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Surface water quality modelling with data scarcity in semi-enclosed coastal regions encompassed distributed islands

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ABSTRACT

Water quality variation in semi-enclosed urban coastal areas with different pollutant sources is a substantial issue. Pollutant entrapment has a significant impact on the lives of the local people. Surface water quality modelling often requires large datasets covering bathymetry, fluid and pollutants boundary conditions, sources and sinks. This is particularly challenging in regions with complex features and poor data availability, such as coastal water bodies featuring a large number of widely distributed islands and estuaries. In this paper, we developed a model of surface water quality and hydrodynamics for Ha Long Bay, in the North of Vietnam and includes 1969 islands, for a one-year period using a water quality dataset obtained for this study. The model utilized extracted bathymetric and geometric data from Admiralty Charts and Admiralty Tide Tables. Water quality coupled with the TELEMAC Model (WAQTEL) Biomass Module was employed to predict pollutant transport in the domain using point and diffused sources while field studies were conducted to collect data for the setting up and calibration of the water quality model. Thirty scattered sampling points were selected, and the water quality parameters were measured during two campaigns. The predicted water level and velocity values matched the local observation data well with a small error (RMSE = 0.19 and 0.16). Both NO_3^--N and PO_4^{3-}-P were high near the shoreline and decrease gradually offshore. The maximum concentrations of NO_3^--N and PO_4^{3-}-P reached 0.476 mg/L and 0.048 mg/L at the end of 2021 with the RMSE = 0.13 and 0.011, respectively. The levels of NO_3^--N and PO_4^{3-}-P and their distributions showed that Ha Long Bay was eutrophic even during the COVID-19 lockdown period.

1. Introduction

Coastal waters provide a habitat for marine species and support economic activities such as tourism, recreation, fishing and aquaculture, and the shipping industry. However, despite their importance, coastal waters worldwide are under pressure from increasing land-based pollutants and natural phenomena, particularly eutrophication. Coastal eutrophication caused by excess nutrient loading is reported to be the greatest threat to the health of coastal and marine ecosystems (Smith, 2003). It may cause an increase in harmful algal blooms, the loss of submerged aquatic vegetation, and the occurrence of anoxic zones (Kelly et al., 2021). Therefore, assessing the water quality and understanding the pollution transportation in coastal regions is essential to protect the regional natural resources and ecosystem services associated with these water bodies.

Water quality affects the economy, food-chains, personal lifestyles, disease spread, and prospects for future developments (Biswas and Tortajada, 2019). In this respect, hydrodynamic simulations are useful to support water quality or water economy models and to better understand changing water quality levels. Such simulations may be

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particularly valuable where local populations are more directly dependent on water related activities and aquacultures (Falkenmark, 2020; King et al., 2021). Water quality issues are rarely related to just one type of pollution. This is because many human activities on the land are sources of different river pollutants, such as plastic debris, nutrients, chemicals, and pathogens (Strokal et al., 2019; Chen et al., 2013). These pollutants are important causes of different water-borne diseases and chronic illnesses. Disease is influenced by water pollution with chemicals, solid waste (mainly plastics), pathogens, insects, and other disease vectors (Wild, 2012). Water-borne and water-related infectious diseases are estimated to account for 3.4 million annual deaths worldwide (Boelee et al., 2019; Pruss-Ustun et al., 2016).

Water quality models are useful to examine both existing phenomena and to predict the possible effects of pollution on the aquatic environment (Ejigu, 2021; Gomes et al., 2020; Villaret et al., 2013). Such modelling is critical for new development in coastal areas (Guo et al., 2021; Kadiri et al., 2014) and has become an essential component of overall coastal environmental management (Dreizis, 2020). Many water quality models have been developed and applied to simulate water quality around the world. Some of these models used for water quality modelling require a large amount of data for calibration and verification (Gao and Li, 2015; Ejigu, 2021; Guo et al., 2020; Hervouet, 2000). TELEMAC 2D was evaluated to be suitable for simulated water quality in coastal waters, particularly in a coastal water with a complex coastline (Stolarska and Skrzypski, 2012).

Several studies have employed TELEMAC 2D to characterize water quality patterns or to estimate the effect of sea level on monitoring water quality variations (e.g., Awad and Darwich, 2009; Tyrrell and George, 2006; Cea et al., 2016; Abu-Bakr et al., 2017; Lavine et al., 2020; Goeury et al., 2022). This model is based on the depth-averaged assumption, of which the hydrodynamic and water quality variables over a vertical water column are assumed to be integrated, and then variations in the water quality parameters within a water column are considered negligible. Accordingly, the model is recommended for dynamic coastal shallow waters where vertical mixing within a water column occurs (Bedri et al., 2011; Hashemi Monfared et al., 2013, 2014). For a coastal region where the tide is the dominant influential factor, TELEMAC 2D is an optimal selection because it has tools to integrate tidal heights as well as current speed and direction and simulate them with the same time intervals coupled with water quality parameters (Pye et al., 2017; Abu-Bakr et al., 2017; King et al., 2021; Hashemi Monfared et al., 2023).

Semi-enclosed coastal bays are commonly recognized as rich biodiversity sites (CBD - Convention on Biological Diversity, 2016). The biodiversity of Ha Long Bay, the subject of this paper, has been monitored and reported by many international and domestic agencies (World Bank Mission Report, 1998; IUCN Mission Report, 2000; Thung et al., 2019). Consequently, this is an important water body in terms of environmental impact and water quality, and, in turn, Ha Long Bay has received considerable attention not only from domestic researchers, managers, and policymakers but also from the international scientific community (Hong et al., 2008; Bui et al., 2012; JICA, 2013; Cao et al., 2020; Anh, 2020). A series of studies from researchers based in Vietnam have attempted to conduct water quality models for the bay (e.g., Uu et al., 2006; Tu et al., 2009; Nguyen, 2014; Cuong and Thao, 2019; Dung, 2020). DELFT3D and MIKE21 were employed for these studies with the assumption that the effects of flow and tide on water quality parameters are similar. However, most of the studies covered only limited areas close to the coast, and areas with complex geometries, e.g., a large number of small islands, were not included in the modelling domain. It is expected that consideration of the limited domain and the exclusion of islands would affect the flow structure outside the bay, which could subsequently affect the transport processes in the bay.

