BORNEO JOURNAL OF SCIENCES AND TECHNOLOGY (BJoST)
VOL. : 7, ISSUE: 2, 59-71
DOI: http://doi.org/10.35370/bjost.2025.7.2-04
e-ISSN: 2672-7439 © 2018, UTS Publisher.

University of Technology Sarawak

ORIGINAL ARTICLE

Source-Sink Dynamics of Coral Larvae: Implications for Ecosystem Management in Pahang

*Muhammad Faiz Mohd Hanapiah and Mohd Zaini Mustapa

Advanced Coastal Research and Innovation, Department of Marine Science, Kulliyah of Science, International Islamic University Malaysia, Jalan Sultan Ahmad Shah, Bandar Indera Mahkota, 25200 Kuantan Pahang

ABSTRACT - Understanding coral larvae dispersal and connectivity is vital for effective ecosystem management and habitat restoration. This study investigates the source-sink dynamics of coral larvae between Marine Protected Areas (MPAs) and nearshore reefs in the Pahang coastal region, Malaysia. Using a biophysical model integrating the Lagrangian particle tracking module with the MIKE 21 FM hydrodynamic model, we simulated dispersal pathways of Acroporid larvae during a spawning event in April 2021. Results revealed northward larvae movement, influenced by prevailing currents, with significant retention within MPAs during the initial dispersal phase (2–6 days). Optimal dispersal (6–8 days) saw broader connectivity, while prolonged dispersal (18–20 days) demonstrated potential for larvae to reach nearshore reefs in southern Pahang. Nearshore reefs, particularly in southern Kuantan, were identified as critical sink sites, emphasizing their importance in ecosystem management strategies. This study highlights the role of MPAs as larvae sources and highlights the interconnectedness of reef systems in supporting coral population sustainability. These findings provide a framework for prioritizing conservation efforts, ensuring resilient reef networks amid environmental challenges.

ARTICLE HISTORY
Received: 20 Dec 2024
Revised: 03 Mar 2025
Accepted: 10 Apr 2025
Published: 31 July 2025

KEYWORDS
Coral larvae dispersal, Marine Protected Areas, Source-sink dynamics, Reef Connectivity, Kuantan.

INTRODUCTION

The dynamic nature of the marine environment offers diverse mechanisms for the dispersion of its ecosystem components within and among populations. Water flow in specific surface current patterns is a primary way of transporting marine organisms between different locations, facilitating the exchange of individuals among populations in distinct habitats. This demographic interconnection, known as connectivity, represents a fundamental process influencing the dynamics of numerous marine ecosystems [1].

Connectivity plays a crucial role in the ecology of sessile marine invertebrates, particularly for non-migratory organisms that are physically attached to the substrate. In the case of corals, connectivity primarily relies on the dispersal of coral larvae. The coral life cycle involves both benthic polyp and planula larval phases. Broadcasting coral species, such as *Acropora*, which represents most coral species, release their larvae into the water column during mass spawning seasons. During this early stage of life, most coral larvae cannot swim horizontally to reach settlement sites and, therefore, heavily depend on the prevailing currents as the primary means of dispersal. These larvae may disperse considerably, ranging from a few meters to hundreds of kilometers, before successfully settling. The resulting alterations in ocean currents can also impact the local retention and downstream spread of corals [2].

The coastal region of Pahang encompasses several nearshore reef patches in Kuantan coastal waters along with the Pulau Tioman Marine Park in the southern part of the region. Despite their pristine

*Corresponding Author: Muhammad Faiz Mohd Hanapiah. International Islamic University Malaysia (IIUM), Email: faizhanapiah@iium.edu.my

condition, the nearshore reefs are susceptible to various anthropogenic influences, such as sedimentation and nutrient enrichment, owing to their proximity to the mainland. Previous study documented 33 coral genera from 13 families at three reef sites in Balok [3]. Coral recruitment pattern indicated that 10 different coral genera recruited at Balok Reef, raising questions about their origin—whether they originated from neighboring reefs or from Pulau Tioman Marine Park remains unknown. This highlights the need for further investigation by studying coral larvae dispersal to determine the source and sink reef patterns. Such information is crucial for future ecosystem management and habitat restoration efforts in this coastal region.

The coastal waters of Pahang, particularly near Kuantan and Tioman Island, exhibit dynamic oceanographic conditions that play a crucial role in shaping coral reef ecosystems. Hydrodynamic modeling studies have shown that tidal forcing is the primary driver of local water circulation, with semi-diurnal tidal cycles governing the movement of water masses and influencing the retention and dispersal of coral larvae [4]. Additionally, the seasonal monsoon system introduces variability, with the Northeast Monsoon (November–March) generating strong southward currents and the Southwest Monsoon (May–August) inducing northward flows [5]. These monsoonal shifts can significantly affect larval transport, potentially linking offshore MPAs such as Tioman Island with nearshore reefs in Kuantan through long-distance dispersal pathways. However, nearshore reefs, such as those in Balok and Raja Muda, face additional environmental pressures from terrestrial runoff and coastal development, leading to increased sedimentation. Studies have documented high sediment loads in these waters, reducing light penetration and influencing coral community structure by favoring stress-tolerant genera such as *Porites* and *Montipora* over more sensitive branching corals like *Acropora* [5]. The combination of strong hydrodynamic forces and sedimentation creates a complex ecological setting where connectivity between reefs is highly dependent on both oceanographic conditions and localized environmental stressors. Understanding these interactions is essential for effective coral conservation and habitat restoration strategies in the Pahang coastal region.

