ASSESSING THE PERFORMANCE OF THE COUPLED SCHISM-WWM MODEL IN TOTAL WATER LEVEL FORECASTING ALONG THE THANH HOA - NGHE AN COAST IN 2025

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Abstract: *The open-source SCHISM model, with its advantages of a high-performance numerical solver and unstructured-grid framework, provides an effective tool for simulating complex hydrodynamic processes in estuarine and coastal areas. In 2025, SCHISM was applied for the first time in Viet Nam to experimentally forecast total water levels along the coast. This study evaluates the results of 24 independent forecast cycles during two strong typhoons, Kajiki (August 2025) and Bualoi (September 2025), using observed water-level data from Hon Dau, Sam Son, Hon Ngu, Quang Chau, and Cua Hoi stations. The results show that the model achieved relatively good forecasting performance, with Skill values ranging from 0.72 to 0.97. Most forecasts satisfy the QCVN 84 quality requirements, with total-water-level errors below 20%; the exception is the 30-hour lead-time forecast during Typhoon Kajiki (August 2025), for which errors at Hon Ngu and Cua Hoi exceed 40%. The study also indicates that total-water-level forecast performance along the Thanh Hoa-Nghe An coast is strongly affected by variations in forecast meteorological forcing. The spatial distribution of maximum total water level in the coastal zone is closely related to storm structure, particularly the distribution of strong winds within the typhoon.*

Keywords: *Total water level forecasting, storm surge, forecast lead time, meteorological forcing, coupled SCHISM model.*

1. Introduction

Along with socio-economic development, the demand for marine forecasting information is increasing, particularly for high-resolution forecasts tailored to specific areas. In coastal regions, accurate forecasting of total storm-induced water levels is crucial for risk assessment, warning, preparedness, response, and damage mitigation, because storm surge and large waves can cause coastal erosion, flooding, and damage to coastal infrastructure.

Numerical models are the primary and most important tools for producing storm-surge and wave forecasts. In particular, unstructured-grid models can represent coastal dynamics more accurately while accounting for complex bathymetry and shoreline geometry. Unstructured grids provide flexibility in representing the study domain and allow local grid refinement within a coarser overall mesh. This flexibility is especially valuable for coastal applications, where shorelines are complex and relevant spatial scales range from basin scale to detailed estuarine and river-channel features. In recent years, unstructured-grid models have been increasingly used in storm-surge research and forecasting, including ADCIRC [1], FVCOM [2], SCHISM [3], [4], and TELEMAC [5]. The open-source SCHISM model has been widely applied in studies of water-level forecasting and coastal flooding [6-14]. These studies have focused on developing, improving, and applying SCHISM to water-level forecasting at global, regional, and local scales and to the analysis of complex compound flooding events.

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At the Institute of Meteorology, Hydrology, Environment and Marine Sciences, SCHISM has been studied and applied to develop integrated forecasting systems with high spatial and temporal resolution for coastal waters, supporting socio-economic development and natural-hazard warning. Within project TNMT.2024.06.03 [15], the model was configured for the Thanh Hoa-Nghe An coastal and estuarine region. SCHISM can simulate coastal total water levels by combining tides, surge (caused by typhoons and monsoons), wave setup, and river discharge. The model is currently being tested for water-level and wave forecasting in this area. This study evaluates the 2025 experimental total-water-level forecasts for two typhoons affecting the region: Kajiki (August 2025) and Bualoi (September 2025). Typhoon Kajiki formed East of the Philippines and intensified to level 14, with gusts to level 16, near the Hoang Sa (Paracel) Islands before making landfall over Southern Nghe An-northern Ha Tinh on the evening of 25 August at intensity level 10-11. Meteorological stations recorded actual winds of level 7-10, with the strongest wind at Dien Chau (26.7 m/s), and waves of 6-9 m occurred from Nghe An to Quang Tri. Although landfall occurred during a mean-tide phase and the surge peak did not coincide with the tidal peak, the storm still produced very high water levels, reaching maxima of 2.18 m at Hon Ngu, 2.03 m at Sam Son, 2.13 m at Quang Chau, and 2.76 m at Cua Hoi. The storm then moved into Laos and weakened into a low-pressure area on the morning of 26 August. Typhoon Bualoi entered the central East Sea on the evening of 26 September with intensity level 12 and gusts to level 15, moved rapidly West-Northwestward, and made landfall over Ha Tinh-Northern Quang Tri on the night of 28 September (level 11, gusting to level 14). It weakened into a low-pressure area over Laos by noon on 29 September. Because landfall coincided with a spring-tide period, the typhoon generated very high water levels over Northern and North-central Viet Nam on the morning of 29 September 2025. Marine stations recorded maximum water levels of 2.44 m at Hon Ngu and 2.15 m at Sam Son, while the two estuarine hydrological stations recorded 2.56 m at Quang Chau and 2.92 m at Cua Hoi.

