanchung@gmail.com (T.V.C.); trancongthinh1@gmail.com (T.C.T.); tutram1300@gmail.com (D.T.T.T.); truongan.tca@gmail.com (D.T.A.); nghhuan@gmail.com (N.H.H.)

² Central Regional Hydrometeorological Center, Da Nang 550000, Vietnam; huantvtp@gmail.com (N.Q.H.)

³ Department of Artificial Intelligence, FPT University, Ho Chi Minh City 700000, Vietnam; duanhd@gmail.com (H.D.D.)

* Corresponding author. E-mail: pmthu@io.vast.vn (P.M.-T.)

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ABSTRACT: Flooding in coastal river basins is shaped by the temporal interaction of upstream hydrological forcing and downstream hydraulic conditions, yet such processes remain difficult to characterize in data-limited regions. This study investigates the hydrological evolution of the November 2025 flood in the Cai Nha Trang River Basin, Vietnam, using water-level observations from the Dong Trang and Dien Phu hydrological stations, discharge observations at Dong Trang, rainfall records, tidal-level data, and post-flood field observations. Hydrograph-derived indicators characterized flood magnitude, evolution, and persistence, with the event examined as two successive flood phases. The first phase reached a water level of 12.24 m and a maximum discharge of $3180 \text{ m}^3 \cdot \text{s}^{-1}$ at Dong Trang, while the second phase reached 13.14 m and $3720 \text{ m}^3 \cdot \text{s}^{-1}$. The second phase followed substantially greater antecedent rainfall and produced longer exceedance of the official flood-warning levels. The observations indicate that the November 2025 flood was characterized by successive hydrometeorological forcing and contrasting upstream–downstream responses. However, the Dien Phu water-level record was interrupted by sensor inundation during the second phase; therefore, the 6.73 m value represents the maximum observed downstream level before the sensor was lost rather than the absolute downstream peak. Downstream field observations of floodplain encroachment, channel narrowing, and hydraulic infrastructure provide evidence of potential constraints on flood conveyance, but do not establish their causal contribution to the event. The findings support ecological river regulation as a basin-scale management perspective emphasizing functional connectivity among rivers, floodplains, estuarine pathways, and coastal waters.

Keywords: Cai Nha Trang River Basin; Ecological river regulation; Flood persistence; Hydrological observations; Watershed–estuary–coastal continuum

1. Introduction

Flooding in coastal river basins is controlled by the interaction of atmospheric, hydrological, fluvial, and coastal processes, not by rainfall or river discharge alone. In coastal and estuarine environments, fluvial discharge, rainfall–runoff, and coastal water levels can occur simultaneously or successively, producing compound or interacting flood responses. A recent systematic review of 279 studies identified fluvial, pluvial, and coastal processes as the three principal drivers of compound flooding in coastal–estuarine regions and emphasized that conventional flood assessments often simplify or treat their interactions independently [1]. This interaction is particularly important in short, steep tropical coastal catchments, where intense rainfall can generate rapid runoff while downstream tidal and estuarine conditions influence flood propagation and recession.

Flood severity also cannot be adequately characterized by peak water level or discharge alone. The duration of critical water levels can substantially influence flood impacts, as prolonged inundation increases the exposure time of buildings, infrastructure, agricultural land, and other assets. Empirical analyses of flood damage have shown that both water level and flood duration are important determinants of damage, with longer inundation associated with greater building and property losses [2]. Flood duration is therefore a useful event-scale indicator for distinguishing between floods with similar peak magnitudes but different persistence characteristics. Recent work on estuarine flooding further demonstrates that hydrograph characteristics, such as volume and duration, can influence flood persistence even when peak discharge remains the principal control on maximum flood depth and extent [3].

Human modification adds another dimension to this hydrological response. Urbanization commonly increases impervious surface area, reduces infiltration, and shortens hydrological response time, thereby modifying runoff generation and flood peaks [4]. However, the effect of urbanization on flood hazard should not be equated automatically with an increase in flood magnitude. Land-use change can simultaneously alter hazard, exposure, and drainage conditions, and the relative importance of these mechanisms varies spatially and among flood events. This distinction matters in floodplains, where urban expansion may increase exposure by placing people and infrastructure closer to hazardous areas, while channel modification and floodplain disconnection alter the river system's capacity to store and convey floodwater [5]. Consequently, understanding a flood event requires separating the observed hydrological response from potential effects of human modification rather than assuming that anthropogenic development is necessarily responsible for a higher flood peak. Recent evidence further highlights that changes in the spatial relationship between human settlements and rivers can substantially influence flood exposure and risk, independently of changes in flood magnitude [6]. However, historical changes in human–river distance were not quantified in the present study because sufficiently resolved spatial data were unavailable.

These challenges are particularly pronounced in coastal basins because downstream hydraulic conditions can influence the propagation and recession of upstream-generated floodwaters. Compound-flood research increasingly recognizes interactions between fluvial discharge and coastal water levels, including astronomical tides, storm surge, and estuarine backwater effects [1]. However, identifying the contribution of individual drivers during an individual event requires observations with sufficient temporal resolution and, ideally, measurements at more than one location along the river. Continuous stage and discharge observations provide direct information on flood onset, peak timing, rising and recession behavior, and threshold exceedance. Such observations can also support short-term flood assessment without necessarily requiring a fully calibrated hydrodynamic model [7]. Nevertheless, observations from a single upstream station provide limited information on whether prolonged high water levels originate primarily from upstream runoff propagation or are additionally influenced by downstream hydraulic

conditions. Combining upstream and downstream water-level records with rainfall and tidal observations, therefore, provides a stronger observational basis for interpreting flood evolution.

The Cai Nha Trang River Basin in central Vietnam provides an appropriate natural laboratory for examining these processes. The river flows from mountainous headwaters through increasingly urbanized lowland areas before entering Nha Trang Bay. Historical hydrological records demonstrate that major floods can produce extreme water levels in the basin; for example, the November 2009 flood reached 13.42 m at Dong Trang and was associated with severe downstream inundation. The lower basin has subsequently experienced continued urban development and modification of river and floodplain environments. These changes may affect flood exposure and drainage, but observations at an upstream station alone cannot establish their contribution to individual flood events. This makes the comparison between the Dong Trang station in the upstream basin and the Dien Phu station in the downstream system particularly valuable for resolving the temporal and spatial characteristics of flood propagation.

