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ASSESSING FLUSHING DYNAMICS AND EUTROPHICATION VULNERABILITY IN SALUT-MENGKABONG LAGOON, SABAH, MALAYSIA

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ABSTRACT. *Flushing time and volume are important initial measurements for understanding the susceptibility of a lagoon to microalgal eutrophication and pollution. The goal of this study is to estimate the flushing time and vulnerability to eutrophication over spring and neap cycles. The MIKE 21 model was used, and eight monitoring points were selected in four areas within the Salut-Mengkabong Lagoon in Sabah, Malaysia - an estuary with a narrow entrance. After calibration, the advection-dispersion module was used to calculate residence times using a virtual dye tracer method. In the period of investigation spanning from October 2015 to August 2016, it was noted that residence times were notably shorter in January 2016, particularly during spring tides, lasting less than a day compared to other months. This phenomenon was attributed to the smaller volume and poor dilution within the inner Mengkabong region, increasing its vulnerability to eutrophication and pollution. The findings of the lagoon hydrodynamics modelling suggest that relocating potential sources of pollutant discharge away from high-risk areas could mitigate the impacts of coastal eutrophication. The model's results have the potential to assist local authorities in effectively managing lagoon water quality by informing development plans in the lagoon vicinity and implementing controls on pollutant discharges into the lagoon.*

INTRODUCTION

Semi-enclosed bar-built lagoons are highly productive ecosystems; however, they are also susceptible to excessive eutrophication and pollution. He and deMarchi (2010) identified that most impairments in coastal areas stem from non-point sources, including agricultural runoff, contaminated sediments, urban runoff, and atmospheric deposition. Compounding these land development pressures, lagoons frequently support extensive aquaculture operations, which can further contribute to eutrophication in surrounding waters (Sara, 2007). Consequently, quantifying the degree of nutrient enrichment and pollutant loading in these water bodies has become a critical focus for effective management. This data can be integrated with lagoonal or estuarine hydrodynamic models to predict the fate of these stressors. On a moderate analytical scale, metrics such as flushing times or residence times are employed to evaluate the dilution capacity and retention rates of nutrients or pollutants. This allows for an assessment of their concentration potential before any biological or physical processes take effect (National Research Council, 2000; Wang *et al.,* 2013; Maraqa *et al.,* 2012).

This assessment rests on the premise that isolated areas of the lagoon - characterized by smaller volumes and longer water retention times - are likely to be more susceptible to nutrient accumulation (National Research Council, 2000). Such evaluations can be examined both in relative and absolute terms. Any significant deviations in nutrient levels from expected hierarchies could justify targeted remediation efforts focused on the lagoon's aquaculture practices or shoreline developments. Should the retention of lagoon water approach or exceed the doubling capacity of microalgae, it could lead to algal blooms, necessitating appropriate management interventions (Braunschweig *et al.*, 2008; Duarte & Vieira, 2009; Defne & Ganju, 2014; Wang & Yang, 2015).

Eutrophication results from two interrelated processes, making it essential to assess both water flushing times and dilution when evaluating vulnerability to eutrophication (Braunschweig *et al.,* 2008; Duarte & Vieira, 2009; Defne & Ganju, 2014; Wang & Yang, 2015). Flushing times are crucial in determining whether conditions are suitable for algal blooms to develop, while dilution influences the potential nutrient concentrations resulting from elevated nutrient loading rates, which ultimately affect the size of the blooms. This information is vital, especially considering that many algal blooms can be toxic to aquatic life and pose risks to users of the waterway, regardless of their cell density.

Traditionally, the calculation of flushing time has relied on bathymetric volume measurements and salinity distributions as a conservative tracer, assuming a near-steady state. However, this methodology necessitates a substantial investment in catchment monitoring services. In systems with significant freshwater inputs, a comprehensive database is essential to accurately describe how the salt content of water bodies reacts to freshwater river flow (Sheldon & Alber, 2006). Conversely, in bar-built lagoons lacking significant freshwater influx, rapid and extensive seasonal intertidal monitoring of resulting hyper-salinities is crucial, along with synchronized measurements of local evaporation rates at a landscape scale (Mudge *et al.,* 2008). In intermediate scenarios, the reliability of the results may diminish significantly (Sheldon & Alber, 2006).

An alternative methodology entails the deployment of robust and rigorously validated hydraulic numerical models, exemplified by the DHI MIKE 21 Hydrodynamic (HD) flexible mesh (FM) model. These models are characterized by their lower data demands, providing a versatile and precise framework for estimating flushing times. Their intuitive user interface, a hallmark of proprietary software, necessitates calibration predominantly through the acquisition of current velocity and directional measurements. Moreover, pertinent data on fluctuations in ocean boundary conditions and tidal influences can be easily sourced, enhancing the model's reliability and applicability. The primary technical requirement for implementation is a bathymetric survey, which, due to its non-urgent nature, can be conducted without extensive time constraints, thereby facilitating timely integration into hydrodynamic analysis workflows.

In less developed regions such as Sabah, Malaysia, which is situated on Northern Borneo, there is a strong incentive to maintain its relatively untouched environment to support both local and regional ecosystem services. The Salut-Mengkabong Lagoon, specifically located in the Tuaran District, has traditionally played a vital role in sustaining the livelihoods of local communities while also attracting tourism. However, recent developments within these communities have sparked concerns about their environmental impact (Mohammad Raduan *et al*., 2008). Compounding these issues, inadequate funding and inconsistent monitoring of nutrient and pollutant loadings in the lagoon's catchment area hinder the availability of crucial data necessary for addressing these environmental challenges, especially in light of ongoing changes leading to eutrophication due to excessive nutrient loading.

Nevertheless, employing a hydrodynamic modeling approach offers significant insights into the vulnerability of lagoons to eutrophication. To accurately assess the current state of this vulnerability, we systematically measured nutrient concentrations in the water column across annual and tidal cycles at multiple locations within the Salut-Mengkabong Lagoon system. This comprehensive nutrient monitoring serves as a foundation for our primary objective: estimating flushing times. By integrating hydrodynamic models with advection and dispersion models, we seek to understand the transport processes affecting nutrient distribution and retention. This integrated approach not only clarifies the dynamics of nutrient cycling but also underscores the lagoon's resilience and capacity to mitigate eutrophic conditions. Furthermore, the findings from this modelling effort can inform effective lagoon management strategies, such as optimizing water flow, implementing nutrient reduction initiatives, and establishing monitoring programs to enhance overall ecosystem health and sustainability.