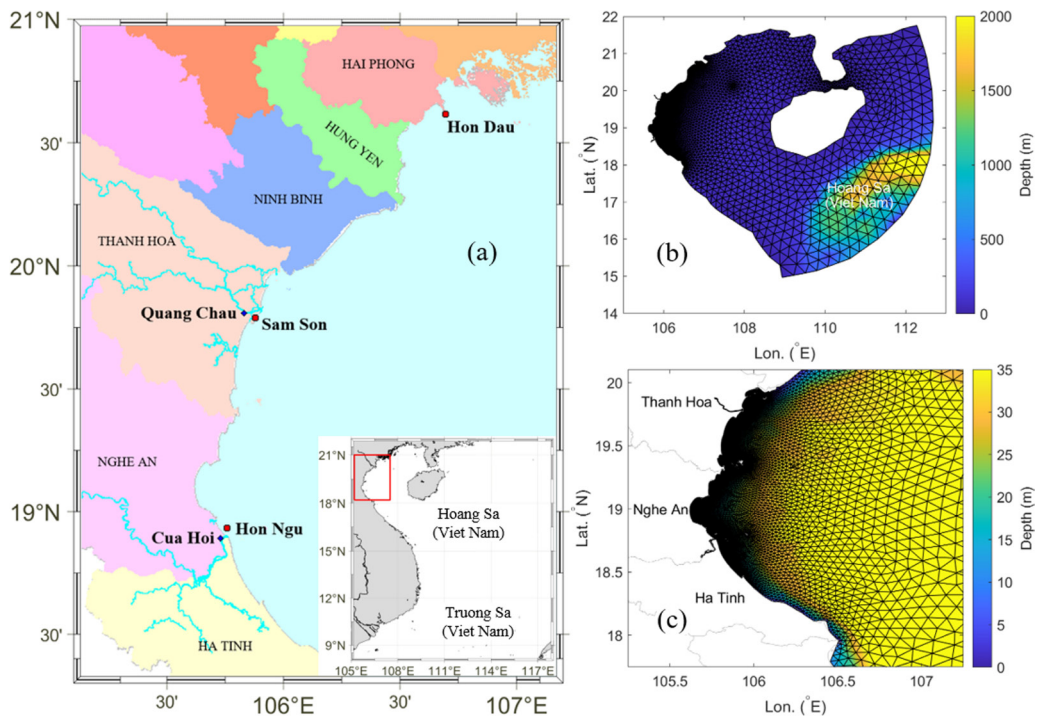


Figure 1. Locations of evaluation points for forecast performance (a), computational domain (b) with a detailed mesh for the coastal area of Thanh Hoa - Nghe An (c)

The experimental application of the coupled SCHISM-WWM model on a high-resolution unstructured grid along the Thanh Hoa-Nghe An coast in 2025 produced very encouraging results. Based on 24 independent forecast cycles for Typhoons Kajiki and Bualoi, the results demonstrate the model's strong potential for practical application in operational total water level forecasting. This provides an important basis for improving coastal hazard warning capability and reducing losses caused by coastal natural disasters.

The objective of this study is to evaluate the performance of the coupled SCHISM-WWM model in forecasting total water levels along the Thanh Hoa-Nghe An coast in 2025. The remainder of the paper is organized as follows. Section 2 describes the data and methods, including the experimental total-water-level forecasts for Typhoons Kajiki (August 2025) and Bualoi (September 2025) and the methodology used to evaluate the SCHISM forecasts. Section 3 presents the main results of the comparison between model-forecast storm-related water levels and observations. Finally, Section 4 summarizes the main conclusions of the study.

2. Data and research methods

2.1. Data

Pham Van Tien et al. (2025) [15-16] configured SCHISM, coupled with the WWM wave model, for the Thanh Hoa-Nghe An coastal area using an unstructured grid with 15,513 nodes. Grid resolution varies from 30 km at the open boundary to 50-100 m in rivers and estuarine areas (Figure 1b-c). The SCHISM model is two-way coupled with the WWM wave model on the same unstructured computational grid. This two-way interaction allows SCHISM to provide water-level and current fields to WWM for the calculation of shallow-water effects, wave refraction, and wave breaking. In return, SCHISM receives the wave radiation-stress contribution from WWM to account for wave-induced setup. This coupled framework enables a more accurate simulation of coastal total water levels, which comprise tidal elevation, wind- and pressure-induced storm surge, and wave setup. Boundary conditions include 23 FES2014 tidal constituents and meteorological forcing consisting of GFS wind and pressure fields at 0.25° × 0.25° resolution. The SCHISM model was calibrated and validated against observed water levels at coastal stations (Hon Dau and Hon Ngu), estuarine stations (Quang Chau and Cua Hoi), and wave observations from drifting and moored buoys. The model was then configured to produce forecasts up to 72 hours, with a hydrodynamic simulation time step of 120 s and a SCHISM-WWM coupling interval of 600 s. To assess the reliability and forecasting capability of this SCHISM configuration, the study selected experimental total-water-level forecasts for Typhoons Kajiki and Bualoi, two representative storms affecting the region in 2025 as described above.

Experimental total-water-level forecasts for Typhoons Kajiki and Bualoi were produced four times per day, consistent with operational forecasting practice for hazardous weather at the Institute of Meteorology, Hydrology, Environment and Marine Sciences. The forecast runs for each typhoon are shown in Table 1. For each typhoon, 12 independent forecast cycles were performed at 6-hour intervals. The corresponding forecast lead times ranged from 72 h to 6 h and were defined relative to the expected typhoon landfall time or the predicted time of peak water level. Each forecast cycle covered a 96-hour simulation period.

2.2. Method for evaluating experimental forecast results

The experimental forecasts were evaluated using observations from five stations: three coastal stations (Hon Dau, Sam Son, and Hon Ngu) and two estuarine stations (Quang Chau and Cua Hoi) (Figure 1a), in order to assess the temporal and spatial water-level forecasting capability of SCHISM. To evaluate the accuracy and similarity between the forecast and observed time series, the study uses the Skill index:

$$Skill = 1 - \frac{\sum_{i=1}^{n} |S_i - O_i|^2}{\sum_{i=1}^{n} (|S_i - \bar{O}| + |O_i - \bar{O}|)^2} \quad (1)$$

Where S_i and O_i are the simulated (forecast) and observed values, respectively; O is the mean observed value, S is the mean simulated value, and n is the number of values.

Because water-level observations at Sam Son station were available only four times per day, the Skill index was not applied to this station due to the insufficient temporal resolution of the observational data.