This study focused on developing a surface water quality model for Ha Long Bay, a complex geometry area with many scattered islands. One of the main challenges of this study was the correct representation of the islands in the computer model due to their large number and the complexity of the bathymetry. A coupled hydrodynamic/water quality model in a TELEMAC 2D environment was developed to predict water quality in the bay. Furthermore, nutrients data collected during field campaigns carried out as a part of this research were used to set up and validate the water quality model. These pollutant sources identified in urban districts along the coast are either discharged directly to the model as the source point or added to the rivers to be transferred to the bay through riverine flows. A frequent checkup and interpolation method was employed to produce a consistent geometry. The model was validated by water elevation and velocity in comparison with the Admiralty Tide Table (UK Hydrographic Office, 2021) and Admiralty Charts of the South China Sea. Since data availability in the region is limited, catchment models and remote sensing data were used to derive the value of the pollutants in the rivers, and global bathymetry datasets were used as the main source of the bathymetry. Using global datasets is expected to be the common approach for hydro-environmental modelling in regions with limited data availability. This study also highlights the inaccuracies in such global datasets, which is potentially due to a lack of ship routes, and provides a methodology to tackle these inaccuracies. The simulation was carried out for a one-year period using the WAQTEL module to predict the fate and transport of nutrients.

2. Materials and methods

2.1. Study area

Ha Long Bay is located within the Quang Ninh Province along the northeastern coast of Vietnam. Situated in the Gulf of Tonkin, Ha Long Bay is between latitude 20°43 to 20°56 and longitude 106°59–107°20. The bay is bounded by the mainland hills and Ha Long City in the north, the open waters of the Gulf of Tonkin in the south, Cat Ba Island in the west, and many small islands in the east. As part of the Gulf of Tonkin, Ha Long Bay (including the buffer zones of Bai Tu Long Bay) has an area of 1553 km^2 including 1969 islands. The central part of Ha Long Bay has an area of 434 km^2, including 775 islands (Fig. 1) (Son, 2002). According to monitoring data from 2015 to 2018 (Tuan, 2020), the climate in the region is humid-tropical, with long hot and rainy summers and short mild and dry winters. The long-term annual mean temperature in the area changes from 21 °C to 26.5 °C, with the monthly averages ranging from 19.4 °C in February to 32 °C in June. Long-term annual precipitation in the area is approximately 1920 mm, ranging from 450 mm in August to 21 mm in December.

Located in the north of Ha Long Bay is the Cua Luc estuary. Three rivers, namely, the Troi, Man, and Dien Vong rivers, discharge into the Cua Luc estuary (shown in Fig. 1). These rivers have extremely low flow rates, usually less than 2 m^3/s, in the dry season (from November to the May of the next year) and high flow rates, usually from 8.3 to 26.5 m^3/s, in the wet season (from June to October). The Dien Vong river has the highest water flow rate and, as it flows through many residential areas and industrial zones, is considered a pollution source for the Cua Luc estuary area (Dung, 2020; Dung and Anh, 2021; Huynh, 2002; Japan Environmental Cooperation Agency, 1999; 2013, 2014).

2.2. Modelling method

Spatial-temporal simulations have been carried out using a depth-averaged two-dimensional model, namely, TELEMAC 2D. TELEMAC is a modelling suite suitable for complex geometries and has a strong coupling with water quality modules especially in two dimensional simulations. It is based on the continuity and momentum equations and is frequently applied for water flow simulations in coastal areas (Samaras et al., 2016; Tassi et al., 2023). The TELEMAC 2D code solves depth-averaged free surface flow equations as derived first by Barré de Saint-Venant based on the finite element method. The main results at each node of the computational mesh are the depth of water, the depth-averaged velocity components, and the tracer concentration.

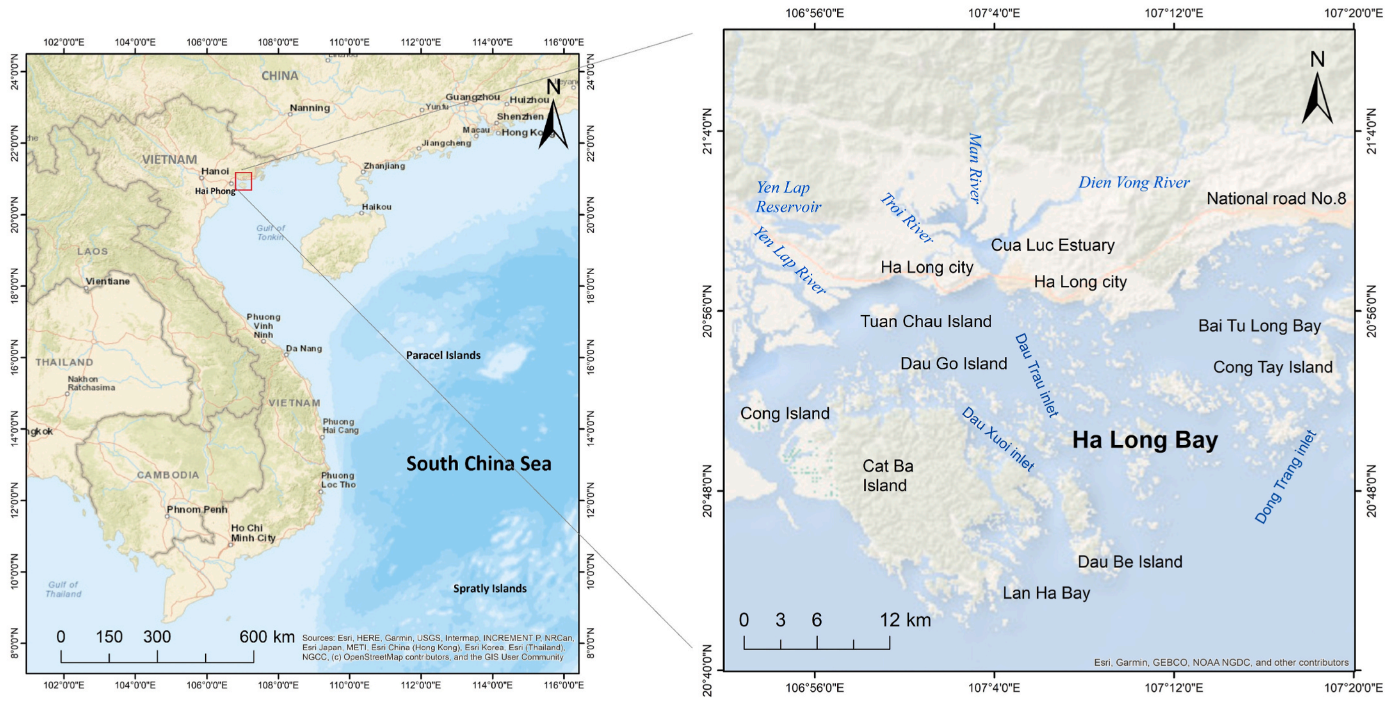

Fig. 1. The location of Ha long Bay and the topographical features of Ha Long Bay.