The downstream consequences extend beyond human settlements. The Cai River discharges directly into Nha Trang Bay, where riverine inputs interact with ecologically sensitive coastal habitats. Nha Trang Bay supports extensive coral reef ecosystems and was established as Vietnam's first marine protected area; recent assessments continue to document substantial changes in coral habitat and identify land-use dynamics, warming, and other anthropogenic pressures among the factors associated with coral loss [8–10]. Observations at the Cai and Tac river mouths also demonstrate that water-quality conditions vary seasonally and that the rainy season can increase nutrient and sediment inputs to the bay [11]. More generally, terrestrial runoff can affect coral growth, recruitment, and survival through increased nutrients, particulate organic matter, turbidity, and sedimentation [12]. These findings provide a strong ecological basis for considering flood management across the watershed–estuary–coastal continuum. Importantly, however, the present study does not directly measure sediment fluxes, nutrient loading, or coral responses during the November 2025 flood; therefore, ecological consequences are considered as potential downstream implications rather than as directly demonstrated impacts.

This watershed–estuary connection also provides a basis for reconsidering the meaning of ecological river regulation. Ecologically functional floodplains depend on hydrological connectivity between the river and floodplain, a variable flow regime, and sufficient spatial extent to maintain ecological processes [13]. Similarly, ecological river restoration has increasingly moved beyond structural channel engineering toward approaches that maintain ecosystem functions and improve the resilience of river systems to external disturbances [14]. In a coastal basin, this approach requires consideration not only of flood protection within the river corridor but also of the downstream consequences of modifying floodplain storage, channel connectivity, estuarine drainage, and freshwater delivery to coastal ecosystems.

Despite these advances, an important methodological gap remains. Many flood assessments emphasize spatial inundation mapping or model-based hazard estimation, whereas fewer event-scale studies use simultaneous upstream–downstream hydrological observations, along with rainfall and tidal records, to distinguish successive flood phases and identify contrasting hydraulic responses. This gap is particularly relevant in data-limited tropical coastal basins, where the availability of channel geometry, bathymetry, boundary conditions, and calibration data may constrain hydrodynamic modeling.

In data-scarce settings, DEM-based geomorphic approaches provide complementary alternatives for spatial flood assessment [15]. Methods such as the Height Above the Nearest Drainage (HAND) and the Geomorphic Flood Index (GFI) can delineate flood-prone areas using terrain information, with limited reliance on detailed hydraulic calibration [15–18]. These approaches are particularly useful for characterizing the spatial dimension of flood exposure, but provide limited information on the temporal evolution of individual flood events. In contrast, continuous hydrological observations can characterize flood onset, peak timing, recession, persistence, and duration above critical water-level thresholds.

Importantly, long-term changes in flood extremes are not spatially uniform. Evidence from European river basins demonstrates substantial regional differences in the direction and magnitude of changes in flood behavior, highlighting that increasing and decreasing tendencies can occur across different regions rather than following a single common pattern [19]. This variability underscores the need to distinguish event-scale flood characteristics from longer-term hydrological or climatic trends. Accordingly, the present study does not assume an increasing or decreasing long-term trend in rainfall or flood extremes; instead, it focuses on the observed hydrological evolution of the November 2025 event.

The November 2025 flood in the Cai Nha Trang River Basin provides an opportunity to address this gap using continuous observations from the Dong Trang and Dien Phu stations, providing water level, river discharge, hourly rainfall, and tidal-level records. The event is examined as two successive flood phases, corresponding to the first peak on 17 November and the second, higher peak on 20 November 2025.

Therefore, this study aims to (1) characterize the magnitude, timing, and persistence of the two flood phases; (2) examine contrasting upstream and downstream hydrological responses in relation to rainfall and tidal conditions; and (3) evaluate how the observed flood dynamics and potential downstream hydraulic constraints inform ecological river regulation across the watershed–estuary–coastal continuum.

2. Materials and Methods

2.1. Study Area

The Cai Nha Trang River Basin is located in Khanh Hoa Province, Vietnam (Figure 1). The basin covers approximately 1732 km², and the Cai Nha Trang River extends for approximately 84 km before discharging into Nha Trang Bay. The basin comprises mountainous headwaters, lowland floodplain areas, and a downstream estuarine reach, providing a hydrological connection between the upstream watershed and the coastal environment of Nha Trang Bay. The region has a tropical monsoon climate with a distinct rainy season from September to December, during which a large proportion of annual rainfall occurs, and major river floods are common.



Figure 1. The Cai Nha Trang River Basin, with the location of Dong Trang Hydrological Station, and field observation sites used for photographic documentation. ★: unimpacted from flooding, △: impacted from flooding.

Two hydrological gauging stations were selected to characterize the spatial evolution of the November 2025 flood (Figure 1). The Dong Trang Hydrological Station (12.28039° N, 109.01229° E) is located in the

upstream part of the basin and provides water-level and river-discharge observations. The Dien Phu Hydrological Station (12.26498° N, 109.133266° E) is located farther downstream and provides water-level observations. The two stations are separated by approximately 13.5 km in straight-line distance and 16 km along the river channel, forming an upstream–downstream observation transect for examining differences in flood-wave timing and water-level evolution. Rainfall observations from the corresponding monitoring locations and tidal-level data provided a hydrometeorological context for the flood event.

2.2. Data Collection

Hourly hydrological and meteorological data were compiled to characterize the November 2025 flood in the Cai Nha Trang River Basin. The dataset included water-level observations from the Dong Trang and Dien Phu hydrological stations, river-discharge observations at Dong Trang, rainfall observations at both stations, and tidal-level data. All hydrological and meteorological observations were provided by the Central Regional Hydrometeorological Center (CRHC), belonging to the Vietnam Meteorological and Hydrological Administration. The observations were used to examine the temporal evolution of the flood and the contrasting responses between the upstream and downstream reaches.

At Dong Trang, water-level and discharge observations were used to characterize flood magnitude, timing, and duration, whereas water-level observations at Dien Phu were used to examine the downstream response. We used the discharge data provided by CRHC and did not derive them independently from water level or reconstruct them using a rating curve. Rainfall observations characterized the meteorological forcing associated with the two flood phases, while tidal-level data provided information on downstream coastal conditions.