MATERIALS AND METHODS

Study Area

The Salut-Mengkabong Lagoon is primarily characterized as a bar-built, tide-influenced estuarine system (Wong, 2005; Hoque *et al.,* 2010), with a notable absence of vertical salinity stratification (Osman *et al.,* 2017). Situated in the Tuaran District of Sabah, Malaysia, just north of the state capital, Kota Kinabalu, this lagoon features a distinctive geomorphological layout comprising a single entrance that bifurcates into two principal sections: Salut and Mengkabong (Figure 1). Over the past decade, the surrounding region has experienced significant land use transformations, transitioning from pristine mangrove ecosystems and coastal forests to various developments, including aquaculture, residential neighborhoods, resorts, commercial establishments, and industrial sites (Osman *et al*., 2017). This rapid change underscores the lagoon's vulnerability to anthropogenic pressures and highlights the need for sustainable management strategies to preserve its ecological integrity.

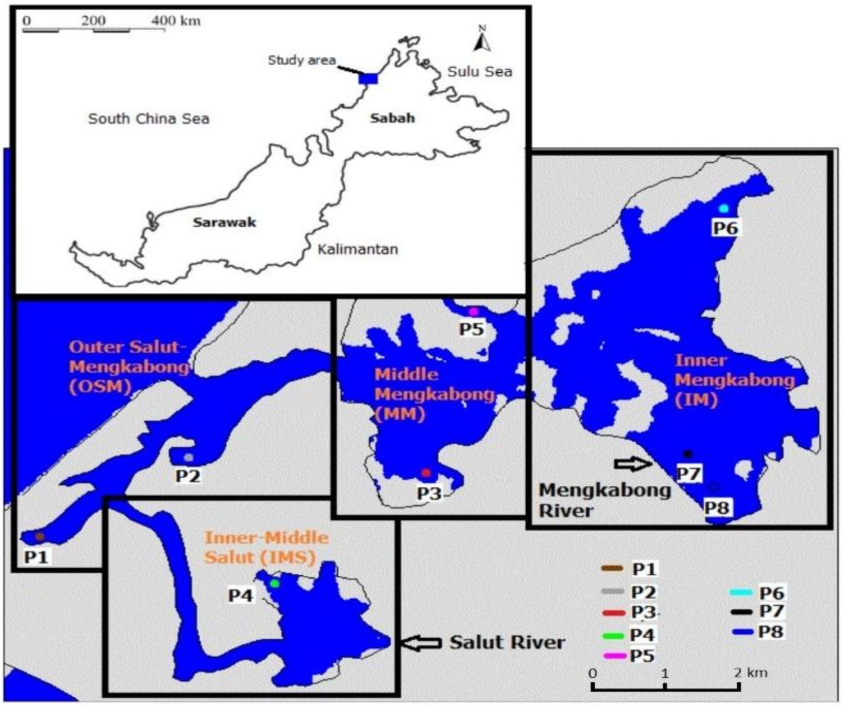

Figure 1. Map showing the study area within the Salut-Mengkabong Lagoon, divided into four main sub-lagoon catchments: Inner Mengkabong (IM), Middle Mengkabong (MM), Outer Salut Mengkabong (OSM), and Inner Middle Salut (IMS). It features eight strategically located monitoring stations (P1-P8) for data collection and analysis.

Water Flushing Measurement

The entire lagoon system is organized into four primary sub-lagoon catchments: Inner Mengkabong (IM), Middle Mengkabong (MM), Outer Salut Mengkabong (OSM), and Inner Middle Salut (IMS). Eight monitoring stations, designated as P1 to P8, were set up to assess water flushing times over a week (Figure 1). Two monitoring points are situated in the Outer Salut-Mengkabong (OSM) area, which is closest to the open sea; one point is located in Inner-Middle Salut (IMS), characterized by a narrow channel and a wide water surface area within the inner lagoon; two points are found in Middle Mengkabong (MM), which has a large water area connected by two narrow channels to the inner and outer lagoons; and three points are in Inner Mengkabong (IM), the deepest section of the Mengkabong lagoon, featuring a wide surface area that receives freshwater from the Mengkabong River.

Hydrodynamic Module Setup

The hydrodynamic simulation of water flow within the Salut-Mengkabong Lagoon was executed using the DHI MIKE 21 FM modeling framework (DHI, 2016). This model incorporates detailed bathymetric data and encompasses an extensive marine area to mitigate boundary disturbances (Figure 2). To establish the computational domain, a Zero Mesh Generator was employed, creating a grid with triangular cells that range in size from 45 meters to 1215 meters, extending to the lagoon's water boundary. This modeling system utilizes a flexible mesh methodology, delivering a numerical solution to the two-dimensional shallow water equations, based on the depth-integrated and incompressible Reynolds-averaged Navier-Stokes equations. In this analysis, adjustments were made solely to the bed resistance parameter (Manning's number) to ensure the accuracy of the results. The effects of wind were deemed negligible, given the area's geomorphological characteristics, so wind data were excluded from the study. Therefore, the primary focus was placed on calibrating the flow dynamics.

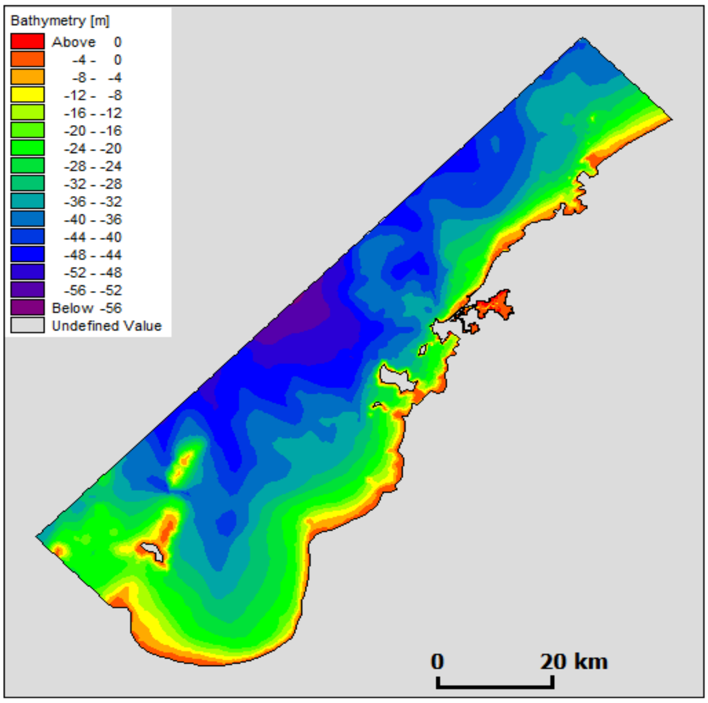

Figure 2. Bathymetry of the regional and local areas used for the MIKE modeling setup.