Simulation of coral larvae dispersal involves integrating physical models with the biological variables of larvae, commonly called biophysical models [6]. Incorporating specific biological processes into these models, including pelagic larval duration, larval release from the source reef, larval mortality, and larvae settlement onto reef habitats, provides a comprehensive understanding of reef connectivity. Despite the limited availability of information on these biological processes, particularly among coral reef species, virtual larval dispersal simulations have demonstrated their ability to forecast population connectivity accurately. This has proven valuable for conservation and management purposes [6]. This study explored the dispersion of larvae particles using the Lagrangian particle tracking module integrated with a 2-dimensional hydrodynamic flexible network model (MIKE 21 FM). Three source reefs (Pulau Tioman, Pulau Seri Buat and Pulau Tokong Burung) were chosen from Pulau Tioman Marine Park. In comparison, the other three reefs (Pulau Berhala, Raja Muda Reef and Balok Reef) are non-protected nearshore reefs area. The primary aim of this study is to delineate the dispersal patterns of coral larvae within the Pahang coastal region. The underlying assumption is that coral reefs in marine protected areas (MPA) and nearshore reefs may exhibit source-sink dynamic population connectivity.

MATERIALS AND METHODOLOGY

Study Area and Model Domain

The Pahang Coastal Region (PCR) spans over 200 km from Cherating in the North and Kuala Rompin in the South. The present study simulated the coral larvae dispersal from six reef locations as shown in Table 1 and Figure 1. Three source reefs (Pulau Tioman, Pulau Seri Buat and Pulau Tokong Burung) were chosen from Pulau Tioman Marine Park. In comparison, the other three reefs (Pulau Berhala, Raja Muda Reef and Balok Reef) are non-protected nearshore reefs area. The recent study of the local hydrodynamic regime revealed that tidal forces primarily govern the local circulation in this region, thereby shaping the current flow pattern [4]. An Acoustic Doppler Current Profiler (ADCP) was positioned in the nearshore reef area (3°51'22.26" N, 103°27'8.82" E) for the purpose of field data collection, as shown in Figure 1.

Table 1. Mechanical Properties of Steel Reinforcement Bars

Source	Latitude	Longitude
Pulau Tioman (PT)	2°48'14.10"N	104° 6'0.15"E
Pulau Seri Buat (PSB)	2°43'10.08"N	103°53'51.97"E
Pulau Tokong Burung (PTB)	2°47'2.01"N	103°57'36.38"E
Pulau Berhala (PB)	3°14'42.13"N	103°39'18.20"E
Raja Muda Reef (RM)	3°38'28.35"N	103°28'3.23"E
Balok Reef (BR)	3°51'23.02"N	103°27'8.08"E

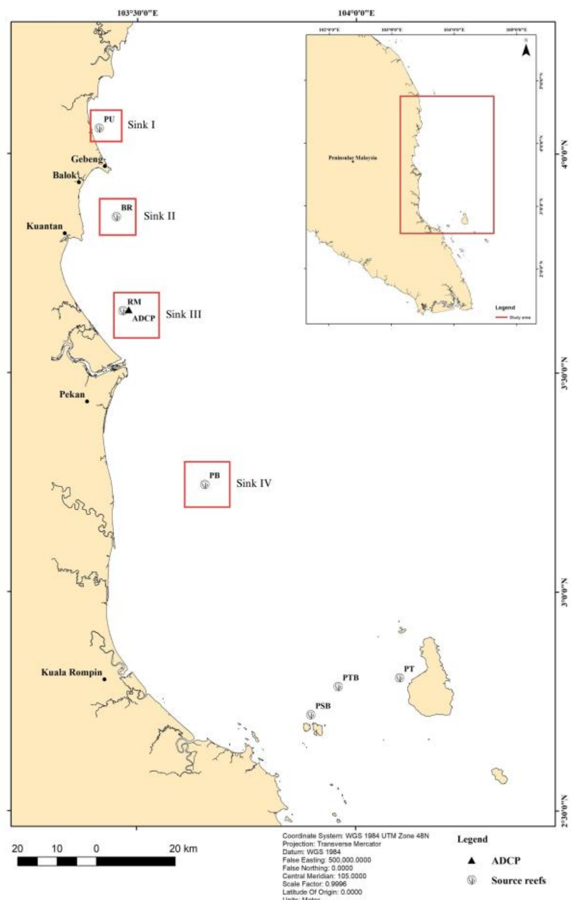

Figure 1. Map of study area of larvae dispersal in Pahang Coastal Region. Pulau Tioman, Pulau Seri Buat and Pulau Tokong Burung) were chosen from Pulau Tioman Marine Park while the other three reefs (Pulau Berhala, Raja Muda Reef and Balok Reef) are non-protected nearshore reefs area. The location of ADCP is indicated in the map.