The Dien Phu water-level record was interrupted when the monitoring equipment was inundated during the high-water stage. Therefore, the highest recorded value at this station was treated as the maximum observed water level before sensor loss, rather than the absolute flood peak. Based on the observed hydrographs, the November 2025 flood was divided into two phases, corresponding to the first peak on 17 November and the second, higher peak on 20 November 2025.

2.3. Data Analysis

Hydrograph-derived indicators were calculated from measured water-level and discharge records to characterize flood magnitude, evolution, and persistence [20–22]. The indicators were evaluated separately for the two flood phases identified during the November 2025 event.

- Flood magnitude: The peak water level ($H_{\max}$) and peak discharge ($Q_{\max}$) were determined as

$$H_{\max} = \max[H(t)] \quad (1)$$

$$Q_{\max} = \max [Q(t)] \quad (2)$$

where $H(t)$ is the observed water level at time t (in m), and $Q(t)$ is the observed river discharge at time t (in $\text{m}^3 \cdot \text{s}^{-1}$).

- Flood evolution: The mean rising and recession rates were calculated as:

$$R_{\text{rise}} = \frac{H_{\max} - H_{\text{start}}}{t_{\text{peak}} - t_{\text{start}}} \quad (3)$$

$$R_{\text{rec}} = \frac{H_{\text{end}} - H_{\max}}{t_{\text{end}} - t_{\text{peak}}} \quad (4)$$

where H_{start} and H_{end} are the water levels at the beginning and end of the corresponding flood phase (m), respectively; t_{start} , t_{peak} , and t_{end} are the corresponding times (h); and $H_{\max}$ is the maximum water level of the phase (m). The resulting rising and recession rates are expressed in $\text{m} \cdot \text{h}^{-1}$.

Because the November 2025 event comprised two successive flood phases, the original single-event time-to-peak (T_p) indicator was not retained. Instead, the timing of each flood peak was reported directly, along with the time lag between the upstream and downstream responses and, where applicable, between the maximum discharge and the maximum water level.

- Flood duration (FD) was defined as the period during which the water level remained above Flood Warning Level I:

$$FD = t_{\text{end}} - t_{\text{start}} \quad (5)$$

where t_{start} is the time when the water level first crossed Flood Warning Level I during the corresponding flood phase, and t_{end} is the time when the water level subsequently receded below this threshold. The duration is expressed in hours (h).

- Flood persistence (DW_i): Flood persistence was quantified as the cumulative duration during which the observed water level exceeded each official Flood Warning Level (DW_i , $i = \text{I, II, III}$):

$$DW_i = \sum_{k=1}^{n_i} \Delta t_k \quad (6)$$

where DW_i is the cumulative duration above Flood Warning Level i (h), n_i is the number of observation intervals during which the water level exceeded the corresponding threshold, and Δt_k is the duration of each exceedance interval (h). The official thresholds were 8.0, 10.0, and 11.5 m for Alert Levels I, II, and III, respectively, at Dong Trang, and 4.5, 5.0, and 5.5 m at Dien Phu.

For threshold-based calculations, crossing times between consecutive hourly observations were estimated by linear interpolation. Where the observation record at Dien Phu was interrupted because of sensor inundation, the resulting maximum water level and persistence estimates were treated as observed or minimum values, as appropriate, rather than complete-event estimates.

3. Results

3.1. Flood Evolution and Hydrometeorological Characteristics

The November 2025 flood exhibited two successive flood phases with distinct hydrological characteristics (Figure 2; Table 1). Phase 1 developed on 17 November, whereas Phase 2 began with a second rise on 18 November and reached the highest water level and discharge at Dong Trang on 20 November. The two phases differed substantially in flood magnitude, persistence, rainfall conditions, and downstream response.

During Phase 1, the water level at Dong Trang first exceeded Alert Level I (8.0 m) at approximately 00:54 on 17 November and reached a maximum of 12.24 m at 13:00. The corresponding maximum discharge was $3180 \text{ m}^3 \cdot \text{s}^{-1}$ at 12:00, approximately 1 h before the water-level peak. The mean rising and recession rates were 0.35 and $-0.54 \text{ m} \cdot \text{h}^{-1}$, respectively (Table 1). At Dien Phu, the water level reached a maximum observed value of 6.40 m at 15:00, approximately 2 h after the Dong Trang water-level peak. Using the station-specific Alert Level I of 4.5 m, the mean rising and recession rates at Dien Phu were 0.12 and $-0.13 \text{ m} \cdot \text{h}^{-1}$, respectively (Table 1). Thus, the first phase showed a sequential upstream–downstream response, with the downstream maximum occurring after the upstream peak.

Following the recession of the first flood pulse, the water level at Dong Trang again exceeded Alert Level I at approximately 17:49 on 18 November, marking the onset of Phase 2. The water level subsequently increased to 13.14 m at 05:00 on 20 November, while the maximum discharge reached $3720 \text{ m}^3 \cdot \text{s}^{-1}$ at 02:00–03:00 on 20 November. The discharge maximum therefore preceded the water-level maximum by approximately 2–3 h. The mean rising and recession rates during Phase 2 were 0.15 and $-0.19 \text{ m} \cdot \text{h}^{-1}$, respectively (Table 1). Both the peak water level and peak discharge were higher than those recorded during Phase 1.