The accuracy of the total-water-level peak (magnitude and time of occurrence) for each forecast run was also assessed according to QCVN 84, the technical regulation for evaluating the quality of marine forecasts and warnings, issued by the Ministry of Natural Resources and Environment (now the Ministry of Agriculture and Environment) under Circular No. 46/2024/BTNMT [17]. Accordingly, a forecast is considered "acceptable" if its forecast error (ΔS) relative to the observed value lies within the allowable range, and "unacceptable" if the error lies outside that range, as described in Table 2. Forecasts with lead times of 54-72 h were assessed against the criteria applicable to the 24-48 h forecast lead-time range.

$$\Delta S = 100 \times \frac{S_i - O_i}{O_i} \quad (2)$$

Table 1. Experimental forecast runs

No.	Water-level forecast runs during Typhoon Kajiki (Aug. 2025)		Water-level forecast runs during Typhoon Bualoi (Sep. 2025)	
	Forecast initialization time	Forecast lead time	Forecast initialization time	Forecast lead time
1	2025082212h	72-hour	2025092512h	72-hour
2	2025082218h	66-hour	2025092518h	66-hour
3	2025082300h	60-hour	2025092600h	60-hour
4	2025082306h	54-hour	2025092606h	54-hour
5	2025082312h	48-hour	2025092612h	48-hour
6	2025082318h	42-hour	2025092618h	42-hour
7	2025082400h	36-hour	2025092700h	36-hour
8	2025082406h	30-hour	2025092706h	30-hour
9	2025082412h	24-hour	2025092712h	24-hour
10	2025082418h	18-hour	2025092718h	18-hour
11	2025082500h	12-hour	2025092800h	12-hour
12	2025082506h	06-hour	2025092806h	06-hour

Note: "2025082212h" denotes the forecast run initialized at 12:00 on 22 August 2025

Table 2. Allowable forecast errors under Circular No. 46/2024/BTNMT (QCVN 84)

Forecast lead time	Allowable error
Water-level magnitude forecast	
Up to 12 h	[-20 ÷ 20] %
12-24 h	[-30 ÷ 30] %
24-48 h	[-40 ÷ 40] %
Forecast time of occurrence	
Up to 12 h	[-3 ÷ 3] h
12-24 h	[-6 ÷ 6] h
24-48 h	[-12 ÷ 12] h

3. Evaluation of experimental total-water-level forecasts

3.1. Results of experimental total water level forecasts for Typhoon Kajiki

The spatial distributions of maximum total water level and the corresponding forecast input wind fields for the 12 forecast runs (lead times from 72 h to 6 h) are shown in Figures 2 and 3, respectively. Variations in storm structure and intensity among the forecast runs clearly affect the coastal distribution of total water level and lead to substantial differences among forecast results. At long lead times (72 h and 66 h; Figures 2a-b), the maximum total water level along the Thanh Hoa-Nghe An coast ranges from 1.5 m to less than 2.0 m. At intermediate lead times (30-48 h; Figures 3e-i), however, the maximum water level varies considerably. Forecast wind fields at these lead times, especially 30 h and 36 h (Figures 3g-h), show a strongly developed cyclone with an expanded strong-wind region and maximum wind speeds exceeding 40 m/s. This produces maximum total water levels of 3.0-3.5 m along the Dien Chau-Cua Hoi coast (Figure 2h). At short lead times, the forecast typhoon wind field begins to converge toward the observed state, with a moderately more compact wind structure (Figures 3j-l). The area of maximum total water level along the Nghe An coast becomes narrower and the peak remains around 2.0-2.5 m (Figures 2j-l), close to observations at Sam Son, Hon Ngu, Quang Chau, and Cua Hoi.

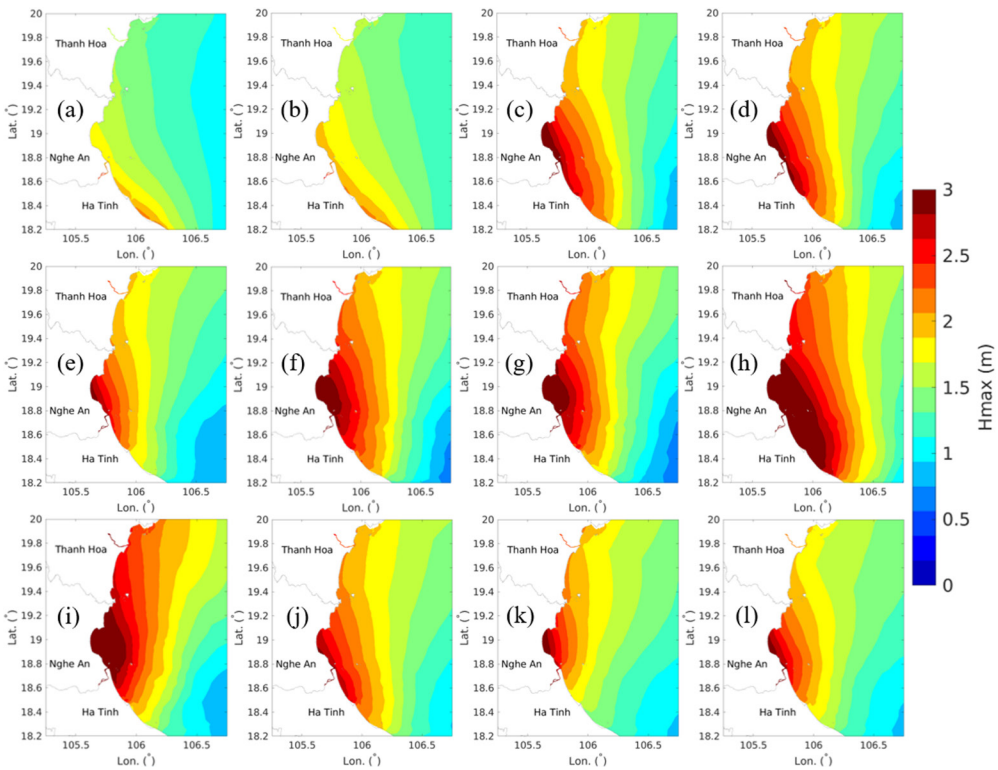


Figure 2. Spatial distribution of maximum total water level for forecast runs during Typhoon Kajiki (2025): (a) 72-hour lead time, (b) 66 h, (c) 60 h, (d) 54 h, (e) 48 h, (f) 42 h, (g) 36 h, (h) 30 h, (i) 24 h, (j) 18 h, (k) 12 h, and (l) 06 h.