The model domain area spans approximately 220 km from Kuala Dungun in Terengganu and Kuala Rompin in the south of Pahang as shown in Figure 2. Due to the extensive size of the model domain area, bathymetry data was generated using secondary input from the Royal Malaysian Navy (RMN) and General Bathymetry Chart of the Ocean (GEBCO) with a resolution of 1 km. The input data was processed using the Mesh Generator tools within MIKE ZERO, which utilized the bathymetry natural neighbor interpolation method to generate the domain area. The model domain is characterized by three open boundaries, namely North, East, and South, as depicted in Figure 2.

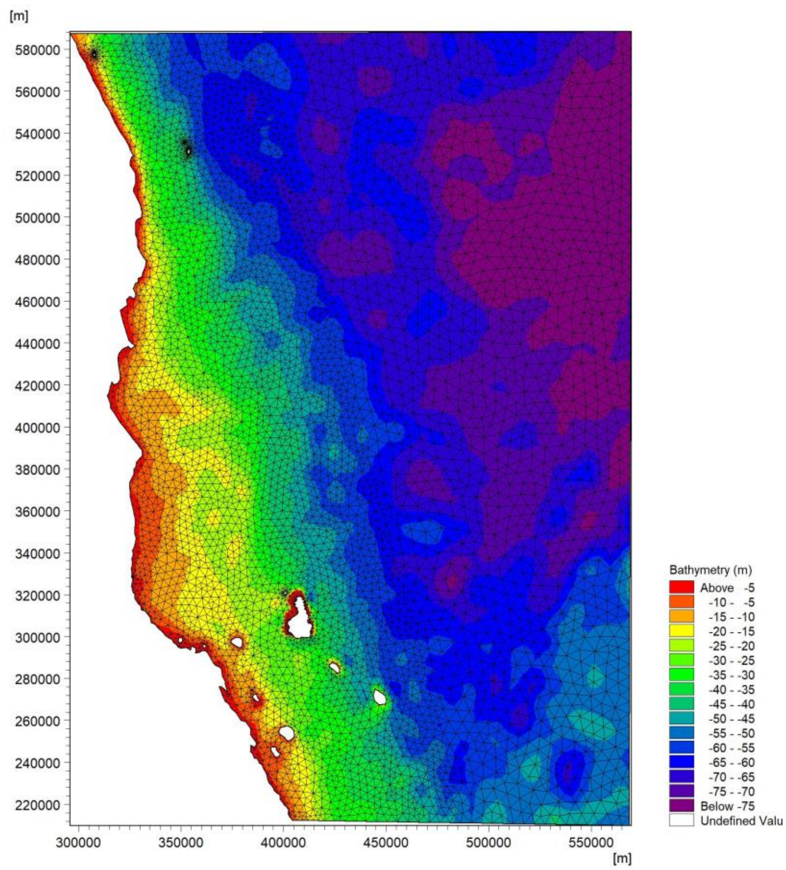

Figure 2. Computational domain for larvae dispersal simulation in Pahang Coastal region.

Model Validation

The MIKE 21 flow model FM, which is based on the numerical solution of the two-dimensional shallow water equation, was employed in the investigation. The depth-integrated incompressible Reynolds averaged Navier Stokes equations govern how this model functions. The MIKE 21 flow Model FM handbook has detailed information about the governing equations for this model [7]. The Royal Malaysian Navy's Admiralty Chart provided the tidal elevation data used to calculate the surface elevation for each simulation interval. Every open boundary in the model domain was fitted with three different sets of surface elevation time series data. Three distinct secondary ports—Chendering in the north, Kuantan in the east, and Sedili in the south—were the source of these. Wind stress is the primary component that drives local current circulation; hence wind flow and velocity are important parameters that could significantly affect the modelling output. The Royal Malaysian Navy provided wind forcing data with a temporal precision of one hour for each simulation period used in the current hydrodynamic simulation. Table 2 displays the configuration used for this simulation.

Table 2. Hydrodynamic model setup

Name	Setting
Module Selection	Hydrodynamic
Run length	7 d
Time step	600s
Flooding and Drying Depth (m)	0.005-0.05
Initial conditions	Wind and water level
Boundary conditions (open)	Tidal elevation
Boundary conditions (closed)	No normal flow
Eddy viscosity coefficient	0.28 m^2/s
Bed resistance coefficient	32 $m^{1/3}/s$

Larvae Dispersal Model

The hydrodynamic simulation's primary model was described by [5] utilizing the MIKE 21 Flow Model FM. The Lagrangian add-on particle tracking module from MIKE 21 FM was employed to generate virtual larvae trajectories. This model, MIKE 21 FM, has been applied to replicate larvae dispersal patterns in Southern Singapore [8] and Karimunjawa, Indonesia [9]. Governed by depth-integrated incompressible Reynolds averaged Navier Stokes equations, the model's governing equations can be found in the MIKE 21 flow Model FM manual [7]. The particle tracking in this model suggests a random walk model, which employs a Lagrangian discrete parcels approach to simulate the virtual larvae's distance increment due to drift and dispersion.