The boundary conditions for the water flow model in the Salut-Mengkabong Lagoon, known as the Salut-Mengkabong Transport Model (SMTM), were defined using a technique called transfer boundary. Details of the setup for the hydrodynamic (HD) simulation of the SMTM are provided in Table 1. This method establishes the interactions occurring at the lagoon's periphery, ensuring that the model accurately represents the hydrodynamic processes involved. By implementing transfer boundary conditions, the model effectively simulates the inflow and outflow dynamics, taking into account various external factors such as tidal movements, rainfall, and freshwater contributions. A comprehensive specification of these boundary conditions is essential for generating reliable and realistic outcomes in the simulation of water movement throughout the lagoon system. In addition to the local Salut-Mengkabong Lagoon area, the study domain has been expanded to include the coastal region of western Sabah, as shown in Figure 3.

Table 1. Description of the setup for the hydrodynamic (HD) simulation of the Salut-Mengkabong Transport Model (SMTM).

Features	Description
Data simulation	Regional: 1 Oct 2015 – 1 Oct 2016 Local: 1 Oct. 2015 – 16 April 2016 (8 days)
Domain	Mesh file: 1. Nodes: 31121 nodes 2. Elements: 59456 elements 3. Time step Interval: 300 seconds Consists of 5 different grid sizes: 1. 45 m (triangular) and, 2. 135 m (quadrangular) grid cells in the lagoons. 3. 135 m, 540 m, and 1215 m (triangular) grid cells towards the water boundary of the domain. The domain extends approximately: 1. 132698.66 m along the Sabah coast, 2. 21618.89 m offshore
Bathymetric data	Regional data - derived from the MIKE C-MAP (version 2010) developed by Jeppesen Marine AS, Norway. Local data - surveyed in 2008
Boundary condition	Open boundaries: sea area Land boundary: the mainland of Sabah
River source	The river discharge based on (DHI, 2013) rates of 1.03 m^3/s and 2.27 m^3/s in Sg. Salut and Sg. Mengkabong respectively.

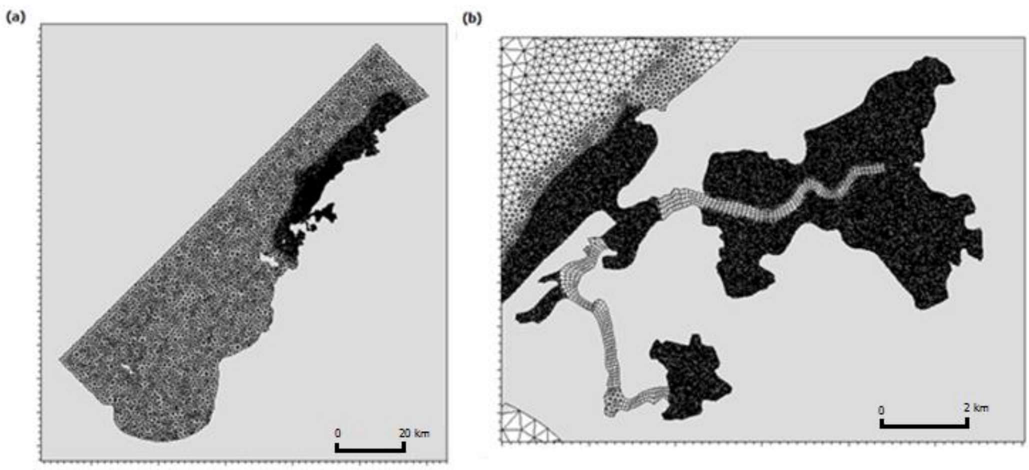

Figure 3. The model grid in MIKE 21 hydrodynamic model: (a) regional scale domain, western coast of Sabah; and (b) local scale domain of Salut-Mengkabong Lagoon.

The assessment of flushing time and vulnerability in the lagoon, particularly for tracer studies, was conducted using the HD and AD models (Li *et al*., 2015; Li & Yao, 2015; Yanagi, 2009). For flushing time calculations, we utilized simplified models based on the methodologies described by Monsen *et al*. (2002) to examine idealized scenarios. To gauge the lagoon's vulnerability, we adopted the estuarine export potential (EXP) classification system established by the National Research Council (2000). This approach facilitates a thorough understanding of the lagoon's dynamics and its susceptibility to external factors. The research framework for these analyses is depicted in Figure 4, providing a representation of both flushing times and vulnerability classifications, enhancing clarity and insight into the study's findings.

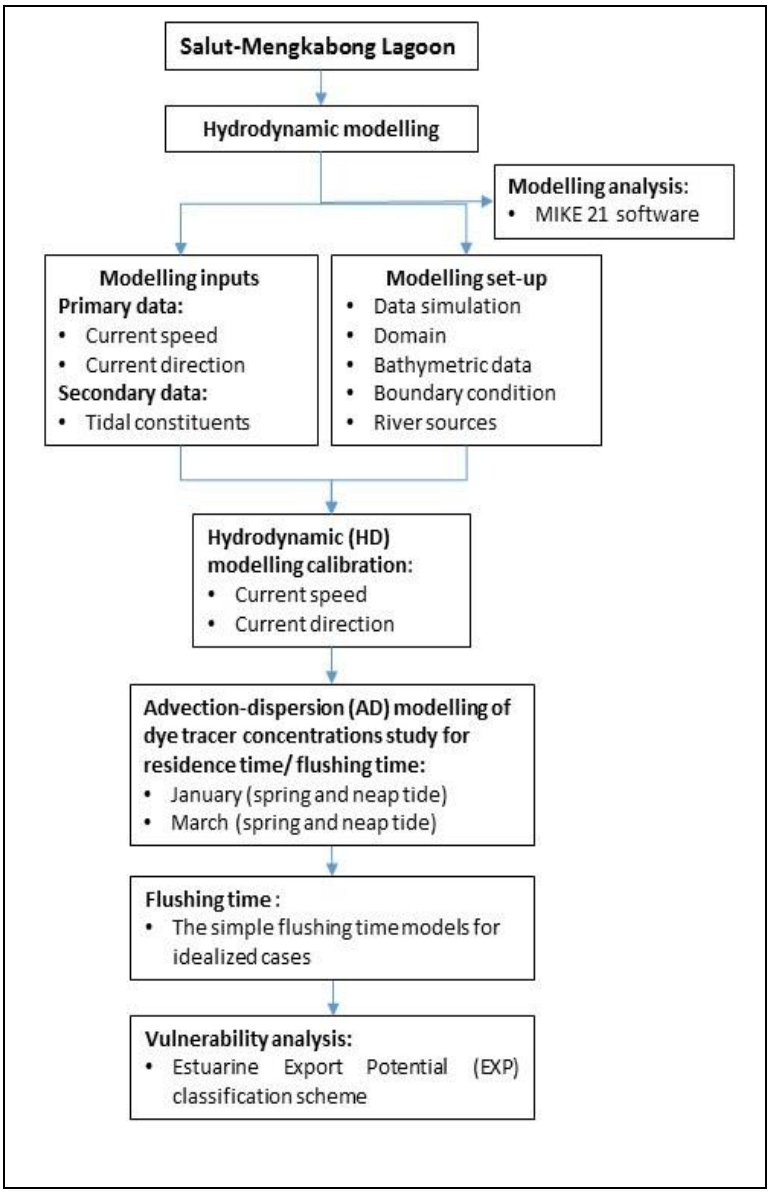

Figure 4. A framework for examining flushing time and susceptibility in the Salut-Mengkabong Lagoon.