TELEMAC-2D code solves the following four hydrodynamic equations simultaneously:

$$\frac{\partial h}{\partial t}+u\vec{\nabla}(h)+hdiv(\vec{u})=S_h \tag{1}$$

$$\frac{\partial u}{\partial t}+\vec{u}\vec{\nabla}(u)=-g\frac{\partial Z}{\partial x}+S_x+\frac{1}{h}div(h\nu_t\vec{\nabla}u) \tag{2}$$

$$\frac{\partial v}{\partial t}+\vec{u}\vec{\nabla}(v)=-g\frac{\partial Z}{\partial y}+S_y+\frac{1}{h}div(h\nu_t\vec{\nabla}v) \tag{3}$$

$$\frac{\partial T}{\partial t}+\vec{u}\vec{\nabla}(T)=S_T+\frac{1}{h}div(h\nu_T\vec{\nabla}T) \tag{4}$$

where h is depth of water (m), u and v are velocity components (m/s), T is passive (non-buoyant) tracer (g/l), g is acceleration due to gravity (m/s^2), ν_t and ν_T are momentum and tracer diffusion coefficients (m^2/s), Z is free surface elevation (m), t is time (s), x and y are horizontal space coordinates (m), S_h is source or sink of fluid (m/s), S_x and S_y are source or sink terms in dynamic equations (m/s^2), and S_T is source or sink of tracer (g/l/s) (Riadh et al., 2014).

According to the above equations, water elevations and velocity fields are needed to track pollutant transport. The bathymetry and geometry of the study area, the specified boundary conditions, and the initial values of both hydrodynamic and water quality parameters are also needed for the simulation. Hence, the first step is to provide the geometry to determine the domain and build the mesh. The GEBCO (https://www.gebco.net/) database was selected for this purpose, and the bathymetric data were extracted with a resolution of 500 m per grid's element. Most of the islands in the region have dimensions of less than 500 m, so the resolution needed to be improved using other resources. Moreover, the investigation of GEBCO revealed the presence of some deep points in the bathymetric data close to the shoreline which were not observed in other databases. It was expected that this would be due to the limited routes available to the ships that measure the depth of the water. Hence, the initial bathymetry derived from GEBCO had a generally higher resolution than the Admiralty Charts. In the next step, the bathymetries from GEBCO, the Admiralty Charts, and the information available locally were compared. The bathymetry was patched with data from the Admiralty Charts where there was a significant discrepancy between two datasets and GEBCO values were inconsistent with other observations. The Admiralty Charts No. 3875 and No. 3889 were selected for this purpose. The water depth for more than 650 points was extracted from the Admiralty Charts, added to the bathymetric file, and controlled in BlueKenue to achieve a consistent geometry of the study area. In order to include the more non-negligible islands in the geometry, bathymetric data are interpolated by ArcGIS, and a grid at 40 m resolution was produced. The geometry was validated by superimposing the maps generated here using BlueKenue and remote sensing data such as the Google Map of the Ha Long Bay. This was carried out to prevent there being dry points directly along the shorelines of the region. Finally, the boundaries of the domain were selected away from the regions of complex geometry and distributed islands, so the flow was fully established before reaching the islands, and the interactions of boundaries and the islands were limited. Grid sensitivity analysis was conducted to ensure the selection of the domain had no significant impact on the simulation.

The coastline data were extracted from USGS map sources (https://earthexplorer.usgs.gov/) and a smooth boundary for 39 islands were considered in the domain. The bathymetric data were interpolated again using the new solid boundaries in order to include the islands. The bathymetry and the height of the points on the map were compared with the Admiralty Charts, and some points were modified manually, especially at the top of the domain, inside the bay, and in the estuary (Fig. 2).

An unstructured triangular mesh was generated by BlueKenue over the domain of interest. Three mesh sizes were considered, specifically, 40, 100, and 200 m for the estuary, the bay, and areas away from the domain of interest, respectively. The mesh sizes and the water depths are shown in Fig. 3.

The nodes were adjusted, and those nodes that were not used were deleted from the integrated mesh of the domain. The values of bathymetry for the mesh were calculated through interpolated eventually and the boundary conditions were defined. Two types of liquid boundary conditions were considered in this study area.

The riverine boundary conditions for the 5 rivers coming from upstream catchments to the bay, indicated by numbers 3 to 7 in Fig. 3, and

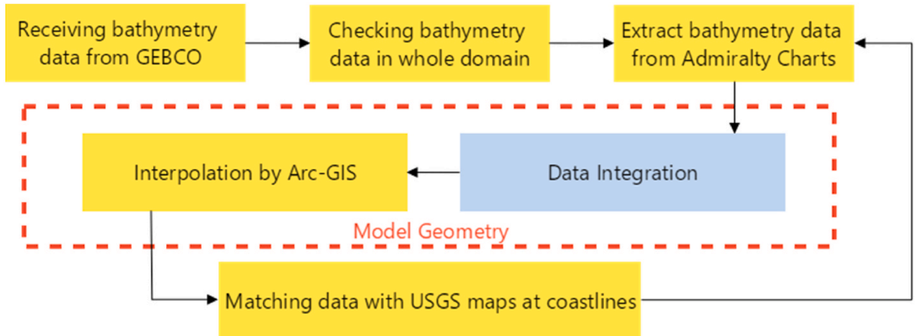

Fig. 2. Refining data to provide model geometry.