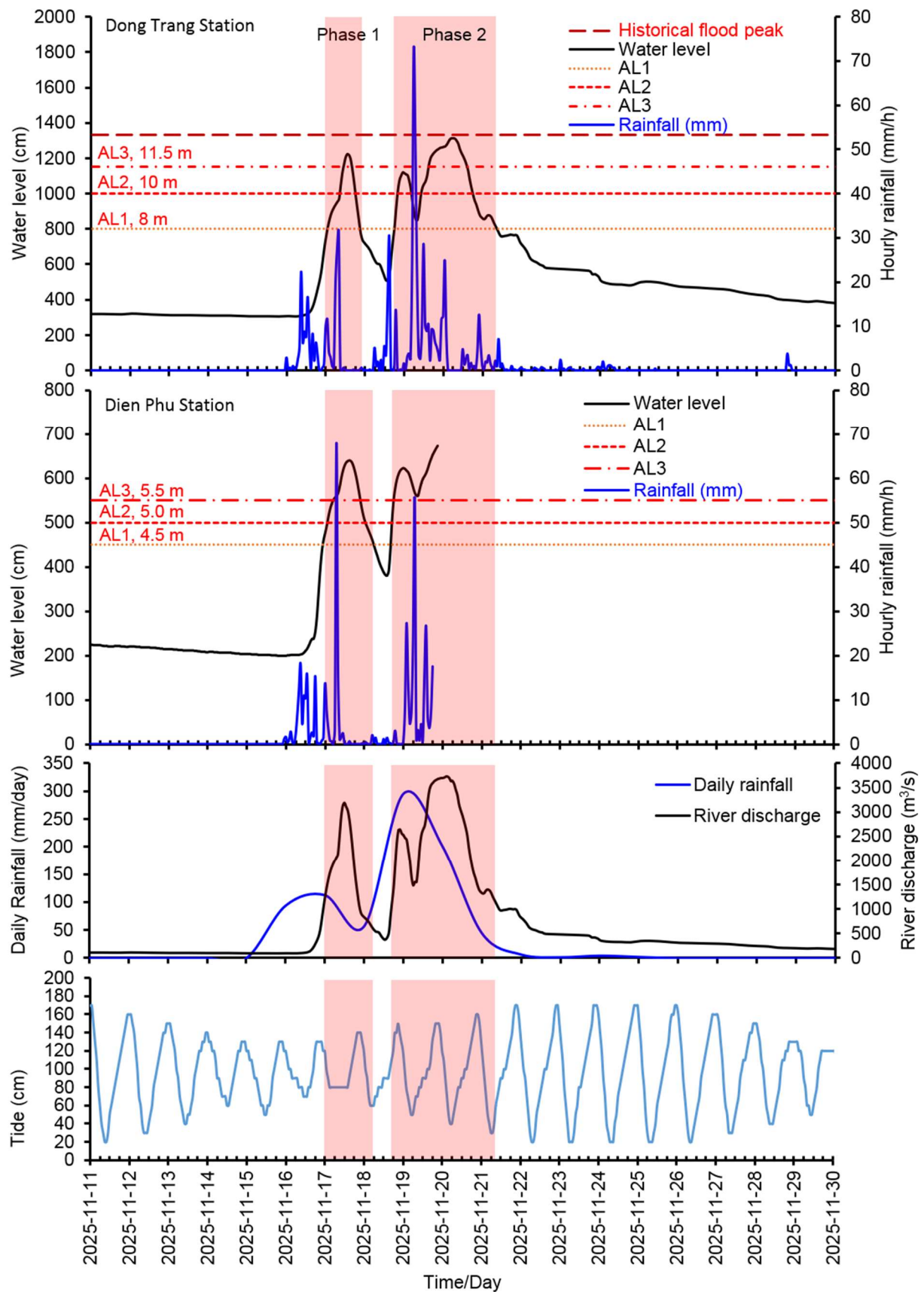


Figure 2. Time series of water level, discharge, rainfall, and tidal level during the November 2025 flood at Dong Trang and Dien Phu stations. The observed tidal level remained approximately 0.8 m from 03:00 to 14:00 on 17 November 2025. Alert Levels I–III are indicated by horizontal dashed lines. The Dien Phu water-level record was interrupted after 21:00 on 19 November 2025 because the monitoring equipment was inundated.

Table 1. Hydrological characteristics of the two flood phases during the November 2025 flood in the Cai Nha Trang River Basin.

Category	Hydrological Indicator	Phase 1 17 Nov 2025	Phase 2 20 Nov 2025
Flood evolution	Flood onset at Dong Trang (AL I = 8.0 m)	00:54, 17 Nov	17:49, 18 Nov
	Peak water level, Dong Trang	12.24 m	13.14 m
	Time of peak water level, Dong Trang	13:00, 17 Nov	05:00, 20 Nov
	Mean rising rate, Dong Trang	0.35 m·h ⁻¹	0.15 m·h ⁻¹
	Mean recession rate, Dong Trang	−0.54 m·h ⁻¹	−0.19 m·h ⁻¹
	Peak discharge, Dong Trang	3180 m ³ ·s ⁻¹	3720 m ³ ·s ⁻¹
	Time of peak discharge	12:00, 17 Nov	02:00–03:00, 20 Nov
Downstream response	Qmax–Hmax lag	~1 h	~2–3 h
	Flood onset at Dien Phu (AL I = 4.5 m)	22:36, 16 Nov	16:12, 18 Nov
	Maximum observed water level, Dien Phu	6.40 m	6.73 m *
	Time of maximum observed level, Dien Phu	15:00, 17 Nov	21:00, 19 Nov *
	Mean rising rate, Dien Phu	0.12 m·h ⁻¹	0.08 m·h ⁻¹
	Mean recession rate, Dien Phu	−0.13 m·h ⁻¹	Not calculated *
	Dien Phu–Dong Trang peak lag	+2 h	−8 h *
Rainfall forcing	Maximum hourly rainfall, Dong Trang	31.3 mm·h ⁻¹	72.5 mm·h ⁻¹
	Maximum hourly rainfall, Dien Phu	67.8 mm·h ⁻¹	55.3 mm·h ⁻¹
	24-h antecedent rainfall at Dong Trang peak	138.7 mm	314.5 mm
Tidal condition	Tide at Dong Trang water-level peak	0.8 m	0.4 m
	Maximum tidal level during phase	1.4 m	1.6 m
Flood persistence	Duration ≥ AL I (8.0 m), Dong Trang	19.9 h	62.9 h
	Duration ≥ AL II (10.0 m), Dong Trang	9.6 h	40.1 h
	Duration ≥ AL III (11.5 m), Dong Trang	5.2 h	23.7 h

Notes: AL I, AL II, and AL III denote Flood Warning Levels I, II, and III, respectively. Threshold exceedance durations were calculated using linear interpolation between consecutive observations. * The Dien Phu water-level record terminated at 21:00 on 19 November 2025 because the monitoring equipment was inundated; therefore, 6.73 m is the maximum observed level before sensor loss, and the −8 h lag should be interpreted as a comparison of the maximum observed downstream level with the subsequent upstream peak, not as the definitive timing of the downstream flood peak. Consequently, the Phase 2 recession rate and threshold-exceedance duration at Dien Phu were not calculated. The meteorological and hydrological authority provided the Dong Trang discharge series, and we used it as supplied; we did not derive it independently from the stage record.