Advection Dispersion Module Setup

The advection-dispersion model was utilized to calculate and estimate the water residence time in the Salut-Mengkabong Lagoon. In this approach, the only variable that was altered was the tidal cycle. A set of 100 virtual particles served as tracers, evenly distributed throughout the lagoon to replicate dispersion during four specific tidal periods: spring tides on January 10 and March 9, 2016, and neap tides on January 17 and March 16, 2016. Figure 5 illustrates the predicted characteristics of the highest spring tide and the lowest neap tide in the Salut-Mengkabong Lagoon.

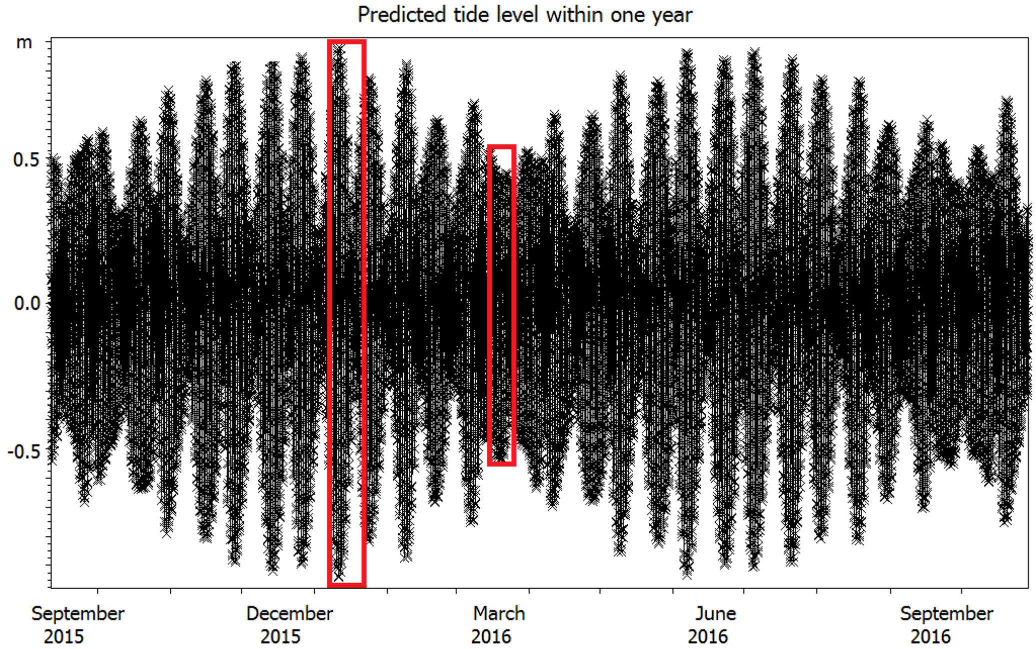

Figure 5. The highest spring and the lowest neap tides in the Salut-Mengkabong Lagoon (red box). (Source: RMN, 2015; RMN, 2016).

The simulation aimed to quantify the e-folding flushing time of the water in the lagoon, offering critical insights into its hydrodynamic behavior and water exchange mechanisms. The time required for the concentration of the tracer in the modeled area to decline served as a metric for assessing the system's flushing efficiency. To accurately determine the e-folding flushing time for each section, a thorough series of 16 simulations, each lasting seven days, was conducted. These simulations took place during the spring and near tides of January and March, building upon foundational data from previous MIKE 21 runs. This structured approach facilitated an in-depth evaluation of flushing dynamics, allowing researchers to gain a better understanding of the lagoon's ability to renew itself and regulate pollutant levels over time. By analyzing various tidal conditions, the study sought to provide a comprehensive overview of flushing efficiency across different regions within the lagoon.

In calculating the flushing time for the selected area in the Salut-Mengkabong Transport Model (SMTM), a key assumption was made: any mass introduced into the system would be uniformly and instantaneously distributed throughout the entire domain. Consequently, the concentration of a substance exiting the area would reflect the concentration throughout the SMTM. To pinpoint eight specific locations around the Salut-Mengkabong Lagoon, it was assumed that a known mass was introduced into the SMTM at time t = 0, resulting in an initial concentration represented as C0. Additionally, it was presumed that no further mass would be introduced after t = 0, and that both the flow and volume of the SMTM would remain constant over time. The concentration within the SMTM was then computed using Equation 1. According to Equation 1, at time t = T_f, the concentration diminishes to the e-folding level of approximately 37% or 1/e of the initial concentration value. The flushing time for the Continuous Stirred-Tank Reactor (CSTR) is represented by the average duration that the "fraction of tracer (water parcels) from the selected region" remains within the system (Monsen *et al*., 2002).

$$C(t) = C0 \times e\text{-}t / T_f \quad (1)$$

$$T_f = M / Mt \quad (2)$$

To determine the e-folding flushing time through the same hydrodynamic simulation, a conservative tracer was introduced into the Salut-Mengkabong Lagoon using the same data and model configuration as the HD model. Initially, the tracer was released at a concentration of 100 kg/m³ in each of the four designated areas, while the concentration outside these areas was set to 0 kg/m³. The flushing time was calculated using the total tracer mass at the initial condition (M) and the average tracer loss rate over time (Mt) as it moved through the system, as expressed in Equation 2. This equation was primarily used to compare the differences among the lagoon areas and was subsequently applied in the "estuarine export potential" (EXP) classification by the National Research Council (2000) to evaluate the lagoon's vulnerability to eutrophication. The EXP framework includes two essential variables: flushing time and lagoon dilution, with the latter being calculated using modeling software to assess the volume of each lagoon area.

RESULTS AND DISCUSSIONS

Simulation and Model Evaluation

There was a notable agreement between the measured and simulated current speeds in the Salut-Mengkabong Lagoon after adjustments were made to the bed resistance (Manning's number) in the simulated data (Figure 6). The correlation coefficient (R-squared) for the current speeds was 0.17, accompanied by a root mean square error (RMSE) of 0.07 and a percentage RMSE of 33.50%. Additionally, the average deviation in current directions between the measured and simulated values was 33.02 degrees. Several limitations contributed to the elevated RMSE and discrepancies in the current direction, particularly the distinct geomorphology of the lagoon. This unique geomorphological feature diverges from typical open coastal waters, which restricts the flow of water from the coastal region into the lagoon.