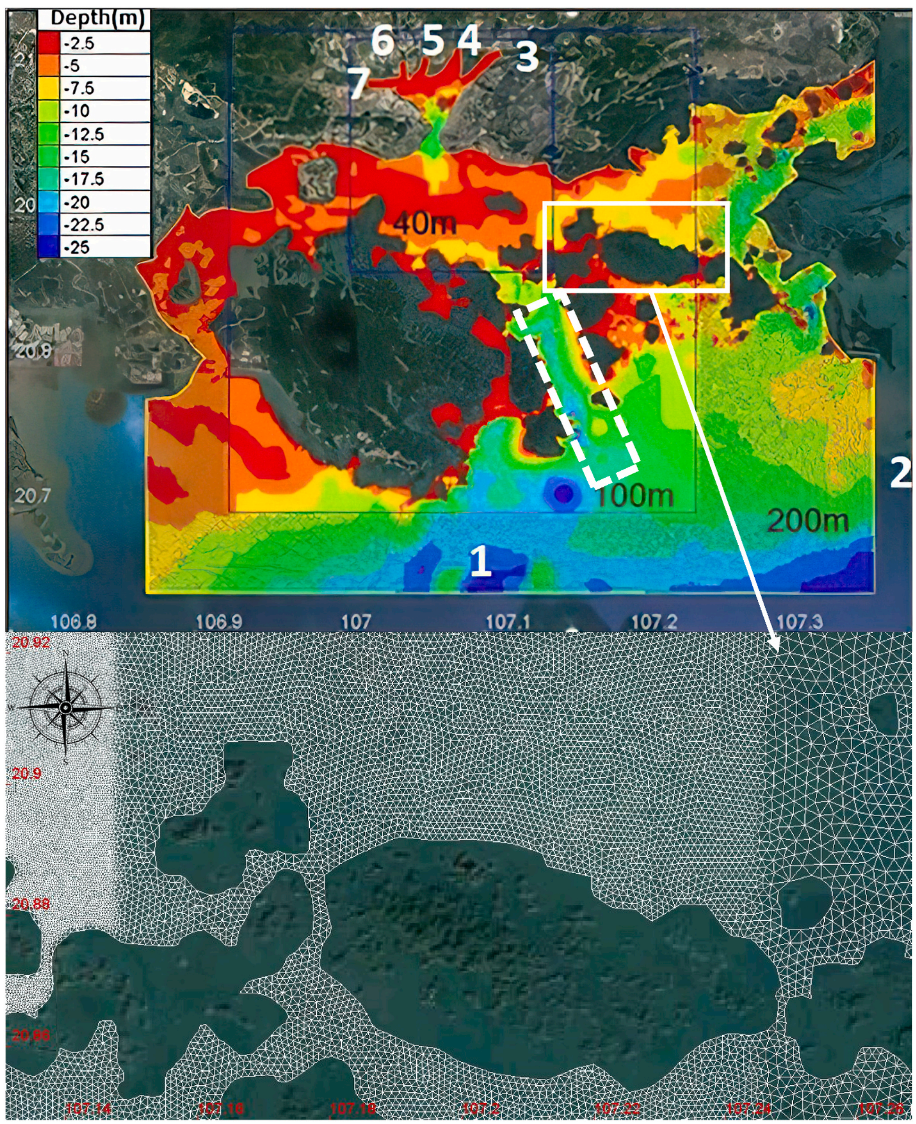

Fig. 3. Unstructured mesh generation in the domain according to bathymetry and geometry (boundary numbers are shown in white, and the map datum is MSL).

the tidal boundary conditions at the bottom of the domain were defined, as indicated by numbers 1 and 2 in Fig. 3. The seasonal flow rates of rivers at the top of the domain were applied by the prescribed flow rate in the steering file using 20-year discharge data of the river. The tidal boundary conditions were considered to be variations in water level and velocity and were defined as the TPXO database for all nodes along the boundary.

The mesh with refined bathymetry and island representation included 251 381 elements and 128 566 nodes. The model was run using the High-Performance Computing (HPC) facilities at Cardiff University, and the runtime was 13 h and 20 min coupling with WAQTEL using 256 processors.

2.3. Field study

The bay is a transitional waterbody located between the estuaries and the sea. Land-based pollutants are typically retained and assimilated before being discharged into the sea. Therefore, water quality modelling in the bay is essential to understand the spatial variation of water quality and pollutant transportation and interaction with hydrodynamic factors and to better understand the interpretation of water pollution sources. Notable features of Ha Long Bay are that it is shallow and dominated by tides, where the amplitude of a spring tide may reach up to 4 m. The bay is subject to low river discharges and is strongly influenced by human activities such as tourism, water transportation, and fishing and aquaculture. Hence, an optimal methodology for water quality modelling in Ha Long Bay must be capable of considering the topographic and hydrodynamic features of the bay flows and water pollutant sources.

Thirty sampling points located in the domain area of Ha Long Bay were selected for investigation as shown in Fig. 4. The site selection for each sampling point was based on the spatial variation. Monitoring was planned to assess the trophic condition and to measure in-field parameters over time and seasons during two campaigns: March 2021 and November 2021. Samples for nutrient and phytoplankton analyses were collected from the water surface. The sampling procedure and analysis followed the ISO 17025 standard. Field measurements included water temperature (°C), pH (using a pH Meter DREL/2010), and dissolved oxygen (percentage of saturated oxygen %, mg/L) (using WTW Oxy 330). Dissolved nitrogen and phosphorous were measured in the form of nitrate (NO_3^-- N) and phosphate (PO_4^{3-}-P).

Each sampling point's location was chosen based on the spatial differences in water quality to represent the overall water quality of the bay and potential effects of various sources on water quality resulting from the distribution of external nutrient inputs. The sampling points were selected to show the water quality variations within the bay, and approximately they are sufficient for verification of the water quality model. Owing to the COVID-19 epidemic's quarantines and the challenges in water sampling over a dynamic coastal region, only two surveys were carried out, that is, in March and September 2021, to capture the seasonal variations of the aquatic environment. A Global Positioning System (GPS) receiver was utilized to locate the sampling points, which remained fixed at monitoring locations throughout both surveys. The water samples were taken at a depth of 30–50 cm using a Van Dorn water sampler (Wildco, Yulee, FL, USA) and were then preserved in cleaned, dark-coloured 1-litre bottles, refrigerated at 4 °C, and transported to the laboratory. Concurrently, field parameters including temperature (°C), pH (using a DREL/2010 pH Meter), and dissolved oxygen (units in % and mg/L saturated oxygen, using WTW Oxy 330) were measured at each sampling point. In the laboratory, the concentrations of the nutrients (NO3–N and PO43–P) were determined by colorimetric analysis using a Labomed UV–VIS spectrophotometer (model: UV-2502, Labomed Inc., Los Angeles, CA, USA), following the methods outlined by Strickland and Parsons (1972) and Salley et al. (1987). The precision of the analysis was determined as ±1.0 % for NO3–N, and ±1.5% for PO43–P, based on the relative standard deviation.