The downstream response during Phase 2 differed from that of Phase 1. At Dien Phu, the water level reached a maximum observed value of 6.73 m at 21:00 on 19 November, approximately 8 h before the Dong Trang water-level peak. The corresponding mean rising rate was approximately 0.08 m·h⁻¹. A recession rate was not calculated because the Dien Phu monitoring record was interrupted after the monitoring equipment was inundated. Therefore, 6.73 m represents the maximum observed level before sensor loss and should not be interpreted as the absolute flood peak at the downstream station. The contrasting timing between the two phases indicates that the downstream water-level response did not follow an identical upstream-to-downstream temporal pattern throughout the event.

In both phases, the discharge maximum preceded the Dong Trang water-level maximum by approximately 1–3 h. This temporal offset is consistent with a hysteretic stage–discharge response under unsteady flow conditions, in which the relationship between discharge and stage can differ between the rising and falling limbs of a flood wave.

Rainfall conditions also differed between the two phases. During Phase 1, maximum hourly rainfall reached 31.3 mm·h⁻¹ at Dong Trang and 67.8 mm·h⁻¹ at Dien Phu, while the 24-h antecedent rainfall preceding the Dong Trang water-level peak was approximately 138.7 mm. During Phase 2, maximum hourly rainfall increased to 72.5 mm·h⁻¹ at Dong Trang and 55.3 mm·h⁻¹ at Dien Phu, and 24-h antecedent rainfall before the Dong Trang peak increased to approximately 314.5 mm. Thus, the second flood phase

developed under substantially wetter antecedent conditions and was accompanied by a stronger upstream hydrological response.

Tidal levels varied throughout the event but did not coincide consistently with the Dong Trang water-level peaks. The tidal level was approximately 0.8 m at the Phase 1 Dong Trang peak and 0.4 m at the Phase 2 peak, while the maximum tidal level within the respective phases reached approximately 1.4 and 1.6 m, respectively. Therefore, the highest tidal conditions did not coincide with the highest upstream water-level or discharge peak.

Flood persistence further distinguished the two phases. At Dong Trang, water levels remained above Alert Levels I, II, and III for approximately 19.9, 9.6, and 5.2 h, respectively, during Phase 1. During Phase 2, the corresponding durations increased markedly to 62.9, 40.1, and 23.7 h. The second phase, therefore, produced not only higher peak conditions but also substantially longer periods of elevated water levels.

Therefore, the November 2025 flood was characterized by two successive flood phases with different magnitudes and contrasting upstream–downstream responses. Phase 1 exhibited a downstream maximum approximately 2 h after the Dong Trang peak, whereas the maximum observed downstream level during Phase 2 occurred approximately 8 h before the Dong Trang peak. The lower rising and recession rates during Phase 2, together with its longer threshold exceedance, further indicate a more persistent flood response than during Phase 1. Together with the stronger antecedent rainfall and longer threshold exceedance during Phase 2, these observations demonstrate that the event cannot be adequately described by a single peak value alone and provide the basis for the subsequent interpretation of downstream hydraulic conditions.

3.2. Downstream Anthropogenic Modifications

Field observations conducted after the November 2025 flood documented substantial anthropogenic modifications along the downstream Cai Nha Trang River and the estuarine system (Figure 3). The most evident modifications included floodplain encroachment, channel narrowing, and hydraulic infrastructure associated with urban development. These modifications were observed throughout the lower river corridor and estuarine reaches, where residential development, transportation infrastructure, and water-regulation structures were present.

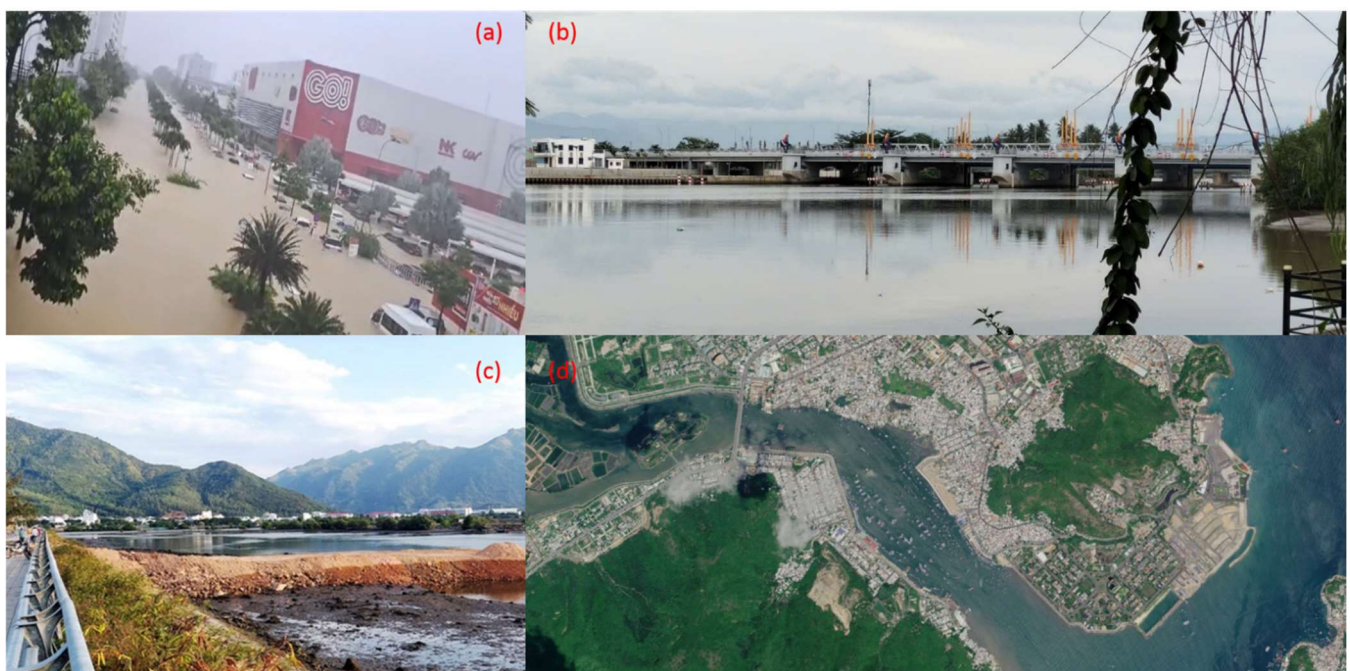


Figure 3. Representative downstream anthropogenic modifications in the Cai Nha Trang River Basin. (a) Flood extent; (b) Cai Nha Trang barrage; (c) Channel narrowing in the Quan Truong River; and (d) Constricted Tac mouth (Google Earth).