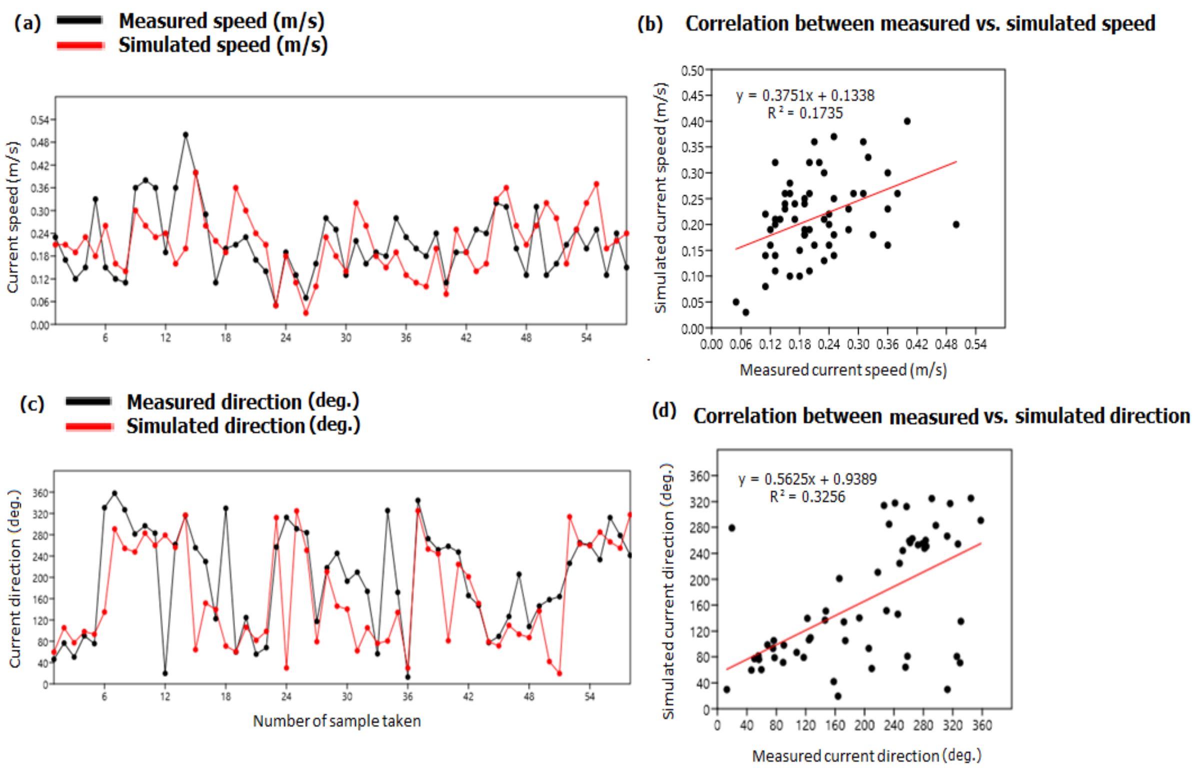

Figure 6. (a) Comparison of measured and simulated current speed; (b) Correlation between measured and simulated current speed; (c) Comparison of measured and simulated current direction; and (d) Correlation between measured and simulated current direction in Salut-Mengkabong Lagoon.

The average measured current speed in the lagoon was recorded at 0.21 m/s, while the average simulated current speed from the hydrodynamic modeling was slightly higher at 0.22 m/s. This close alignment suggests that the model's current speed predictions are valid for simulation purposes. However, a discrepancy was observed when evaluating the average current direction: the average measured current direction was 198.42 degrees, while the average simulated current direction from the hydrodynamic model was relatively lower at 165.40 degrees. This variation in current direction can be attributed to the complex hydrodynamic conditions prevalent within the lagoon, exacerbated by various obstacles at most sampling stations, which stem from the lagoon's unique geomorphological features. These physical barriers can significantly impact water movement, resulting in variations in both direction and speed across different areas of the lagoon. Consequently, while the model's current speed predictions are reliable, the intricacies of the lagoon's structure may explain the observed differences in current direction.

Flushing Analysis

In this study, flushing times were estimated at eight monitoring stations distributed across four sub-lagoon catchments: Outer Salut Mengkabong (OSM), Inner Middle Salut (IMS), Middle Mengkabong (MM), and Inner Mengkabong (IM). The data were presented as a time series for four distinct spring and neap tidal events (Figure 7). The findings indicate that the January Spring tide (Figure 7a) exhibited a higher flushing capacity than the other tidal cycles. According to Laws (2013), phytoplankton in tropical and subtropical regions typically have a doubling time of about one day. When the doubling time is extended while the flushing time remains short, phytoplankton is likely to be washed out from the isolated areas of MM (P3 and P5) and IM (P7 and P8), especially during the January Spring tide. There is also potential for washout in certain parts of MM (P5) and IM (P7) during the March Spring tide (Figure 7b).

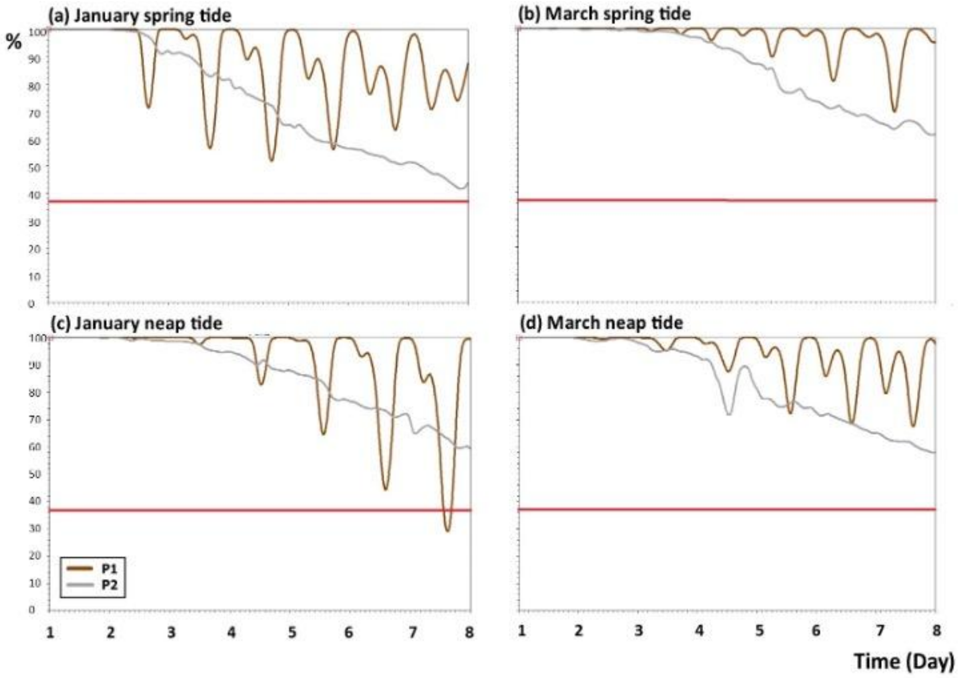

Figure 7. Time series analysis of flushing times in the Salut-Mengkabong Lagoon entrance (P1 and P2), simulated using OSM during four distinct spring and neap tide cycles.