It should be noted that the measurements presented herein pertain solely to surface conditions and may be influenced by hydrometeorological variables, such as waves, winds, tides, and coastal currents. The initial survey conducted on 20–21 March 2021 occurred during cold, humid, and foggy conditions with air temperatures ranging from 18 to 19 °C. Relative humidity exceeded 85%, with a northeast wind with velocities of 2–4 m/s, the water surface temperature was between 16 and 17 °C, and the average wave heights ranged from 0.4 to 0.6 m. In contrast, the subsequent survey was performed during hot and humid conditions on 27–28 September 2021, with air temperatures of around 28–30 °C, relative humidity over 85%, a southeast wind with a speed of about 2 m/s, a water surface temperature of approximately 26–27 °C, and lower wave heights of less than 0.5 m. Moreover, in 2021, Vietnam implemented strict social distancing measures, which effectively curtailed tourism and aquaculture activities in the bay. As a result, the potential impacts of these human activities on water quality are considered negligible.

3. Results and discussion

The model was validated for the water elevation and velocity of several points (extracted from the Admiralty Charts) in the study area. Typical changes in water elevation are shown in Fig. 5 for one month

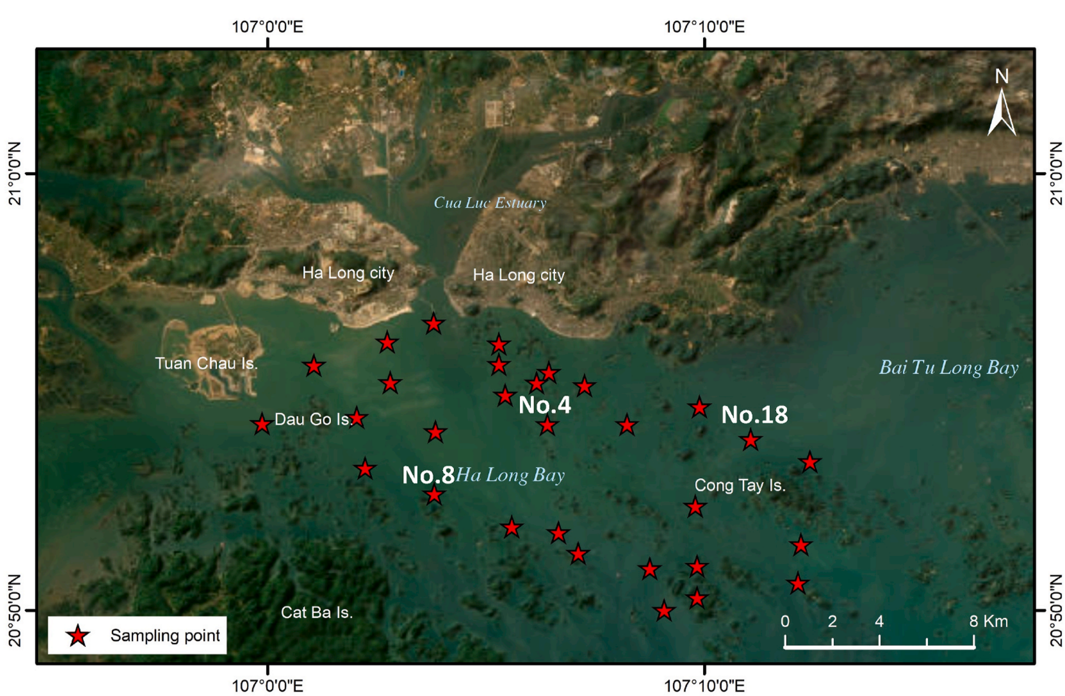

Fig. 4. The location of different sampling points in Ha Long Bay.

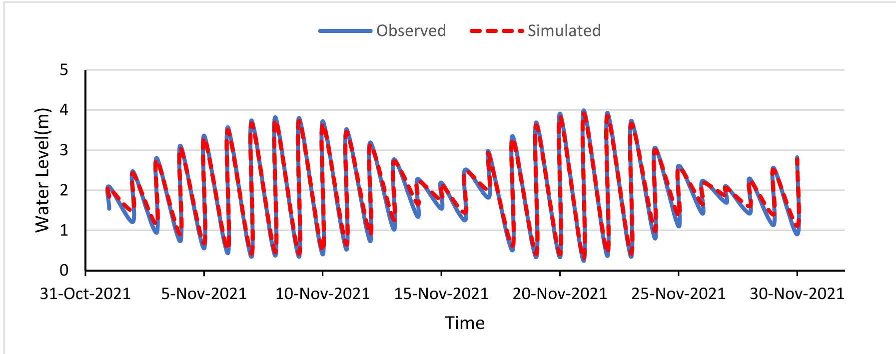

Fig. 5. The simulated values of the water elevation in comparison with the observed values at the verification point (20.95 N 107.067 E) in August 2021 (the Mean Sea Level is at 1.9 m).

(November 2021) at (20 57 N 107 04 E ~ 20.95 107.067) in comparison with the observed data of the Admiralty Tide Tables (2021). The RMSE calculated for this point was 0.19, which is mostly related to the amplitudes of close low and high water. The correlation is equal to 0.938, and the fluctuations are approximately harmonic. The observed values seem to be higher than the simulated values in high water and lower than the simulated values in low water (Fig. 5). The water elevations are also in good agreement with the TPXO data in the domain during 2021 with an RMSE less than 0.09.

The model was also validated for velocity in a one-year period at point (20 43 9 N 106 54 8 E ~ 20.72 106.9). The first three months of the simulation were considered for model warmup, and the mean values of the velocity magnitude and directions were compared with the Admiralty Tide Tables in Fig. 6. The maximum velocity was equal to 0.79 m/s at this point, which was in close agreement with the measured velocities. The measured maximum value was 0.72 m/s at this point. The directions of the velocities in high and low water are shown in Fig. 6. This shows an RMSE equal to 0.16, which is related to the difference of velocities after high water in the direction of 135–225°.

Furthermore, careful comparison of the velocity magnitudes and directions in the domain highlighted that there were greater discrepancies in the velocity magnitudes and directions in the regions connecting the sea and coastal areas of the bay. The maximum velocity was calculated up to 2.51 m/s in the approximate narrow path (dotted line in Fig. 3) that connects Ha Long Bay to the sea flows. The mean velocity magnitude in the entire domain was 0.41 m/s in the domain. It was observed that the velocity magnitudes increased near the region where a number of islands existed.