Virtual larvae were released 10 nights after full moon (27th April 2021) between 7.00 pm and 11.00 pm in April 2021 to represent larvae dispersal of *Acropora* in this region. To estimate connectivity pattern and source-sink dynamic between nearshore reefs, about 10,000 larvae particles were released at each time step (10 minutes interval) between 8:00 pm and 11:00 pm for each release date. About 180,000 virtual larvae were released from each source reef throughout the simulation. Simulations were made up to 24 days after predicted coral spawning during full moon in April 2021. Dispersal pathways were illustrated using MIKE Zero Plot from the simulation output to demonstrate larvae dispersal pattern from all three source reefs.

Several assumptions were made in this study to characterize the dispersal pattern. The virtual larvae particles were presumed to be neutrally buoyant and passive, hence the dispersal pattern was dependent on ocean current as larval movement was minimal during the pelagic larvae duration, as suggested by [10]. The pelagic larvae duration was categorized as minimum (2-4 DAS) and optimum (6-8 DAS) as suggested by [11], who observed the dispersal capacity of *Acropora cerviconis* in the Florida Reef Tract, USA. Prolonged larvae dispersal (18-20 DAS) pattern was also simulated to observe potential connectivity between source reefs within MPA and non-protected nearshore reefs. Erosion, settling rates, and decay for virtual coral larvae were not included in the simulation due to the absence of existing data. This approach has been utilized in several coral larvae dispersal studies across reef regions, such as those reported by [8; 9]. The drift profiles for virtual larvae were determined by hydrodynamic data from the model with a 600s (10 minutes) time step interval, and a minimum particle mass of 1×10^{-11} µg was applied with a maximum particle age of 30 days.

RESULTS AND DISCUSSION

The hydrodynamic model utilized in this study, based on the MIKE 21 framework, demonstrated strong validation results. Surface elevation and water levels predicted by the model correlated well with field measurements, indicating an RMS error of less than 10%. This high level of accuracy suggests the model is well-configured in terms of bathymetry, hydraulics, and geometry. The tidal pattern observed throughout the simulation period was predominantly mixed semidiurnal, with two high and two low tides per cycle, matching the model's predictions closely.