Additionally, two observations of flushing time were conducted in the OSM sub-lagoon. Monitoring station P1 is located deeper within the sub-lagoon, while P2 is situated closer to the outer edge. During the January Spring tide (Figure 7a), P1 exhibited significant fluctuations on day 2, followed by a decrease in tracer concentration from day 5 to day 7. In contrast, P2 showed a steady decline in tracer concentration. The January neap tide (Figure 7c) revealed a 37% reduction in tracer concentration at P1 by day 7. However, during the March Spring (Figure 7b) and neap (Figure 7d) tides, both P1 and P2 exhibited minimal changes, although their fluctuation patterns differed. The point at which the tracer concentration dropped to 37% of its initial value (100%) is indicated by a thick red line in Figure 7. Regardless of the prevailing tidal conditions, it is expected that phytoplankton will proliferate in the isolated zone of OSM.

A single monitoring station, P4, was established in the inner section of the Inner Middle Salut (IMS) due to its isolation from the flow of the Salut River (see Figure 8). The simulation, which explored variations in flushing times, indicated that P4 suffered from poor circulation, leading to the accumulation of pollutants. During the January Spring tide (Figure 8a), P4 exhibited more frequent fluctuations over the seven-day observation period compared to other tidal cycles, although the decrease in tracer concentration was relatively small. In the January neap tide (Figure 8c), fluctuations began on day 5, resulting in a more pronounced reduction in tracer concentration by day 7 than noted in earlier tidal cycles. Minimal variation was observed during the March Spring (Figure 8b) and neap (Figure 8d) tides. Consequently, phytoplankton will probably thrive in the isolated area of IMS, irrespective of the existing tidal conditions.

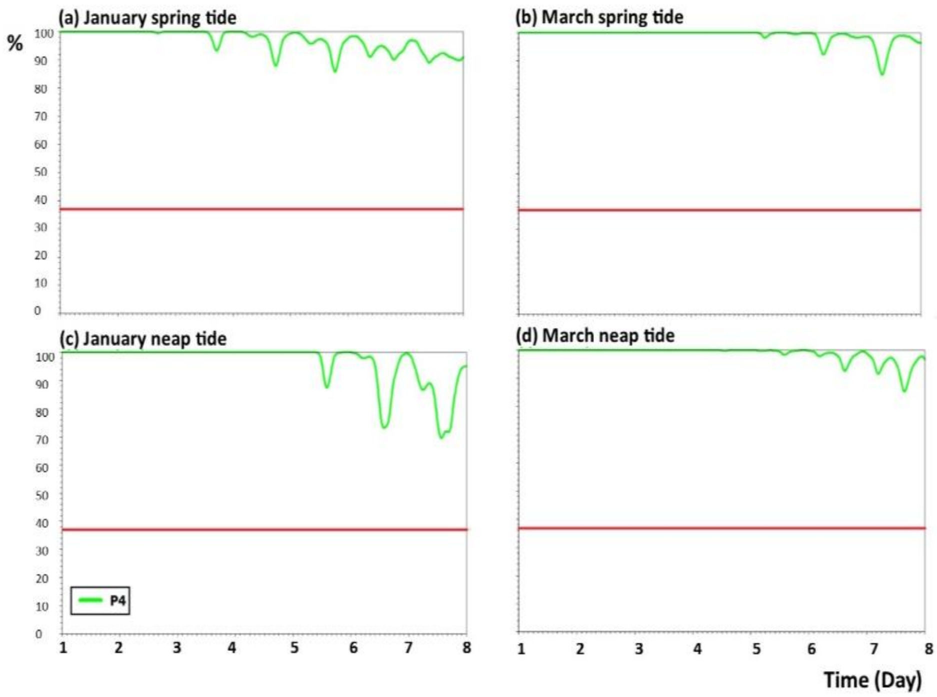

Figure 8. Time series analysis of flushing times in the IM (P4), simulated across four different spring and neap tide cycles within the Salut Lagoon.

Two monitoring stations were selected within the Middle Mengkabong (MM) sub-lagoon: P3, situated near a seagrass area, and P5, located close to the Prawn Farm Channel in Mengkabong Lagoon. During the January Spring tide, the tracer concentration at both P3 and P5 declined to 37% by day one (Figure 9). In the case of P3, during the January neap tide (Figure 9c), as well as the March Spring (Figure 9b) and March neap (Figure 9d) tides, the concentration also reached 37% by day five. For P5, the concentration dropped to 37% by day two in both the January neap (Figure 9b) and March neap (Figure 9d) tides, indicating a more rapid flushing response during the spring tide. Interestingly, despite P5 covering a smaller area, P3 exhibited a longer flushing time. This suggests that P3 may be more prone to retaining pollutants if they are discharged during neap tides. The point at which the tracer concentration fell to 37% of its initial value (100%) is marked by a thick solid black line in Figure 9. Consequently, phytoplankton are likely to be flushed out of the isolated MM areas (P3 and P5) during the January Spring tide, as well as from specific regions of MM (P5) during the March Spring tide.