3.1. Spatial-temporal change of water quality in Ha Long Bay

To investigate the water quality in the bay, the concentration of nitrate and phosphate were investigated in the domain. The mean values of these parameters were used to represent river discharge at the points where rivers discharged into the bay, and the variations were predicted using the Biomass Module coupled with TELEMAC 2D. The initial values of NO_3^-- N and PO_4^{3-}-P were measured directly by the authors in the study area and are shown in Table 1.

Moreover, 30 sampling points in the domain, as shown in Fig. 4, were

Table 1
The concentration of measured nitrate and phosphate at liquid boundaries of the domain at the start of simulation.

Boundary	1	2	3	4	5	6	7
NO_3^-- N **(mg N/l)**	0	0	1.494	0.4	0.638	1.39	0.6
PO_4^{3-}-P **(mg P/l)**	0	0	0.106	0.01	0.02	0.101	0.06

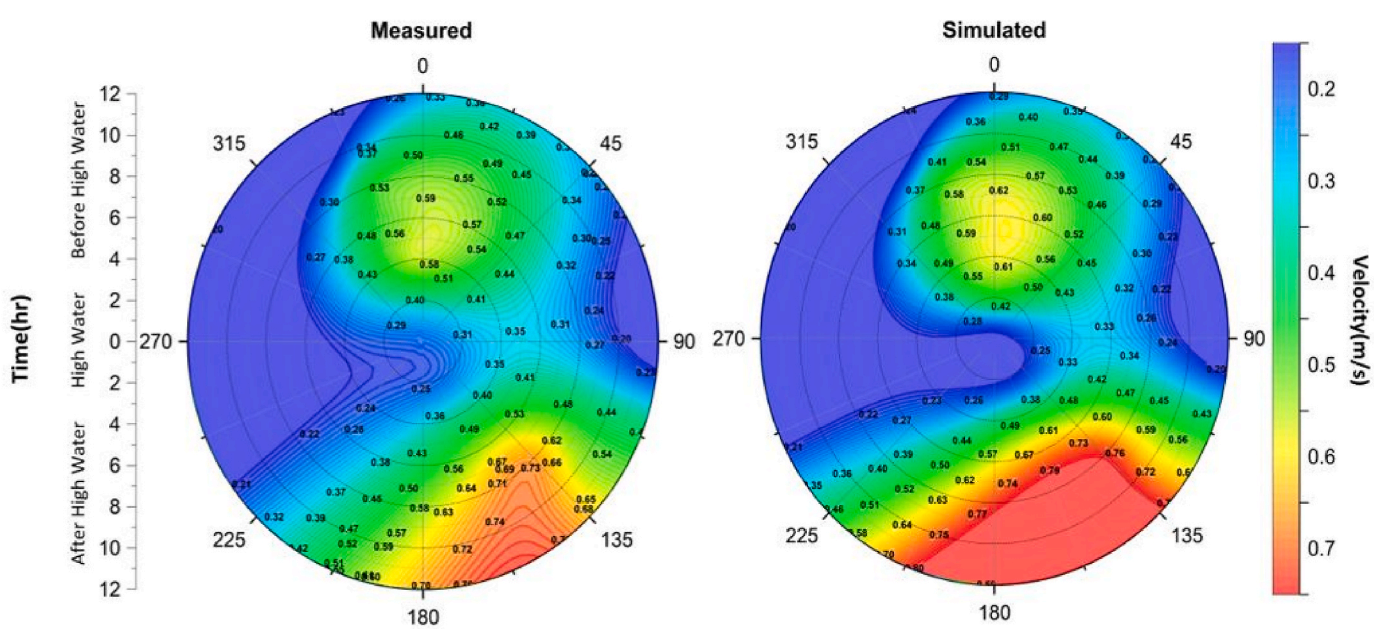

Fig. 6. Simulated vs observed values for mean velocity magnitude and direction at the verification point (20.72 106.9).

used to investigate the variation of nitrate and phosphate in Ha Long Bay. The concentration of diffused nitrate and phosphate at the coastline and at the islands was implemented in the model by adding the concentrations to the closest mesh points by sources using a constant discharge.

The RMSE calculated using predicted and measured values at 30 sampling points of the domain for the NO_3^-- N was 0.13 with a correlation of 0.920. Sampling point No.18 is approximately located inside the bay where the pollution transport path occurred and hydrodynamically is important because of the maximum velocities calculated in this region (dotted line in Fig. 3). The concentration of NO_3^-- N at sampling point No.18 (Fig. 4) was calculated to be 0.47 mg/L and the mean value was 0.349 mg/L. The measured value at this point was 0.395 mg/L at the end of 2021 (Fig. 7). The increasing rate of NO_3^--N in the domain is mostly limited to the north of Ha Long Bay and had reached a maximum concentration of 0.519 mg/L at the end of 2021. The maximum difference between calculated and measured values of NO_3^-- N is up to 0.19 and belongs to sampling point No.8 at the west of the bay while the minimum difference occurred in sampling point No.4 at the centre of the bay. The concentration at the top of the domain where rivers discharge into the coastal area is generally more than 1 mg/L during the study period, which is considered as the permissible threshold for clean water.

The RMSE for PO_4^{3-}-P in 30 sampling points of the domain was 0.016, and the correlation was 0.889. The concentration of nitrate and phosphate increased in the eastern part of the bay, which indicated that that region might be potentially worth considering for algal cultivation and aquaculture. Similarly, the maximum concentrations of PO_4^{3-}-P were up to 0.099 mg/L at the riverine boundaries and were spread to the coastal area after a one-year simulation. The concentration of phosphate increased mostly in the eastern part of the domain. This was thought to be due to the direction of seasonal flows and maximum velocities through this region. Previous studies revealed a similar pattern in long-term simulations of phosphate (Son, 2002). Also, the maximum concentration of PO_4^{3-}-P at sampling point No.18 was 0.046 mg/L with a mean value of 0.037 mg/L. The measured value at this point was 0.02 mg/L in November of 2021 (Fig. 8). The concentrations at top right of the domain, where rivers which include discharges from highly polluted sources discharged to the bay, were higher than the permissible value for clean water, namely 0.1 mg/L). Various management options, including land use adjustments and implementation of nature-based solutions, can be used to reduce high concentration of nutrients in this region.

The variations of the NO_3^-- N and PO_4^{3-}-P at sampling point No.18 in November of 2021 are displayed in Figs. 9 and 10 in hourly time intervals. The maximum concentration predicted was 0.47 mg/L and 0.046 mg/L for nitrate and phosphate, respectively. Also, the maximum concentration of nitrate inside the estuary was 1.35 mg/L while the maximum concentration of phosphate occurred at boundary No.3 and was 0.12 mg/L.