The downstream floodplain of the Cai Nha Trang River, particularly within and around Nha Trang City, is extensively occupied by residential areas, commercial developments, roads, and other urban infrastructure (Figure 3a). Field observations showed that these developments occupy areas formerly used for agriculture and floodplain functions. In several locations, urban development extends directly to the riverbanks, leaving only narrow riparian corridors and limited space for natural floodplain inundation during high-flow conditions.

Field observations documented anthropogenic modifications along the two principal flood-discharge pathways to Nha Trang Bay (Figure 3b–d). The northern flood-discharge pathway is regulated by the Cai Nha Trang salinity-control barrage (Figure 3b), which controls river discharge into the northern part of Nha Trang Bay. The southern flood-discharge pathway comprises the Quan Truong River and the Tac River, where channel encroachment (Figure 3c) and hydraulic structures at the Tac River estuary (Figure 3d) alter the downstream flow pathway into the southern part of the bay. Collectively, these observations document potential constraints on downstream flood conveyance and hydrological connectivity under high-flow conditions, but they do not, by themselves, establish a causal relationship between the observed modifications and the extent of flooding during the November 2025 event.

3.3. Hydrological Mechanisms Driving Widespread Flooding

The combined observations indicate that the November 2025 flood developed as a two-stage hydrological event, characterized by successive rainfall inputs, distinct upstream flood responses, and contrasting downstream water-level behavior (Figure 2 and Table 1). The first phase exhibited a downstream response following the upstream peak, whereas the second phase showed a substantially different temporal relationship between the upstream and downstream records. This contrast indicates that the downstream evolution of the flood was not governed by a single, uniform upstream-to-downstream propagation pattern throughout the event.

The rainfall and tidal observations provide a complementary hydrometeorological context for this contrasting behavior, while the field observations document potential constraints on downstream flood conveyance and hydrological connectivity associated with floodplain encroachment, channel narrowing, and hydraulic infrastructure. However, the available observations do not allow the individual contributions of rainfall, tidal conditions, downstream hydraulic effects, or anthropogenic modifications to be quantitatively separated. The results therefore support an event-scale interpretation in which flood magnitude and persistence reflect successive hydrometeorological forcing, while the contrasting downstream response highlights the potential importance of downstream hydraulic conditions. This observational evidence provides the basis for considering flood resilience and ecological river regulation across the watershed–estuary–coastal continuum (Figure 4).