Forecast total water levels at the stations for lead times from 6 hours to 72 hours are shown in Figure 4. Comparison of forecast and observed time series at the marine stations (Hon Dau and Hon Ngu) and estuarine hydrological stations (Quang Chau and Cua Hoi) shows that, except for the first two runs at lead times of 72 and 66-hour, which underestimate observations at all stations, the shorter-lead forecasts generally overestimate peak water levels at most locations.

A quantitative assessment shows that the 12-hour forecast has the best performance and is in closest agreement with the observed time series (Figure 4 and Table 3). Under the influence of Typhoon Kajiki, a coastal strip extending from Ha Tinh to Thanh Hoa experienced total water levels above 2.0 m (Figure 2), with the highest values occurring from Dien Chau Bay to Cua Hoi. Observations at Hon Ngu and Cua Hoi (Figures 4b and 4d) show that water levels remained high for an extended period after reaching the peak. However, the hydrodynamic model did not reproduce this behavior.

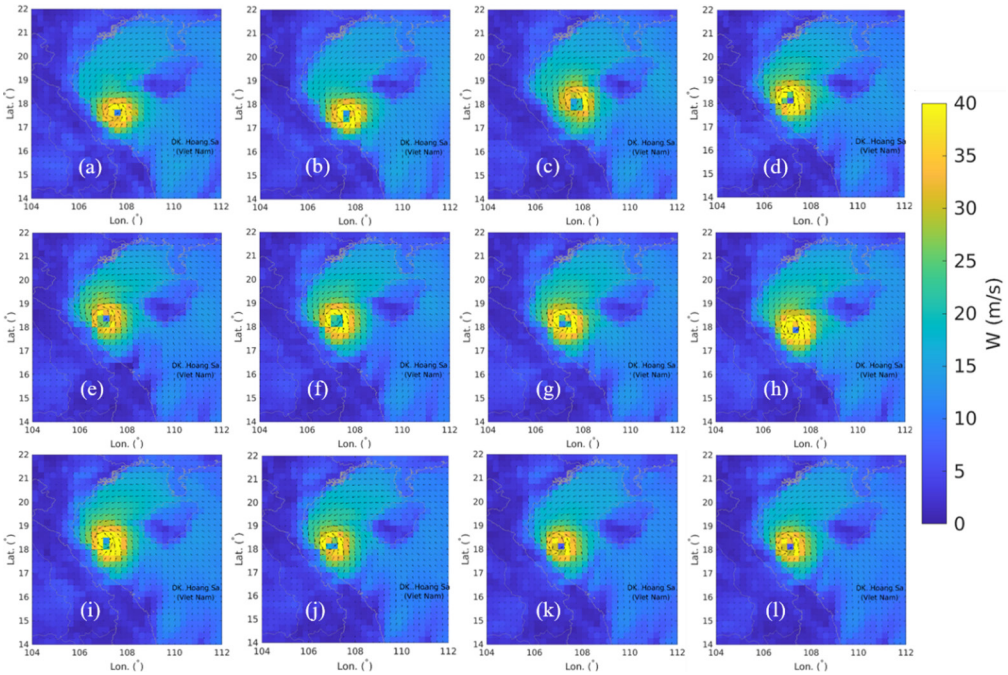


Figure 3. Forecast wind field at 06:00 on 25 August 2025 for forecast runs during Typhoon Kajiki (2025): (a) 72-hour lead time, (b) 66 h, (c) 60 h, (d) 54 h, (e) 48 h, (f) 42 h, (g) 36 h, (h) 30 h, (i) 24 h, (j) 18 h, (k) 12 h, and (l) 06 h

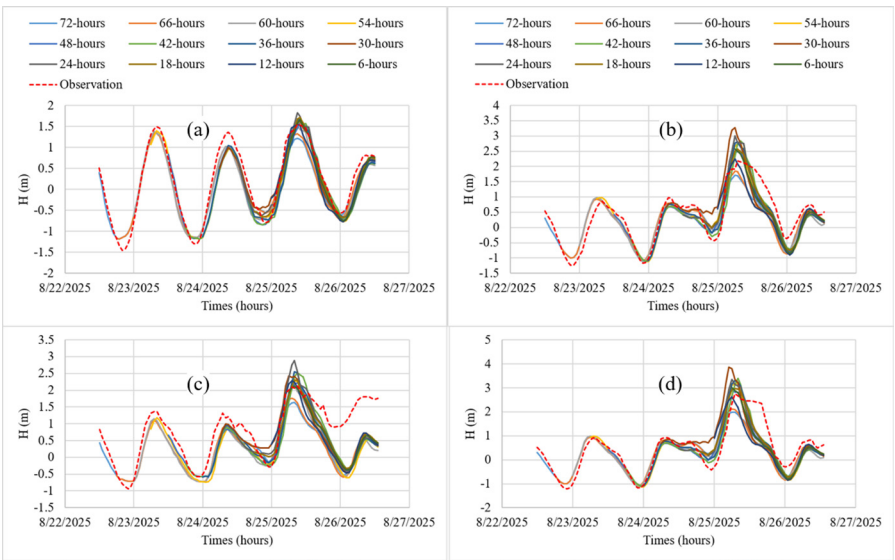


Figure 4. Comparison of forecast and observed total water levels during Typhoon Kajiki (2025) at (a) Hon Dau, (b) Hon Ngu, (c) Quang Chau, and (d) Cua Hoi

Comparison of peak water level (Hmax) and peak time (Tmax) between forecasts and observations shows inconsistent performance across lead times (Tables 3 and 4). At long lead times (66-72 h), the model substantially underestimates observations at all stations, with the largest differences at Sam Son (-30.2%) and Cua Hoi (-28.1%). At intermediate lead times (24-48 h), the model tends to overestimate peak water levels. At the 30-hour lead time, forecast errors reach 40.2% at Cua Hoi and 50.4% at Hon Ngu, exceeding the allowable QCVN 84 limits and therefore failing to meet forecast-quality requirements. At short lead times (06-18 h), errors generally decrease and remain below 20%, with the smallest errors of -1.2% at Hon Dau, -2.8% at Sam Son, and 2.9% at Hon Ngu.