The hourly variations in the concentrations for nitrate and phosphate were found to be dependent on the tidal status, e.g., high or low water, in the domain, and the fluctuations were approximately similar. The amplitude of the fluctuations was higher for the points inside the estuary while also following the high and low water. The mean values of nitrate and phosphate were generally in close agreement with the measurement considering all the sampling points. The predicted concentrations of nitrate and phosphate were higher at the north-eastern parts of the bay, and they were transported to the eastern side starting from March 2021 and had reached a maximum concentration by the end of November. Therefore, the eastern and north-eastern parts of the domain with a higher concentration of nutrients could potentially be suitable for the utilization of nature-based solutions, such as the cultivation of algae or filter feeders, to reduce the pollution levels or deploy new aquaculture sites. This study also showed that Ha Long Bay was in a slightly eutrophic condition.

There are many pollutants from diffused sources around several islands, such as Cat Ba Island, in the domains that were considered in the modelling. These pollutant sources were applied to the joints of the mesh by some input concentrations within the domain. Therefore, some sources were applied to the closest node of the mesh. In 2021, tourist activities were limited to only a small number of domestic Vietnamese visitors. Therefore, 2021, which was the year in which particular sampling was conducted for this study, is not a representative year for the water quality status of Ha Long Bay. The model can also be improved by including all nutrient sources and sinks in the modelling region.

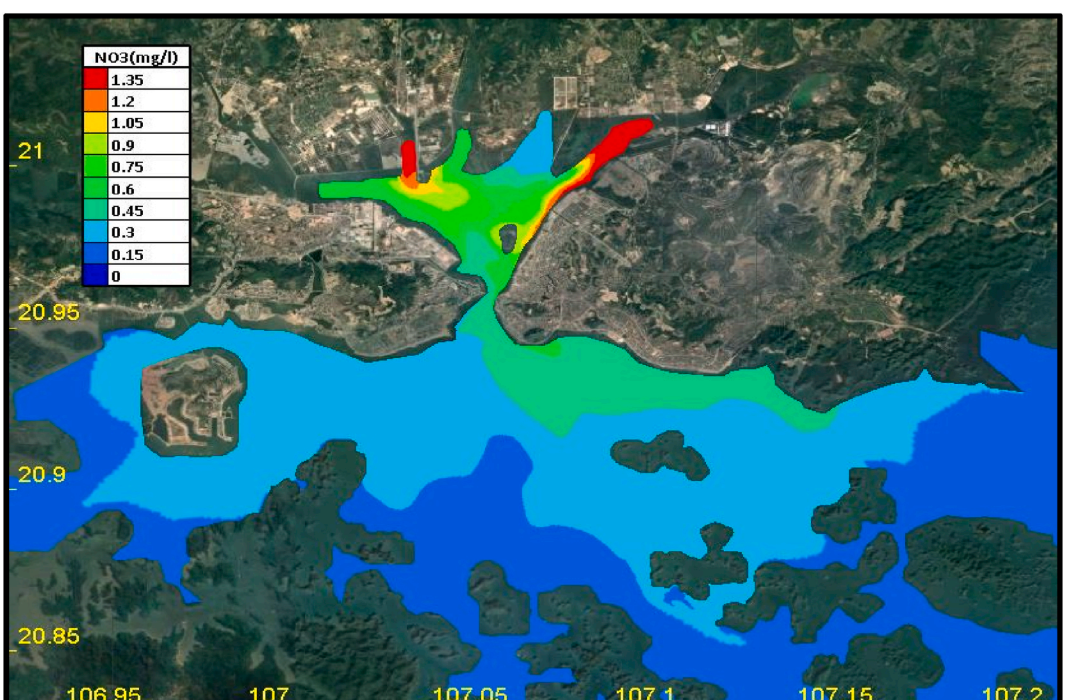

Fig. 7. The concentration of NO_3^-- N in domain in November of 2021.

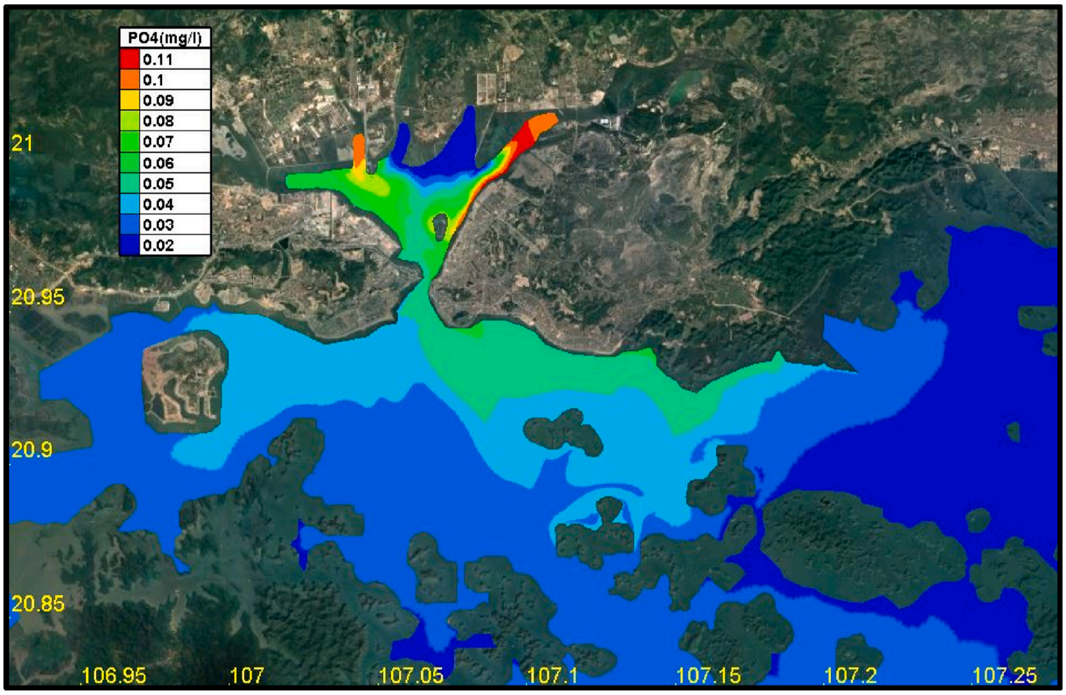

Fig. 8. The concentration of PO_4^{3-}-P in the domain in November of 2021.