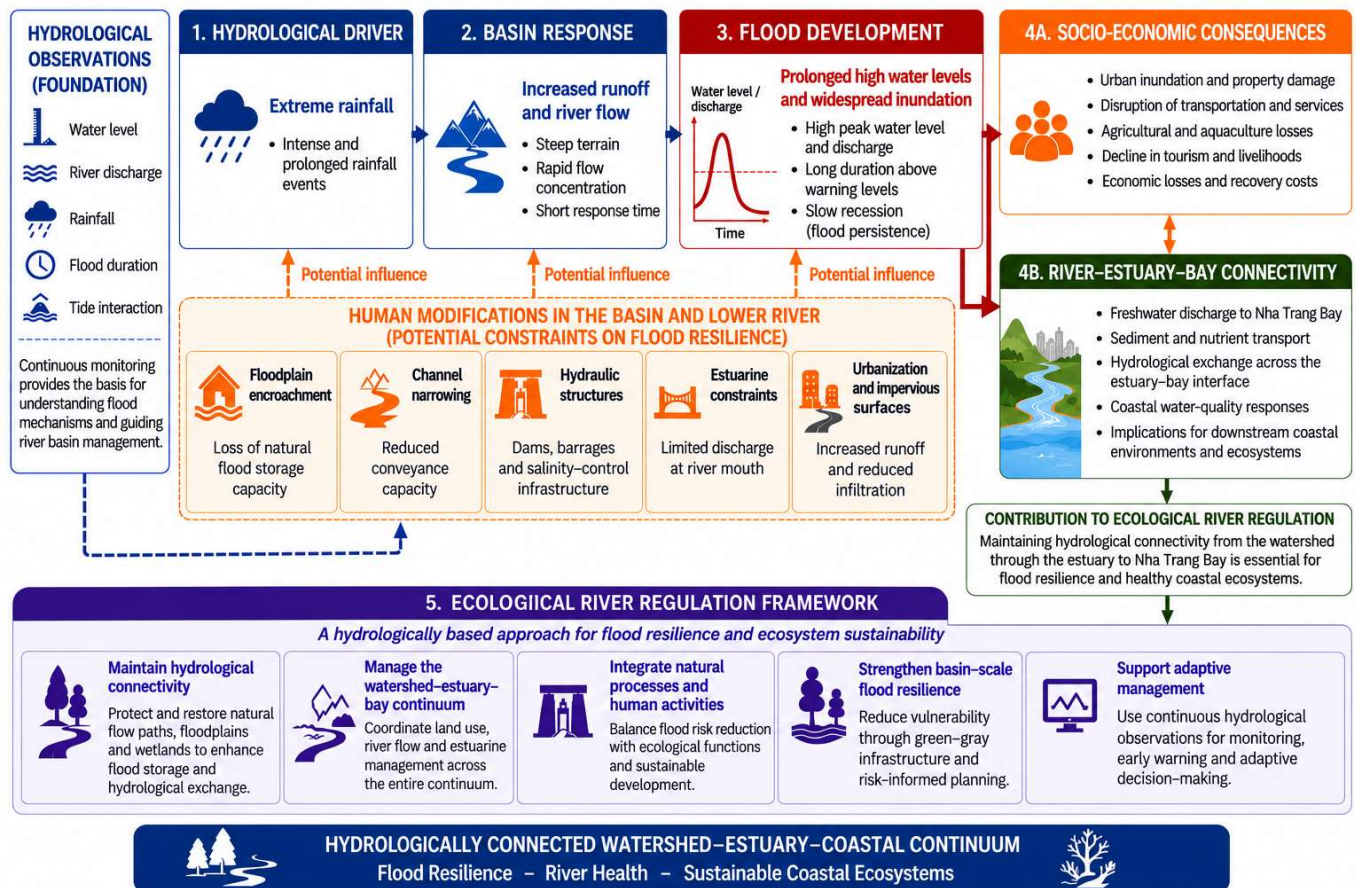


Figure 4. Conceptual synthesis of the November 2025 two-stage flood, linking hydrometeorological forcing, upstream–downstream hydrological responses, potential constraints associated with downstream anthropogenic modifications, and the implications for ecological river regulation in the Cai Nha Trang River Basin. The relationships involving anthropogenic modifications are conceptual and indicate potential influences rather than demonstrated causal effects.

4. Discussion

4.1. Hydrological Mechanisms Underlying Widespread Flooding

Flood dynamics in coastal river basins are governed not only by the magnitude of upstream runoff but also by the timing and persistence of hydraulic responses throughout the river–estuary system. Hydrographs are particularly useful in this context because they retain the temporal structure of flood development, including rising and recession behavior, as well as the duration of elevated water levels [23,24]. This distinction is relevant to the November 2025 event in the Cai Nha Trang River Basin, where the flood developed through two successive phases rather than as a single isolated peak. The observed sequence, therefore, provides an opportunity to examine flood evolution in temporal terms, while avoiding attribution of the event to any single forcing mechanism.

The rainfall observations strengthen this interpretation. The second flood phase occurred following substantially greater antecedent rainfall than the first phase, indicating that the two peaks were associated with different hydrometeorological conditions. This pattern is consistent with the established role of antecedent precipitation and successive rainfall pulses in controlling runoff accumulation and flood persistence in river basins. However, because the present study does not include a rainfall–runoff model or basin-wide runoff measurements, the observations cannot be used to quantify how much of the difference between the two phases was attributable to rainfall intensity, antecedent wetness, or catchment storage. The appropriate interpretation is therefore that successive rainfall forcing provided an important hydrometeorological context for the two-stage response, rather than that rainfall alone determined the flood evolution.

An additional finding is the difference in the temporal response between the two gauging stations. The downstream response during the first phase was broadly consistent with the expected downstream propagation of a flood wave, whereas the second phase did not show the same temporal sequence. In coastal and estuarine rivers, such departures from simple upstream-to-downstream propagation can occur when river discharge interacts with downstream boundary conditions, including tidal water levels, channel geometry, and estuarine hydraulics [25–27]. Nevertheless, the present observations cannot establish which of these processes controlled the second-phase response. In particular, the interruption of the Dien Phu record during the high-water stage means that the observed downstream maximum represents only the highest recorded level before sensor loss, and not necessarily the true downstream peak. This limitation is important when interpreting the apparent temporal reversal between the two stations.

The tidal observations provide further evidence for a cautious interpretation. Previous studies have demonstrated that river–tide interactions can substantially influence flood levels and drainage in coastal and estuarine environments, particularly when elevated river discharge coincides with unfavorable downstream water levels [26,27]. In the present event, however, the highest tidal level did not coincide with either of the maximum upstream water levels. The observations, therefore, do not support a direct explanation of the Dong Trang flood peaks by tidal forcing. Instead, tidal conditions should be regarded as a potential downstream boundary condition whose influence on water-level persistence and recession requires further hydraulic analysis. This distinction is important because the available observations demonstrate temporal relationships but do not provide sufficient information to quantify backwater effects.

The findings, therefore, support a more restrained interpretation of the flood dynamics. The November 2025 event is best understood as a two-stage hydrological response to successive rainfall forcing, with contrasting temporal behavior between upstream and downstream observations. The available observations are consistent with a possible influence of downstream hydraulic conditions on flood propagation or persistence, but they do not permit the relative contributions of rainfall, tidal forcing, and downstream hydraulic controls to be quantified. Further assessment using channel geometry, downstream discharge measurements, and hydraulic modelling would be required to resolve these processes.

4.2. From Flood Vulnerability to Ecological River Regulation

Conventional flood-control approaches generally focus on increasing conveyance capacity, containing river flows, or protecting specific exposed areas. However, flood vulnerability in coastal river basins also depends on how river channels, floodplains, and downstream drainage pathways function as an interconnected system [13,26,28]. Floodplains are not merely areas exposed to inundation; they can provide storage, conveyance, and attenuation functions that influence the temporal evolution and spatial consequences of floods.

This perspective is particularly relevant to the Cai Nha Trang River Basin. The observations presented in this study documented extensive downstream development, channel encroachment, channel narrowing, and hydraulic infrastructure along the lower river and its associated discharge pathways. These observations do not demonstrate that individual modifications caused or quantitatively amplified the November 2025 flood. Rather, they indicate that the downstream river system has undergone substantial modification, potentially reducing the space and connectivity available for floodwater storage and conveyance. Such changes can increase the vulnerability of downstream areas when high-flow conditions persist, even when the magnitude of upstream discharge alone does not explain the temporal characteristics of downstream flooding [13,26].

The distinction between flood hazard and flood vulnerability is therefore important for interpreting the November 2025 event. The observed hydrological records characterize the magnitude, timing, and persistence of the flood hazard, whereas the field observations provide contextual evidence concerning the capacity of the downstream river system to accommodate and convey floodwater. The combination of these

two perspectives suggests that flood resilience should not be assessed solely by peak discharge or peak water level, but also by the condition, connectivity, and functional capacity of the river–floodplain–estuary system [13,26].

This concept is consistent with the broader development of river management from predominantly structural flood control toward approaches that seek to maintain or restore river-system functions [29]. River restoration increasingly recognizes the importance of hydrological connectivity, floodplain processes, and ecological functions alongside hydraulic objectives [29,30]. The Dutch Room for the River approach provides an established example in which restoring space and functional connectivity within river corridors is part of an integrated strategy to reduce flood vulnerability while improving environmental conditions [30,31]. These approaches do not imply that structural measures should be abandoned, but rather that engineering interventions should be considered together with the capacity of the river system to store, convey, and attenuate floodwaters.