Table 3. Forecast peak total water level and peak time at stations during Typhoon Kajiki (2025)

Forecast lead time / Station	Parameter	Hon Dau	Sam Son	Quang Chau	Hon Ngu	Cua Hoi
72-hour	Hmax (m)	1.35	1.42	1.63	1.70	1.99
	Tmax (h)	16 (Aug. 25)	14 (Aug. 25)	15 (Aug. 25)	13 (Aug. 25)	14 (Aug. 25)
66-hour	Hmax (m)	1.34	1.53	1.76	1.85	2.11
	Tmax (h)	16 (Aug. 25)	14 (Aug. 25)	14 (Aug. 25)	13 (Aug. 25)	13 (Aug. 25)
60-hour	Hmax (m)	1.52	1.91	2.16	2.75	3.31
	Tmax (h)	16 (Aug. 25)	14 (Aug. 25)	14 (Aug. 25)	14 (Aug. 25)	14 (Aug. 25)
54-hour	Hmax (m)	1.65	1.99	2.27	2.73	3.22
	Tmax (h)	17 (Aug. 25)	15 (Aug. 25)	15 (Aug. 25)	14 (Aug. 25)	15 (Aug. 25)
48-hour	Hmax (m)	1.60	1.90	2.22	2.48	2.90
	Tmax (h)	17 (Aug. 25)	15 (Aug. 25)	16 (Aug. 25)	14 (Aug. 25)	13 (Aug. 25)
42-hour	Hmax (m)	1.63	2.4	2.52	2.83	3.38
	Tmax (h)	16 (Aug. 25)	17 (Aug. 25)	16 (Aug. 25)	15 (Aug. 25)	15 (Aug. 25)
36-hour	Hmax (m)	1.67	2.20	2.55	2.81	3.30
	Tmax (h)	17 (Aug. 25)	15 (Aug. 25)	15 (Aug. 25)	14 (Aug. 25)	14 (Aug. 25)
30-hour	Hmax (m)	1.65	2.09	2.43	3.28	3.87
	Tmax (h)	17 (Aug. 25)	15 (Aug. 25)	13 (Aug. 25)	13 (Aug. 25)	12 (Aug. 25)
24-hour	Hmax (m)	1.82	2.49	2.89	3.00	3.35
	Tmax (h)	16 (Aug. 25)	14 (Aug. 25)	15 (Aug. 25)	13 (Aug. 25)	13 (Aug. 25)
18-hour	Hmax (m)	1.72	2.01	2.31	2.56	2.97
	Tmax (h)	17 (Aug. 25)	15 (Aug. 25)	15 (Aug. 25)	14 (Aug. 25)	14 (Aug. 25)
12-hour	Hmax (m)	1.54	1.97	2.27	2.24	2.62
	Tmax (h)	16 (Aug. 25)	14 (Aug. 25)	14 (Aug. 25)	13 (Aug. 25)	13 (Aug. 25)
06-hour	Hmax (m)	1.67	1.80	2.12	2.56	3.00
	Tmax (h)	17 (Aug. 25)	15 (Aug. 25)	15 (Aug. 25)	13 (Aug. 25)	13 (Aug. 25)
Observed	Hmax (m)	1.56	2.03	2.13	2.18	2.76
	Tmax (h)	18 (Aug. 25)	18 (Aug. 25)	18 (Aug. 25)	16 (Aug. 25)	16 (Aug. 25)

Total water level forecast errors are strongly influenced by the forecast wind and atmospheric pressure fields from the Global Forecast System (GFS), particularly by the model's ability to capture and reproduce the actual structure of the typhoon wind field. In general, forecast

errors tend to decrease as the forecast lead time becomes shorter. However, this tendency is not always observed. For Typhoon Kajiki (August 2025), for example, the forecast errors at lead times of 48-54 h were smaller than those at shorter lead times. This may be because, for these forecast cycles, the GFS wind fields reproduced the typhoon structure and intensity more realistically than those from the other forecast cycles.

For the timing of the water-level peak, the model forecasts are generally 1-4 h earlier than observations (most commonly 2-3 h), but these errors remain within the allowable QCVN 84 limits.

The Skill values for total-water-level forecasts during Typhoon Kajiki (August 2025), presented in Table 7, are all relatively high, ranging from 0.72 to 0.88. This indicates that the configured SCHISM model has good forecasting skill and reproduces the observed trends and magnitudes of total water level at all four stations. Overall, Skill increases as forecast lead time decreases (from 72 h toward 06 h). The highest Skill values occur at short lead times (18 h, 12 h, and especially 06 h). Even at long lead times of 48-72 h, Skill remains consistently high (above 0.72), indicating that the model can reliably capture the trend of total water level variations 2-3 days in advance.

Table 4. Differences in peak total water level and peak time between forecasts and observations at stations during Typhoon Kajiki (2025)

Forecast lead time / Station	Peak water-level error (%)					Time-of-occurrence error (h)				
	Hon Dau	Sam Son	Quang Chau	Cua Hoi	Hon Ngu	Hon Dau	Sam Son	Quang Chau	Cua Hoi	Hon Ngu
72-hour	-13.1	-30.2	-23.3	-28.1	-21.8	-2	-3	-2	-2	-3
66-hour	-13.9	-24.6	-17.4	-23.4	-15.3	-2	-3	-3	-3	-3
60-hour	-2.7	-5.9	1.6	19.9	26.4	-2	-3	-3	-2	-2
54-hour	5.9	-2.2	6.5	16.6	25.0	-1	-2	-2	-1	-2
48-hour	2.5	-6.5	4.0	5.0	13.6	-1	-2	-1	-3	-2
42-hour	4.3	5.5	18.4	22.6	29.7	-2	0	-1	-1	-1
36-hour	6.9	8.3	19.6	19.6	28.8	-1	-2	-2	-2	-2
30-hour	6.0	2.9	14.1	40.2	50.4	-1	-2	-4	-4	-3
24-hour	16.7	22.5	35.7	21.4	37.8	-2	-3	-2	-3	-3
18-hour	10.4	-1.1	8.6	7.6	17.5	-1	-2	-2	-2	-2
12-hour	-1.2	-2.8	6.8	-5.1	2.9	-2	-3	-3	-3	-3
06-hour	6.9	-11.2	-0.5	8.9	17.5	-1	-2	-2	-3	-3