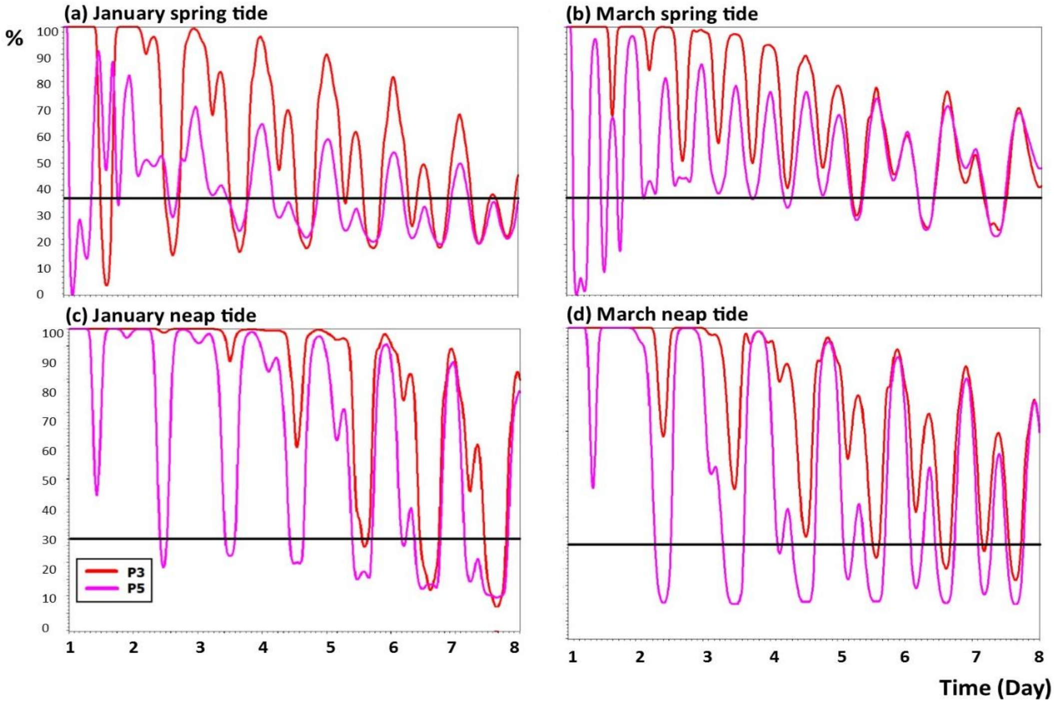

Figure 9. Time series analysis of flushing times in the MM (P3 and P5), simulated across four distinct spring and neap tide cycles within the Mengkabong Lagoon.

P6 is positioned in the northern section of the Inner Mengkabong (IM), while P7 is located in the southern part, where it benefits from robust water flow from the Mengkabong River. In contrast, P8 represents an isolated area with minimal influence from river flow. The flushing times observed during the January (Figure 10a) and March (Figure 10b) spring tides exhibited notable differences: both P7 and P8 reached a 37% concentration by day one during the January Spring tide.

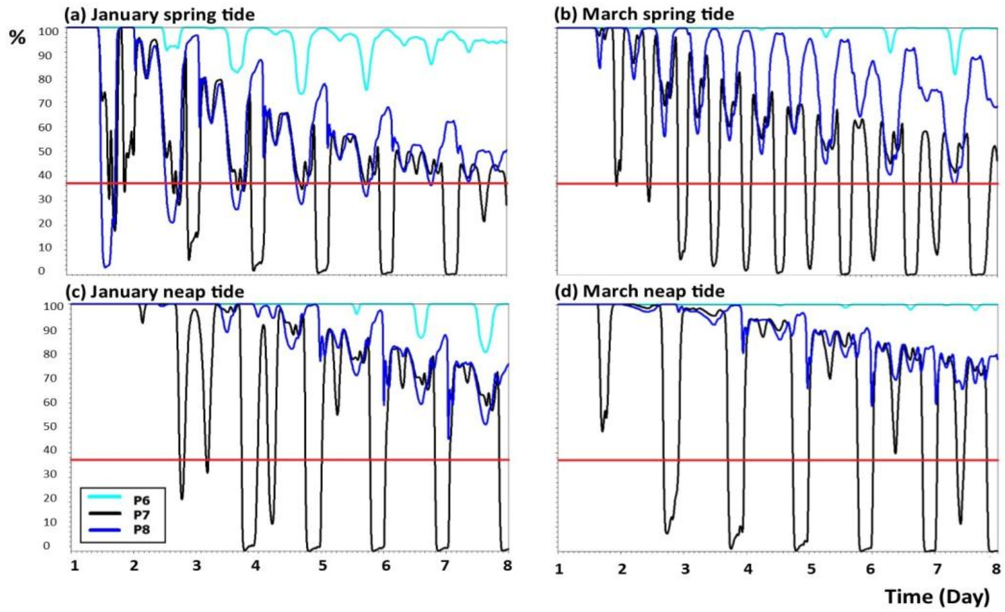

Figure 10. Time series analysis of flushing times in the IM (P6, P7, and P8), simulated across four distinct spring and neap tides within Mengkabong Lagoon.

However, during the March Spring tide, P7 achieved a 37% concentration by day two, whereas P8 took over a week to attain the same level. For both the January (Figure 10c) and March (Figure 10d) neap tides, P7 had a flushing time of just two days, while P8 required significantly longer to be completely flushed. P6 demonstrated particularly poor flushing characteristics, especially during the March neap tide (Figure 10d), suggesting it is unsuitable for aquaculture or waste disposal. The point at which the tracer's concentration diminished to 37% of its initial value (100%) is indicated by a thick solid red line in Figure 10. Consequently, phytoplankton is likely to be flushed out from the isolated areas of IM (P7 and P8) during the January Spring tide and only minimally from specific regions of IM (P7) during the March Spring tide.

Flushing Time and Vulnerability of the Lagoons

Flushing time serves as an integrative measure within the system, and the choice of an appropriate transport scale depends on guiding questions. In this context, flushing time is used to compare the general characteristics of four different sub-lagoons within the Salut-Mengkabong Lagoon system across four distinct tidal cycle scenarios. Calculations of flushing time suggest that the lagoon is particularly vulnerable to pollutants, especially in the IM and IMS regions. These findings underscore critical insights regarding transport and flushing dynamics in both lagoons and provide support for field-based hypotheses. According to previous research (Osman *et al*., 2017), higher concentrations of PO_4 and NO_3 were found in Inner Mengkabong compared to other areas, which can be attributed to the system's capacity to flush out pollutants. This indicates that the Outer Salut-Mengkabong (OSM) experiences a rapid exchange of water with lower nutrient concentrations than other regions. Assessing a system's flushing capability is a valuable indicator of its relative potential for phytoplankton blooms in certain areas. However, determining bloom concentrations is contingent on dilution; the volume of the system influences the density and ultimately the toxicity of pollutant loads or bloom discharges.

This framework enables a comprehensive assessment of vulnerability to eutrophication and pollutant toxicity, particularly relevant in estuarine and semi-enclosed coastal areas, which are especially sensitive due to their limited water exchange with open coastal waters. By analyzing flushing times alongside system vulnerabilities, stakeholders can acquire essential insights that inform their operational strategies in fish farming and aquaculture. Understanding the flushing dynamics of a particular area allows aquaculture operators to optimize their feeding schedules, ensuring that nutrient inputs are managed effectively to mitigate the risk of triggering harmful algal blooms. Moreover, detailed information regarding flushing times can inform decisions about the optimal timing for discharging waste or conducting maintenance activities, allowing such operations to take place when the system is better equipped to assimilate or dilute potential contaminants. This approach is crucial for maintaining water quality; poorly timed discharges can result in nutrient accumulation and subsequent eutrophication, which negatively impacts aquatic life and diminishes overall ecosystem health.