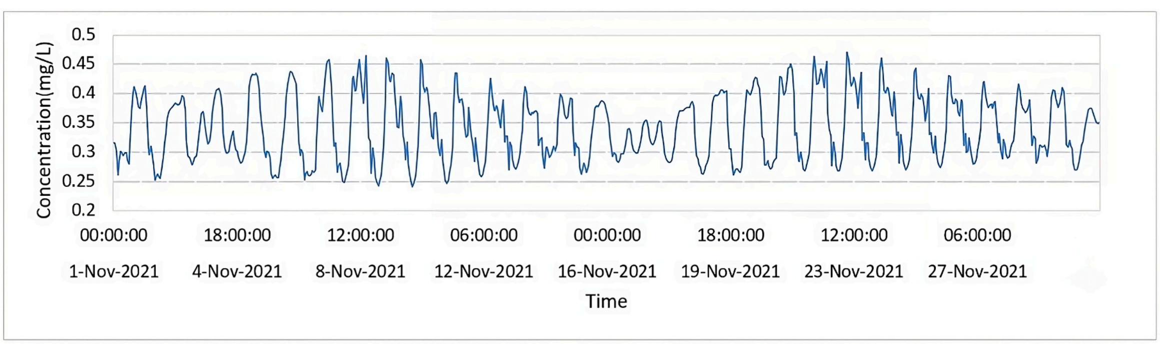

Fig. 9. The variation of NO_3^-- N at sampling point No.18 during November 2021.

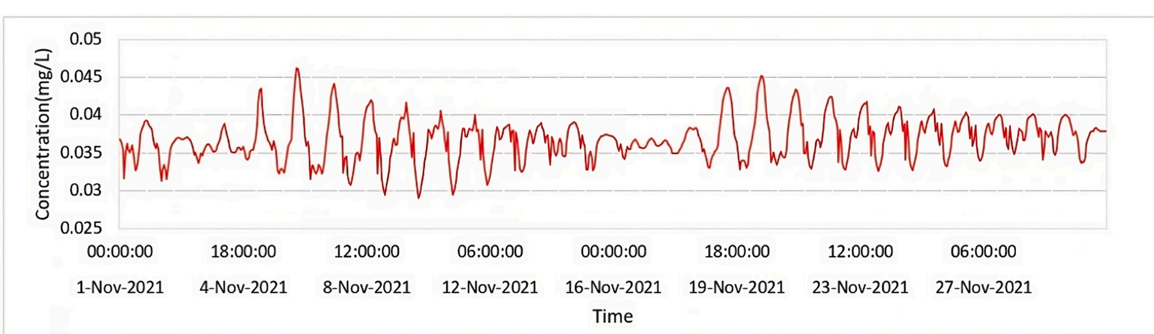

Fig. 10. The variation of PO_4^{3-}-P at sampling point No.18 during November 2021.

Moreover, further field studies and data acquisition could enhance the representation of the region and improve water quality modelling.

4. Conclusion

A two-dimensional hydrodynamic and water quality model was developed to predict water elevation and velocity and the concentration of nitrate and phosphate using TELEMAC 2D coupled with WAQTEL in

Ha Long Bay, Vietnam. Due to the lack of data, the project also commissioned nutrient data collection campaigns within the bay to support the model set up and validation. The bay includes a large number of small islands, which required extending the domain further to reduce the impacts of the islands on the boundaries. The modelling domain selected for this study was 2500 km^2. The domain included seven liquid boundaries (riverine and tidal). The discharge time series used for the river boundaries and seawards boundaries, both water levels and velocities, were extracted from TPXO. An unstructured mesh was used for this study with the minimum element size of 40 m due to the complexity of the geometries in the modelling domain. The first three months of the simulation were used as the warmup period, as information regarding the concentration of the nutrients within the domain was not available everywhere. The measured values from the Admiralty Tide Tables were used for calibration of the hydrodynamic model, while water levels and velocity from the Admiralty Charts were used for validation. The RMSE for the water elevation predicted by the model and reported in the Admiralty Charts was 0.19, which indicated that the model was in close agreement with the measured values. Water quality parameters were measured over 30 sampling points within the domain during the field studies. The concentrations of nitrate and phosphate were also predicted within the domain using the Biomass Module of WAQTEL. The model predictions for nitrate and phosphate concentrations were in close agreement with the measured values at this point. Results show that the maximum concentrations of NO_3^-- N and PO_4^{3-}-P were 0.47 mg/L and 0.046 mg/L during November of 2021. The study showed that the coastal area of Ha Long Bay could be eutrophic even during the Covid-19 lockdown period when the nutrients discharged into the bay as a result of tourist activities were minimal. Essentially, our results highlight the sensitivity of semi-enclosed regions, such as Ha Long Bay, to high level of nutrients and the urgency of addressing water quality concerns in such regions. As pollution reaches worrying levels, proactive measures must be taken to maintain the health of these vital aquatic ecosystems. Ultimately, ensuring water quality is not just a scientific imperative but an obligation to ensure the well-being of current and future generations. In conclusion, our investigations in Ha Long Bay highlighted that not only the intricacies of hydrodynamics and water quality but also the delicate balance between human activity and environmental health. The scarcity of data and data quality had been one of the key challenges which is expected to affect such modelling studies in large regions around the world. Our model illuminates the eutrophic conditions that persisted in this coastal region even during the Covid-19 lockdown. The model developed in this study demonstrated strong potential to be used for the simulation of nutrients and possible management options and remedial solutions, and therefore, such models could play an important role in managing pollutants in data-scarce regions. However, they still require minimum data for calibration and validation, which is critical for ground truthing of the models.

CRediT authorship contribution statement

Seyed Arman Hashemi Monfared: Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Investigation. **Reza Ahmadian:** Writing – review & editing, Supervision, Investigation, Formal analysis, Data curation. **Michael Harbottle:** Writing – review & editing, Resources, Methodology. **Rupert Perkins:** Writing – review & editing. **Max Munday:** Writing – review & editing. **Muaaz Wright-Syed:** Writing – review & editing. **Thu-Huong Thi Hoang:** Writing – review & editing, Data curation. **Thi Thu Ha Nguyen:** Writing – review & editing. **Thi Lan Phuong Nguyen:** Writing – review & editing.

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.

Data availability

Data will be made available on request.

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