For the Cai Nha Trang River Basin, the findings therefore suggest that improving flood resilience requires consideration of the entire downstream river–floodplain–estuary system, rather than focusing exclusively on individual hydraulic structures or isolated river reaches. Maintaining appropriate floodplain space, avoiding further constriction of critical flow pathways, and preserving hydraulic connectivity between the river network and estuarine outlets represent potential directions for integrated flood management. These implications support an ecological river regulation perspective in which flood resilience is pursued by maintaining and restoring hydrological connectivity and functional interactions across the river–floodplain–estuary system.

4.3. Ecological River Regulation as a Basin-Scale Management Framework

Integrated river-basin management recognizes that hydrological processes extend across connected watershed, river, estuarine, and coastal systems rather than functioning as isolated components [31,32]. This perspective is particularly relevant to coastal river basins, where upstream runoff, river conveyance, floodplain storage, and downstream hydraulic conditions are connected through a continuous river–estuary system. For the Cai Nha Trang River Basin, the November 2025 observations therefore support consideration of flood resilience beyond the performance of individual river reaches or hydraulic structures.

Ecological river regulation provides a framework for this broader perspective by considering the maintenance of river-system structure, function, and connectivity alongside conventional flood-management objectives [26,29,30]. Rather than treating the river solely as a conduit for rapidly conveying floodwater, this approach recognizes the functional roles of floodplains, channels, distributary pathways, and estuarine connections in storing, conveying, and attenuating water [26]. The Room for the River approach provides an established example of integrating flood risk management with the restoration of river space and ecological functions [31]. Importantly, such approaches do not imply that structural measures should be abandoned; rather, structural interventions can be considered together with the capacity of the river system to retain and convey water under different hydrological conditions.

For the Cai Nha Trang River Basin, this perspective is supported by the observed connection between upstream flood development and contrasting downstream water-level responses, together with the documented modification of downstream flood-conveyance pathways. However, the present study does not quantify the hydraulic effects of individual structures, channel narrowing, or estuarine constriction. Nor does it directly measure ecological responses in Nha Trang Bay. Ecological river regulation should therefore be regarded in this study as a management framework informed by hydrological observations and established river-restoration literature, rather than as a quantitatively evaluated ecological intervention.

Within this framework, flood management should consider the functional connectivity of the watershed, river channels, floodplain areas, downstream distributary pathways, and estuarine outlets. In practical terms, this includes maintaining critical flood-conveyance pathways, avoiding further loss of functional floodplain

space, and evaluating hydraulic structures in relation to their effects on downstream connectivity. Such measures should be assessed at the basin scale because modifications at one location may alter hydraulic conditions elsewhere within the connected river–estuary system [26,29,30].

The role of hydrological monitoring is particularly important in data-limited basins. Continuous observations of water level, discharge, rainfall, and downstream water levels can provide evidence of changes in flood magnitude, timing, persistence, and spatially contrasting responses. Such observations cannot by themselves quantify channel conveyance or establish the effects of individual anthropogenic modifications, but they provide a practical basis for identifying changes that warrant further hydraulic and spatial assessment. Future studies combining hydrological observations with channel-geometry surveys, hydraulic modelling, and spatial flood mapping would allow the proposed management framework to be evaluated quantitatively and would provide stronger evidence for selecting specific river-regulation measures.

5. Conclusions

The November 2025 flood in the Cai Nha Trang River Basin exhibited a distinct two-stage hydrological evolution. The first phase reached a water level of 12.24 m and a maximum discharge of $3180 \text{ m}^3 \cdot \text{s}^{-1}$ at Dong Trang, while the second phase reached 13.14 m and $3720 \text{ m}^3 \cdot \text{s}^{-1}$. The second phase followed substantially greater antecedent rainfall and produced much longer exceedance of the official flood-warning levels, demonstrating that flood persistence and successive hydrometeorological forcing were important characteristics of the event.

The available records suggest an apparent contrast between phases, but the Dien Phu sensor loss prevents definitive assessment of downstream peak timing and propagation. The observations are consistent with a possible influence of downstream hydraulic conditions on flood persistence and propagation, but the available data do not allow the relative contributions of rainfall, tidal forcing, and downstream hydraulic controls to be quantified. Similarly, field observations of floodplain encroachment, channel narrowing, and hydraulic infrastructure provide evidence of potential constraints on downstream conveyance, but do not establish their causal contribution to the 2025 flood.

The study highlights the value of combining routine hydrological observations with rainfall, tidal information, and field observations to characterize flood magnitude, persistence, and spatially contrasting responses in a data-limited coastal basin. The observed hydrological patterns also highlight the potential relevance of ecological river regulation as a basin-scale management perspective, emphasizing the maintenance of functional connectivity among rivers, floodplains, estuarine pathways, and coastal waters.

6. Limitations and Future Research

The interpretation of the present findings is constrained primarily by the scale and completeness of the available observations. The study examines a single flood event using two hydrological stations, and the interrupted record at Dien Phu limits the ability to resolve the complete downstream hydrograph. The absence of downstream discharge measurements further restricts direct assessment of flood-wave propagation and attenuation. These constraints mean that the observed two-stage behavior should be interpreted as event-specific hydrological evidence rather than as a generalized pattern for the basin.

The study also does not quantitatively resolve the mechanisms underlying the observed downstream response. In particular, no hydraulic or hydrodynamic modelling was undertaken, and the effects of channel geometry, tidal forcing, and anthropogenic modifications were not independently quantified. Likewise, ecological responses were not monitored during the event, so the proposed ecological river regulation framework remains a management perspective rather than an empirically tested ecological response. Finally, the available dataset is insufficient for assessing long-term trends in rainfall, discharge, or flood extremes. Future studies should combine longer hydrological records with hydraulic modelling, spatial inundation

mapping, quantitative assessment of channel and floodplain modifications, and ecological monitoring to further evaluate flood propagation and the applicability of ecological river regulation in the Cai Nha Trang River Basin.

Statement of the Use of Generative AI and AI-Assisted Technologies in the Writing Process

During the preparation of this manuscript, the authors used Grammarly in order to assist with grammatical refinement during manuscript revision. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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The data are available from the corresponding author upon reasonable request.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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