3.2. Experimental total-water-level forecast results for Typhoon Bualoi

The simulated maximum total water levels for the Bualoi forecast runs are shown in Figure 5. The spatial distribution of maximum total water level varies less among forecast runs than in the Kajiki forecasts. Analysis of the forecast wind fields shows a similar pattern: maximum wind speed and the spatial distribution of the strong-wind region are relatively stable among forecast runs. Overall, Typhoon Bualoi produced total water levels above 2.3 m along a long coastal stretch from Ha Tinh to Thanh Hoa. Total water levels above 2.5 m were concentrated along the Dien Chau-Cua Hoi coast, with many locations in the two provinces experiencing storm-related total water levels above 3.0 m.

Comparison of the temporal evolution of forecast and observed total water levels at the stations in Figure 6 shows good agreement at all stations for most forecast runs. Forecast-error assessment also indicates that these forecasts

perform better than those for Typhoon Kajiki. However, the forecast peak total water level is lower than observed in most runs (Figure 6 and Table 5 and 6). This underestimation may lead to insufficient preparedness if the forecast risk is assessed too low.

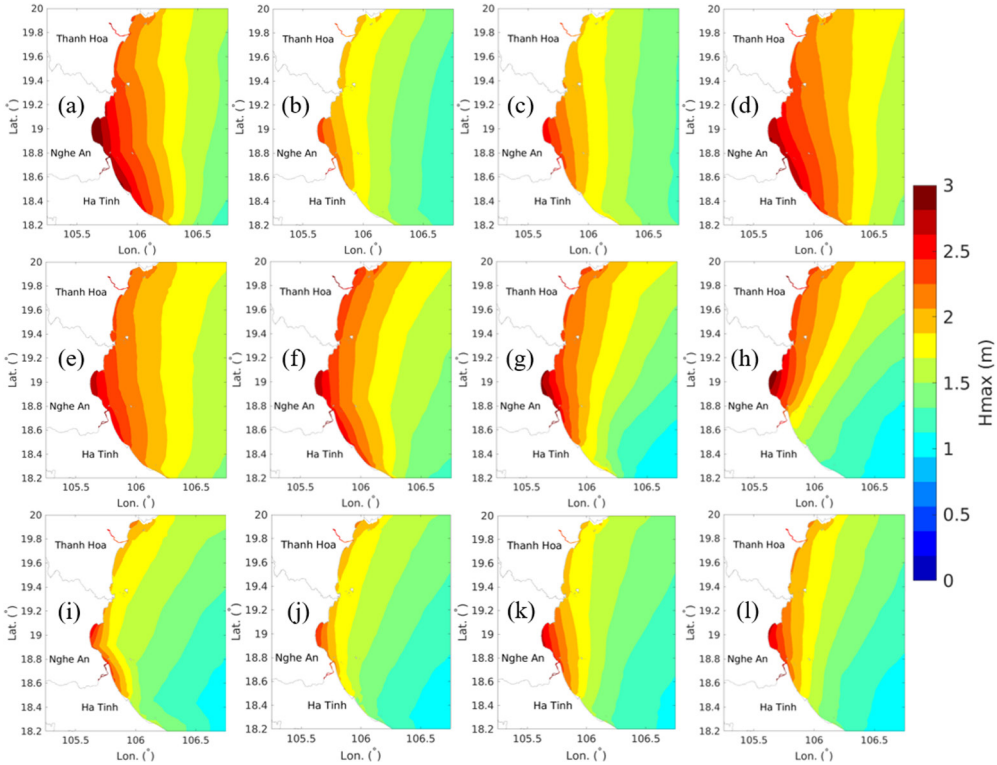


Figure 5. Spatial distribution of maximum total water level for forecast runs during Typhoon Bualoi (2025): (a) 72-hour lead time, (b) 66 h, (c) 60 h, (d) 54 h, (e) 48 h, (f) 42 h, (g) 36 h, (h) 30 h, (i) 24 h, (j) 18 h, (k) 12 h, and (l) 06 h

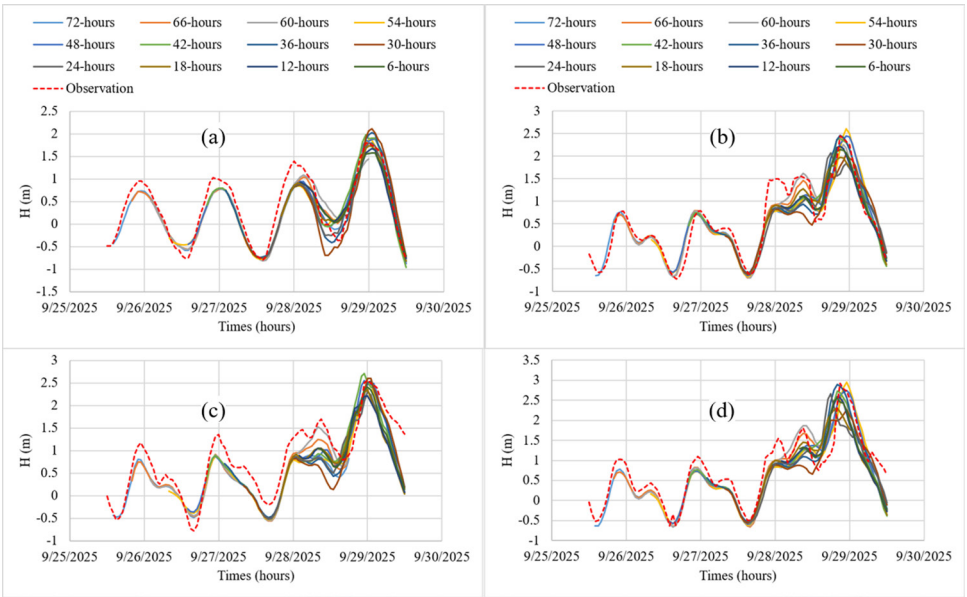


Figure 6. Comparison of forecast and observed total water levels during Typhoon Bualoi (2025) at (a) Hon Dau, (b) Hon Ngu, (c) Quang Chau, and (d) Cua Hoi