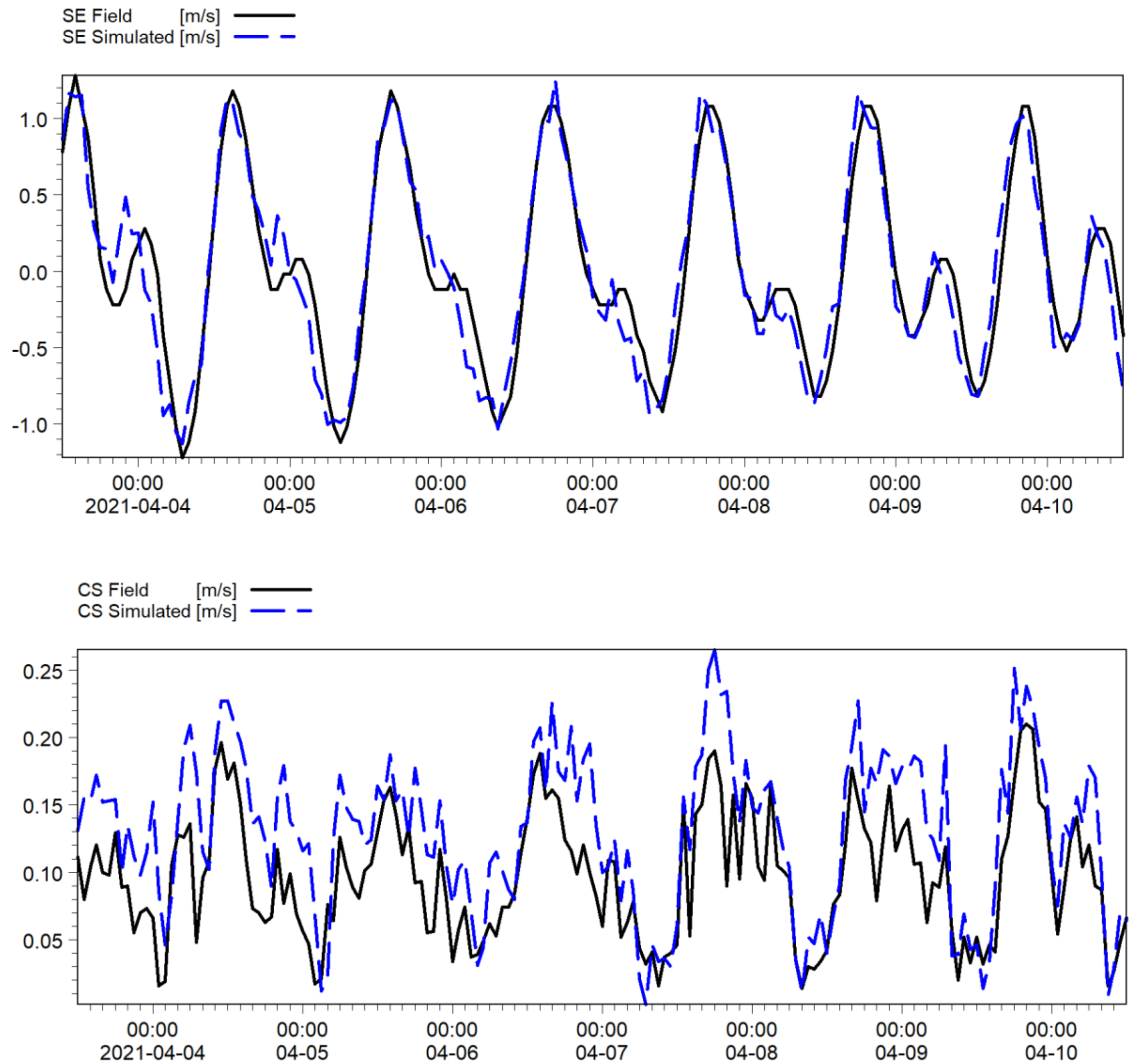

Figure 3. Validation of the model through direct measurement and comparison of the sea surface height predicted by the model.

The dispersal patterns of Acroporid larvae from six source reefs in the Pahang Coastal Region were tracked until 24th day after spawning (DAS) as shown in Figure 4. The dispersal pathways for both type of source reefs (MPA and Non-MPA) depict how larvae spread and moved within the region. The simulation indicated a northward movement of larvae throughout the dispersal period. During the initial dispersal phase (2-6 DAS), the larvae originating from MPA reefs (in blue) tend to remain concentrated closer to the source reefs while the non-MPA reefs (in red) exhibit more rapid larvae dispersal towards the northern region.

During the optimal dispersal phase (10-14 DAS), the larvae from both MPA and non-MPA sources have dispersed over a much larger area. The larvae from MPAs continue to be concentrated but have spread more towards adjacent regions. In contrast, the non-MPA larvae are more dispersed across the coastal waters, with clear trajectories pushing them northward along the coastline. At this stage, dispersal is more widespread for both groups, but the patterns suggest that non-MPA larvae follow more extensive oceanographic pathways, leading to greater spatial coverage.

In the prolonged dispersal phase (18-24 DAS), larvae from both MPA and non-MPA sources have been transported across a significant portion of the coastal region. The dispersal pathways now show considerable overlap between MPA and non-MPA larvae, with large distributions extending towards the north. The larvae from MPAs maintain a relatively consistent presence in the southern regions, with slower, more localized movement. Non-MPA larvae, on the other hand, have extended further north, covering broader and more distant areas.

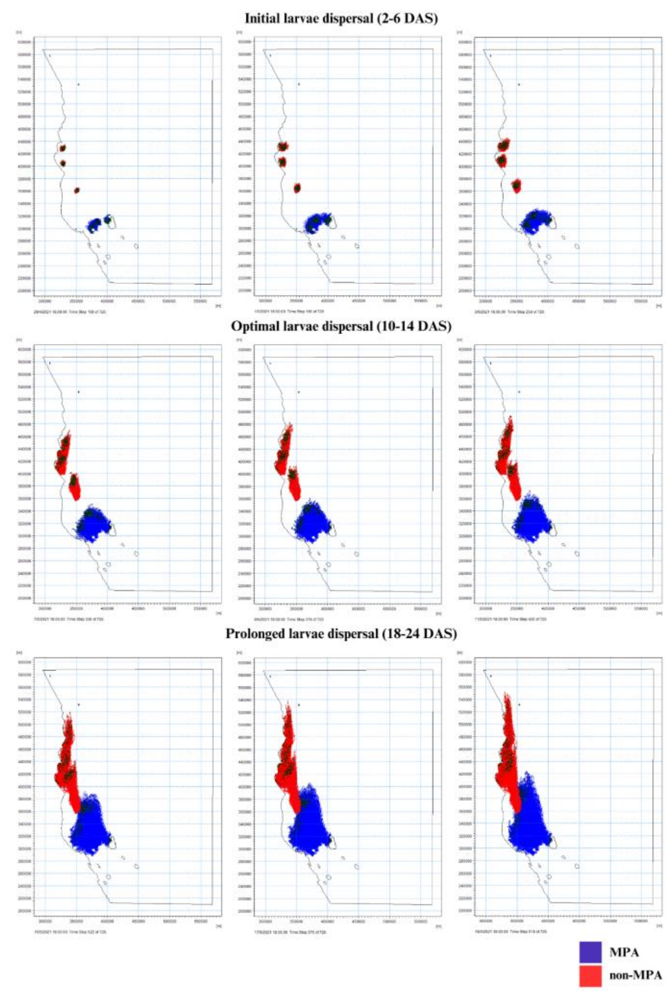

Figure 4. Dispersal pathways of Acroporid larvae originated from six source reefs during predicted coral spawning in April 2021. Dispersal pathways were plotted as larvae density per m3 (µgm-3) from 2nd day after spawning (DAS) until 24th DAS.