For instance, Table 2 illustrates that during the March neap tide in the Inner Mengkabong (IM) sub-lagoon, the extended flushing time renders it the least favorable period for any type of discharge, emphasizing the heightened risk of pollutant accumulation within the system. With this information, operators can adopt the best management practices aligned with tidal cycles, thereby promoting the sustainability of their operations while safeguarding the ecological integrity of the lagoon system. Overall, this framework not only aids in enhancing operational efficiency but also supports the long-term health and resilience of sensitive coastal ecosystems.

To accurately assess the lagoons' responses to nutrient enrichment, it is essential to consider several key factors that influence their eutrophication. These factors include geomorphological setting, the primary production base, nutrient load, dilution, flushing time, stratification, hypsography, phytoplankton grazing, suspended material load, light extinction, denitrification, as well as the spatial and temporal distribution of nutrient inputs and allochthonous organic matter (National Research Council, 2000). However, this study found that the vulnerability analysis employed a simple classification scheme of EXP for assessing eutrophication (and other forms of pollution), serving as a reference to prevent excessive nutrient discharge into the lagoons. The susceptibility indices developed by Bricker *et al*. (1999; 2003) (Table 3) aid in evaluating the degree of nutrient over-enrichment in coastal systems, focusing primarily on dilution and flushing characteristics. According to the modified matrix for assessing the susceptibility levels of estuaries, the Salut-Mengkabong lagoon is categorized as microtidal (< 2.5 m) and exhibits a high level of susceptibility, with an average flushing time ranging from 7 to 30 days and a smaller volume (10^{-09} to 10^{-07}).

Table 2. Flushing time of four sub-lagoon catchments in four different simulations.

	Outer Salut-Mengkabong (OSM)				Inner-Middle Salut (IMS)				Middle Mengkabong (MM)				Inner Mengkabong (IM)			
	Js	Jn	Ms	Mn	Js	Jn	Ms	Mn	Js	Jn	Ms	Mn	Js	Jn	Ms	Mn
Mean dye Tracer (%)	23.1	33.2	27.4	29.5	59.9	76.9	70.0	77.5	27.4	45.3	34.8	42.9	54.4	80.2	63.8	82.8
Est. volume (m^3)	7×10^7				4×10^7				7×10^7				1×10^8			
Flushed (days)	9.1	10.5	9.7	9.9	17.5	30.4	23.3	31.1	9.6	12.8	10.7	12.3	15.3	35.4	19.4	40.6

Note: Js=January-Spring; Jn=January-Neap; Ms=March-Spring; Mn=March-Neap.

Table 3. Matrix for assessing the susceptibility of the Salut-Mengkabong Lagoon to nutrient over-enrichment, based on flushing time and the inverse of volume.

Flushing Time (Days)	**Index**		
Slow (> 30)	Low	Low	Moderate
Moderate (7 - 30)	Low	Moderate	High
Faster (< 7)	Moderate	High	High
1/Dilution (Volume)	**Larger ($10^{-13 \sim -11}$)**	**Moderate ($10^{-11 \sim -09}$)**	**Smaller ($10^{-09 \sim -07}$)**

Source: Modified from Bricker *et al*. (1999); National Research Council (2000)

Utilizing the modified classification scheme for 138 estuaries outlined in the Estuarine Eutrophication Assessment (Figure 11) (National Research Council, 2000), systems located in the lower right area of the graph, characterized by smaller volumes and faster flushing rates, demonstrate a higher susceptibility to eutrophication.

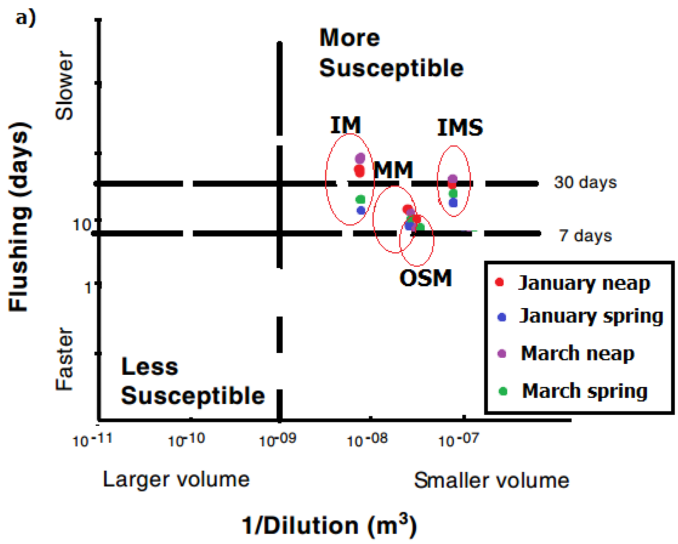

Figure 11. Relationship between expected flushing time (days) and dilution volume (m³) for assessing system vulnerability, modified from the Estuarine Eutrophication Assessment by NOAA.

Conversely, systems exhibiting extremely large dilution volumes and shorter flushing times are deemed the least susceptible to nutrient-enhanced eutrophication. In contrast, systems anticipated to be highly susceptible to eutrophication are represented in the upper right area of the graph, where the dilution volumes are smallest and flushing rates are slowest. For the Salut-Mengkabong Lagoon classification, Inner Mengkabong (IM) is predicted to be particularly vulnerable to eutrophication, especially during the March neap tide, followed closely by the January neap tide.

CONCLUSION

The dye tracer study conducted to evaluate the e-folding flushing time revealed that the monitoring stations P4 (located in the Inner Middle Salut, IMS) and P6 (in the Inner Mengkabong, IM) demonstrated inadequate flushing characteristics. This finding underscores the critical need for regular monitoring of the Mengkabong Lagoon due to the significant risks associated with deteriorating water quality and extended residence times of pollutants. Specifically, the flushing times recorded in the inner lagoon areas (IM and IMS) - ranging from approximately 15 to 40 days - are considerably longer than those observed in the outer lagoon (approximately 9 to 10 days) and in the intermediate lagoon (approximately 9 to 13 days). These extended flushing times in the inner regions can lead to the accumulation of nutrients and pollutants, resulting in detrimental effects on water quality and aquatic life.

A deeper understanding of the hydrodynamic processes within and surrounding the watershed enhances our ability to develop more effective management strategies for land managers and regulatory authorities. Such strategies are imperative for maintaining and improving water quality throughout the lagoon system. Furthermore, the implications of prolonged flushing times in the inner sections of the Salut-Mengkabong Lagoon suggest that elevated concentrations of thermal energy, phytoplankton, and dissolved substances are likely to build up. The presence of dead-end areas combined with weak water circulation exacerbates this problem, potentially leading to eutrophication and its associated ecological repercussions. Consequently, proactive measures must be implemented to mitigate these risks and promote the overall health of the lagoon ecosystem.

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