Comparison of peak water level and peak time between forecasts and observations (Tables 5 and 6) shows that at 60-72-hour lead times the model substantially underestimates observations at most stations. The largest peak-water-level errors are -25.0% at Sam Son, -20.0% at Hon Ngu, -15.0% at Quang Chau, and -14.5% at Cua Hoi. At lead times of 30-54 h, the model tends to overestimate the peak, but errors remain below 20% and are commonly between -10.0% and 10.0%. At lead times of 06-24 h, the model generally underestimates observations, with errors mainly between -10.0% and 10.0%. Overall, all total-water-level forecasts for Typhoon Bualoi (September 2025) remain within the allowable QCVN 84 limits and therefore satisfy forecast-quality requirements.

For the timing of the water-level peak, the model forecasts are generally 1-4 h earlier than observations, but these errors remain within the allowable QCVN 84 limits.

Table 5. Forecast peak total water level and peak time at stations during Typhoon Bualoi (2025)

Forecast lead time / Station	Parameter	Hon Dau	Sam Son	Quang Chau	Hon Ngu	Cua Hoi
72-hour	Hmax (m)	1.68	2.21	2.48	2.63	2.98
	Tmax (h)	23 (Sep. 28)	21 (Sep. 28)	21 (Sep. 28)	20 (Sep. 28)	20 (Sep. 28)
66-hour	Hmax (m)	1.34	1.90	2.18	2.09	2.34
	Tmax (h)	22 (Sep. 28)	20 (Sep. 28)	21 (Sep. 28)	19 (Sep. 28)	19 (Sep. 28)
60-hour	Hmax (m)	1.49	1.91	2.24	2.25	2.54
	Tmax (h)	0 (Sep. 29)	21 (Sep. 28)	21 (Sep. 28)	20 (Sep. 28)	20 (Sep. 28)
54-hour	Hmax (m)	1.85	2.18	2.50	2.60	2.94
	Tmax (h)	0 (Sep. 29)	22 (Sep. 28)	22 (Sep. 28)	21 (Sep. 28)	21 (Sep. 28)
48-hour	Hmax (m)	1.88	2.20	2.55	2.45	2.75
	Tmax (h)	0 (Sep. 29)	23 (Sep. 28)	21 (Sep. 28)	21 (Sep. 28)	21 (Sep. 28)
42-hour	Hmax (m)	1.97	2.34	2.70	2.39	2.73
	Tmax (h)	22 (Sep. 28)	20 (Sep. 28)	21 (Sep. 28)	19 (Sep. 28)	18 (Sep. 28)
36-hour	Hmax (m)	2.03	2.21	2.54	2.46	2.89
	Tmax (h)	0 (Sep. 29)	22 (Sep. 28)	23 (Sep. 28)	19 (Sep. 28)	18 (Sep. 28)
30-hour	Hmax (m)	2.12	2.27	2.60	2.04	2.26
	Tmax (h)	0 (Sep. 29)	22 (Sep. 28)	23 (Sep. 28)	21 (Sep. 28)	21 (Sep. 28)
24-hour	Hmax (m)	1.79	1.95	2.31	2.06	2.66
	Tmax (h)	0 (Sep. 29)	22 (Sep. 28)	22 (Sep. 28)	15 (Sep. 28)	15 (Sep. 28)
18-hour	Hmax (m)	1.73	1.95	2.35	1.97	2.30
	Tmax (h)	23 (Sep. 28)	21 (Sep. 28)	22 (Sep. 28)	19 (Sep. 28)	18 (Sep. 28)
12-hour	Hmax (m)	1.67	1.87	2.21	2.22	2.59
	Tmax (h)	0 (Sep. 29)	21 (Sep. 28)	22 (Sep. 28)	19 (Sep. 28)	18 (Sep. 28)
06-hour	Hmax (m)	1.57	2.02	2.40	2.14	2.55
	Tmax (h)	0 (Sep. 29)	22 (Sep. 28)	22 (Sep. 28)	19 (Sep. 28)	18 (Sep. 28)
Observed	Hmax (m)	1.79	2.15	2.56	2.44	2.92
	Tmax (h)	1 (Sep. 29)	21 (Sep. 28)	21 (Sep. 28)	22 (Sep. 28)	22 (Sep. 28)

Table 6. Differences in peak total water level and peak time between forecasts and observations at stations during Typhoon Bualoi (2025)

Forecast lead time / Station	Peak water-level error (%)					Time-of-occurrence error (h)				
	Hon Dau	Sam Son	Quang Chau	Cua Hoi	Hon Ngu	Hon Dau	Sam Son	Quang Chau	Cua Hoi	Hon Ngu
72-hour	-6.1	2.7	-3.0	7.7	2.2	-1	-1	-1	-1	0
66-hour	-25.0	-11.7	-15.0	-14.5	-20.0	-2	-2	-1	-2	-1
60-hour	-17.0	-11.1	-12.7	-7.7	-13.0	0	-1	-1	-1	0
54-hour	3.6	1.4	-2.5	6.7	0.8	0	0	0	0	1
48-hour	4.9	2.4	-0.3	0.4	-5.9	0	1	-1	0	1
42-hour	10.2	8.9	5.6	-2.0	-6.5	-2	-2	-1	-2	-2
36-hour	13.4	3.0	-0.9	0.7	-1.1	0	0	1	-2	-2
30-hour	18.2	5.6	1.6	-16.5	-22.7	0	0	1	0	1
24-hour	0.2	-9.5	-9.9	-15.4	-8.9	0	0	0	-4	-3
18-hour	-3.2	-9.2	-8.2	-19.1	-21.3	-1	-1	0	-2	-2
12-hour	-6.9	-12.9	-13.8	-9.1	-11.1	0	-1	0	-2	-2
06-hour	-12.1	-5.9	-6.4	-12.4	-12.6	0	0	0	-2	-2