The arrival patterns of virtual larvae in four sink regions were analyzed across a 26-day period, with significant fluctuations observed based on pelagic larvae duration (PLD). Relative settlement percentage patterns varied across the sink regions. During the initial pelagic larvae duration (PLD), Sink IV received the highest percentage of larvae from Pulau Berhala by day 2, while Raja Muda larvae dominated Sink III by day 4 (Figure 5). During the optimal PLD, Sink III received 94.8% of Raja Muda larvae by day 6, while Sink IV showed 80.2% of the same larvae (Figure 6). In the prolonged PLD (day 18 onward), there was a reduced settlement percentage, with Sink IV receiving minimal larvae from multiple sources (Figure 7). In Sink Region I (Figure 8), the number of larvae arriving peaked between the 18th and 20th DAS, with larvae from Balok (B) and Raja Muda (RM) being the most prevalent.

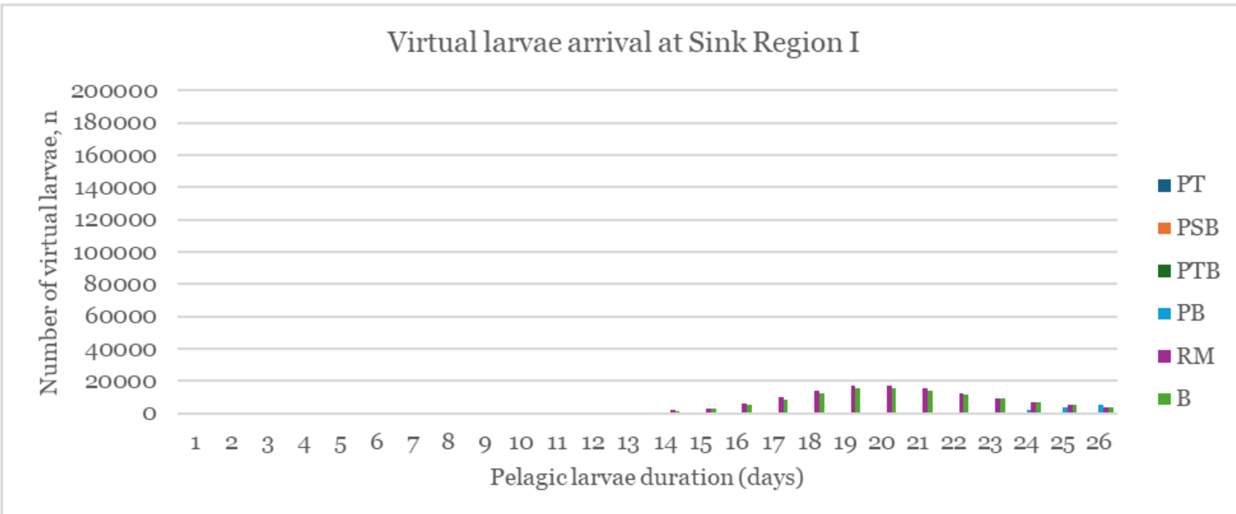

Figure 5. Virtual larvae arrival in sink region I from various sources, PT: Pulau Tioman; PSB: Pulau Seri Buat; PTB: Pulau Tokong Burung; PB:Pulau Berhala; Raja Muda: RM and Balok:B

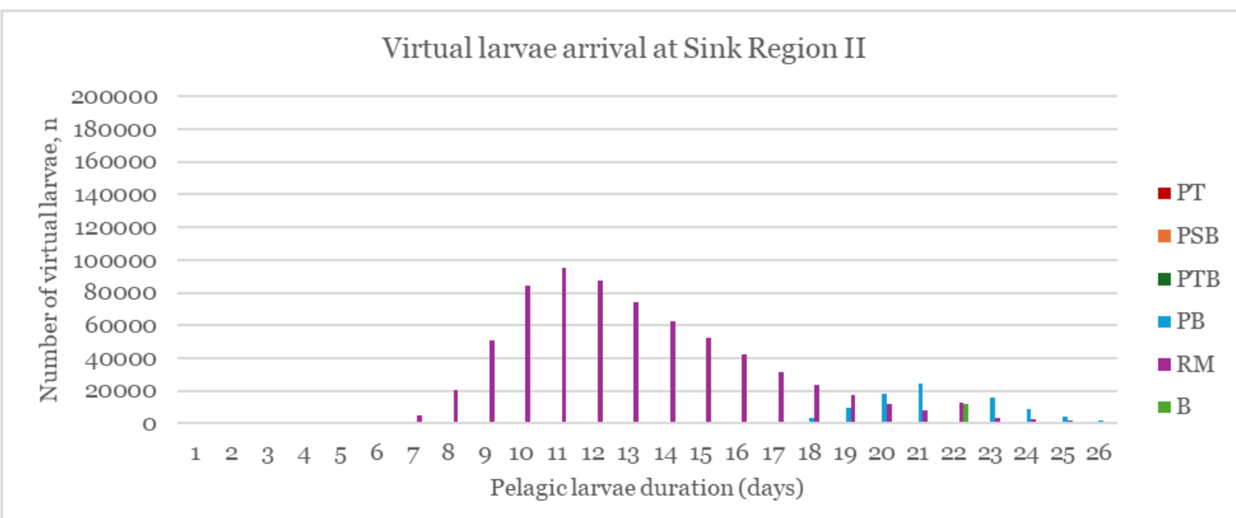

Figure 6. Virtual larvae arrival in sink region II from various sources, PT:Pulau Tioman; PSB: Pulau Seri Buat; PTB: Pulau Tokong Burung; PB:Pulau Berhala; Raja Muda: RM and Balok:B

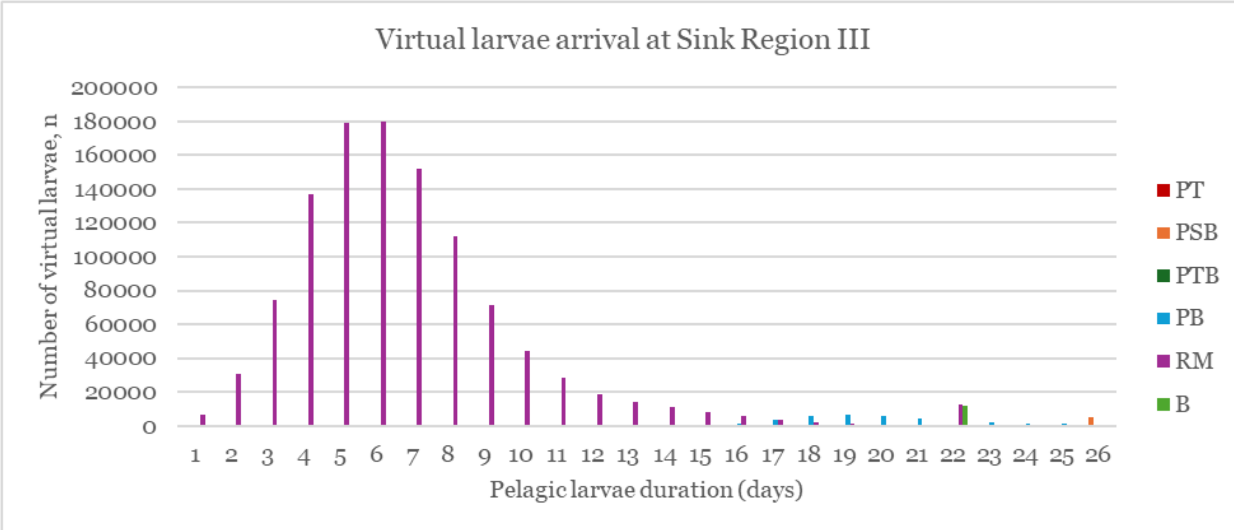

Figure 7. Virtual larvae arrival in sink region III from various sources, PT:Pulau Tioman; PSB: Pulau Seri Buat; PTB: Pulau Tokong Burung; PB:Pulau Berhala; Raja Muda: RM and Balok:B

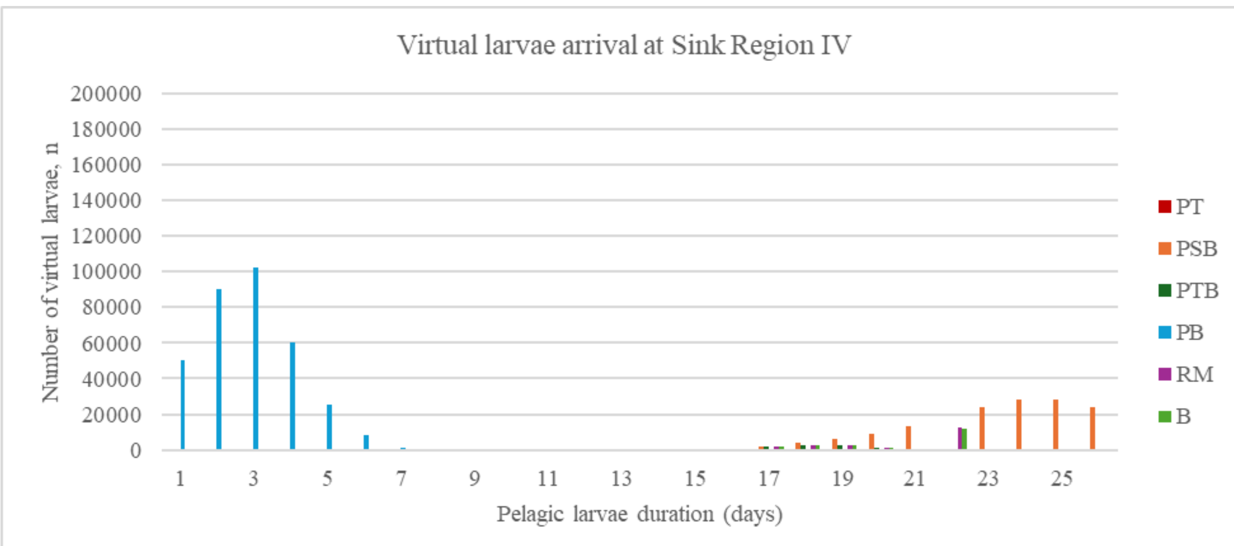

Figure 8. Virtual larvae arrival in sink region IV from various sources, PT: Pulau Tioman; PSB: Pulau Seri Buat; PTB: Pulau Tokong Burung; PB:Pulau Berhala; Raja Muda: RM and Balok:B