Table 7. Skill index for total-water-level forecasts at stations during Typhoons Kajiki (2025) and Bualoi (2025)

Forecast lead time / Station	Typhoon Kajiki (Aug 2025)				Typhoon Bualoi (Sep 2025)			
	Hon Dau	Hon Ngu	Quang Chau	Cua Hoi	Hon Dau	Hon Ngu	Quang Chau	Cua Hoi
72-hour	0.79	0.81	0.77	0.80	0.79	0.80	0.77	0.76
66-hour	0.79	0.81	0.77	0.80	0.80	0.79	0.78	0.74
60-hour	0.78	0.77	0.76	0.76	0.79	0.77	0.76	0.72
54-hour	0.78	0.76	0.76	0.75	0.81	0.82	0.79	0.77
48-hour	0.79	0.78	0.78	0.77	0.82	0.82	0.81	0.78
42-hour	0.79	0.76	0.76	0.77	0.83	0.84	0.83	0.80
36-hour	0.82	0.77	0.78	0.76	0.82	0.87	0.84	0.84
30-hour	0.85	0.74	0.81	0.72	0.80	0.88	0.83	0.84
24-hour	0.84	0.77	0.77	0.77	0.87	0.86	0.86	0.83
18-hour	0.85	0.80	0.83	0.79	0.93	0.87	0.93	0.85
12-hour	0.88	0.85	0.84	0.83	0.95	0.91	0.95	0.88
06-hour	0.88	0.83	0.85	0.83	0.97	0.93	0.96	0.90

The Skill values presented in Table 7 show that model forecast performance is above 70%, with relatively high Skill values ranging from 0.72 to 0.97. At all four stations, Skill tends to increase as lead time decreases. At lead times of 72-60 h, Skill ranges from 0.72 to 0.80; at lead times of 18-06 h, it increases to 0.85-0.97. Comparison of the two storms shows that Bualoi (September 2025) was forecast more accurately than Kajiki (August 2025). At long lead times (72-48 h), Skill values for the two storms are similar, approximately 0.75-0.83. At shorter lead times

(24-06 h), however, Bualoi forecasts are more accurate, with most Skill values in the 0.85-0.97 range, whereas Kajiki forecasts at these short lead times attain only 0.77-0.88.

The experimental total-water-level forecasts for Typhoons Kajiki (August 2025) and Bualoi (September 2025) show that the coupled SCHISM-WWM model is capable of forecasting coastal total water levels in the Thanh Hoa-Nghe An region with good skill. However, several issues warrant further discussion. The close relationship between the distribution of strong winds around the storm center and the spatial distribution of maximum total water level demonstrates the important role of forecast wind and pressure fields in SCHISM water-level forecast performance. The accuracy of total-water-level forecasts depends strongly on the quality of wind and atmospheric-pressure forecasts from the GFS global atmospheric model. During Typhoon Kajiki, large peak-water-level errors exceeding QCVN 84 at 30-36-hour lead times (50.4% at Hon Ngu and 40.2% at Cua Hoi) resulted from GFS forecasting a more developed and broader wind field than indicated by the reanalysis data, which are considered closest to actual conditions. By contrast, during Typhoon Bualoi the GFS meteorological fields were more stable across forecast runs, allowing the model to maintain superior Skill values (0.85-0.97 at short lead times), with all runs satisfying QCVN 84. To reduce the impact of errors associated with relying on a single forecast wind and pressure field, an ensemble forecasting approach using multiple meteorological forecast datasets as SCHISM inputs could provide an effective means of controlling water-level forecast errors.

The results from 24 independent forecast cycles during Typhoons Kajiki and Bualoi indicate that total water level forecast errors do not necessarily decrease consistently with shorter forecast lead times, but instead vary depending on how realistically the meteorological forcing represents actual storm conditions. Accordingly, forecast cycles in which the GFS wind fields more accurately reproduce the typhoon structure and intensity tend to yield smaller errors and higher forecast accuracy, regardless of the nominal forecast lead time.

Overall, the experimental results for Typhoons Kajiki and Bualoi demonstrate the feasibility of applying the SCHISM-WWM model to operational coastal water level forecasting. However, because the number of real-case evaluations remains limited, the model's robustness under different meteorological forcing scenarios requires further verification. These findings support continued development of the SCHISM-WWM system for future coastal hazard forecasting applications.

4. Conclusions

This study conducted a detailed evaluation of experimental operational forecasts of coastal total water level for the Thanh Hoa-Nghe An region using the SCHISM numerical model during two representative typhoons in 2025: Typhoon No. 5 Kajiki and Typhoon No. 10 Bualoi. The main conclusions are as follows:

The coupled SCHISM-WWM model demonstrates good forecasting skill for total water levels along the coastal and estuarine areas of Thanh Hoa-Nghe An, with Skill values ranging from 0.72 to 0.97 and generally increasing as the forecast lead time becomes shorter.

Most forecast cycles during Typhoons Kajiki (August 2025) and Bualoi (September 2025) met the quality requirements specified in QCVN 84, except for the 30-hour forecast cycle during Typhoon Kajiki, for which peak water level errors at Cua Hoi and Hon Ngu stations exceeded 40%.

Total water level forecast performance was strongly affected by the GFS forecast wind and atmospheric pressure fields. Smaller forecast errors were generally obtained for forecast cycles in which the GFS wind fields reproduced the observed typhoon structure and intensity more realistically.

Although the experimental results indicate that the coupled SCHISM-WWM model has potential for total water level forecasting along the Thanh Hoa-Nghe An coast and could

potentially be extended to other coastal regions of Viet Nam, the number of evaluation cases in this study remains limited. Therefore, further testing and evaluation are required before the model can be fully implemented in operational forecasting.

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