The settlement patterns of Acroporid larvae varied across the four sink regions depending on the pelagic larvae duration (PLD) and the originating source reef. During the initial PLD (2-4 DAS), Sink III had the highest settlement percentage, with up to 76% of larvae from Raja Muda (RM) successfully settled by the 4th DAS (Table 3). Sink IV also recorded early settlement, with over 56% of the larvae from Pulau Berhala (PB) settling by the 3rd DAS. In contrast, Sink I and Sink II showed no significant settlement during this early period, suggesting that larvae took longer to reach these regions.

Table 3. Relative settlement percentage pattern of Acroporid larvae during initial pelagic larvae duration from each source reef.

PLD (DAS)	Sink region	Source reefs					
		PT	PSB	PTB	PB	RM	B
2	Sink I	0.0	0.0	0.0	0.0	0.0	0.0
	Sink II	0.0	0.0	0.0	0.0	0.0	0.0
	Sink III	0.0	0.0	0.0	0.0	17.2	0.0
	Sink IV	0.0	0.0	0.0	50.2	0.0	0.0
3	Sink I	0.0	0.0	0.0	0.0	0.0	0.0
	Sink II	0.0	0.0	0.0	0.0	0.0	0.0
	Sink III	0.0	0.0	0.0	0.0	41.2	0.0
	Sink IV	0.0	0.0	0.0	56.8	0.0	0.0
4	Sink I	0.0	0.0	0.0	0.0	0.0	0.0
	Sink II	0.0	0.0	0.0	0.0	0.0	0.0
	Sink III	0.0	0.0	0.0	0.0	76.0	0.0
	Sink IV	0.0	0.0	0.0	33.6	0.0	0.0

As the larvae progressed through the optimal PLD (6-8 days), settlement remained concentrated in Sink III, with 94.8% of larvae from RM settling by 6^{th} DAS. Sink IV also exhibited a high settlement rate of 80.2%, primarily from RM. Although settlement in Sink II was lower, it was still notable, with 10.7% of larvae from RM settling by day 8 (Table 4).

Table 4. Relative settlement percentage pattern of Acroporid larvae during optimal pelagic larvae duration from each source reef.

PLD (days)	Sink region	Source reefs					
		PT	PSB	PTB	PB	RM	B
6	Sink I	0.0	0.0	0.0	0.0	0.0	0.0
	Sink II	0.0	0.0	0.0	0.0	0.3	0.0
	Sink III	0.0	0.0	0.0	0.0	94.8	0.0
	Sink IV	0.0	0.0	0.0	0.0	80.2	0.0
7	Sink I	0.0	0.0	0.0	0.0	0.0	0.0
	Sink II	0.0	0.0	0.0	0.0	2.5	0.0
	Sink III	0.0	0.0	0.0	4.5	0.0	0.0
	Sink IV	0.0	0.0	0.0	0.7	0.0	0.0
8	Sink I	0.0	0.0	0.0	0.0	0.0	0.0
	Sink II	0.0	0.0	0.0	0.0	10.7	0.0
	Sink III	0.0	0.0	0.0	0.0	59.1	0.0
	Sink IV	0.0	0.0	0.0	0.0	0.0	0.0

During the prolonged PLD (18-20 days), the settlement dynamics shifted. Sink II and Sink IV began to show increased settlement from different sources, particularly Pulau Berhala (PB) and Pulau Seri Buat (PSB) (Table 5). Sink II experienced a significant rise in settlement from RM, with up to 10% settling by day 20, while Sink III maintained steady but reduced settlement rates compared to the earlier optimal PLD period.

Table 5. Relative settlement percentage pattern of Acroporid larvae during optimal pelagic larvae duration from each source reef.

PLD	Sink	Source reefs					
		PT	PSB	PTB	PB	RM	B
18	Sink I	0	0	0	0	8	7
	Sink II	0	0	0	2	13	0
	Sink III	0	0	0	3	1	0
	Sink IV	0	2	1	0	1	1
19	Sink I	0	0	0	0	9	8
	Sink II	0	0	0	5	10	0
	Sink III	0	0	0	4	1	0
	Sink IV	0	3	1	0	1	1
20	Sink I	0	0	0	0	10	9
	Sink II	0	0	0	10	7	0
	Sink III	0	0	0	3	0	0
	Sink IV	0	5	1	0	1	1

The findings from the study on the larvae dispersal patterns and connectivity in the Pahang Coastal Region highlight several critical aspects of marine ecology and conservation. The hydrodynamic model validation demonstrated that the mixed semidiurnal tidal pattern dominated the simulation period, aligning well with field observations. This validation is pivotal as it confirms the model's accuracy in simulating water movements, which is crucial for predicting the dispersal of coral larvae.

The dispersal patterns of Acroporid larvae revealed in this study offer significant insights into the connectivity between reefs in the Pahang Coastal Region. The northward movement of larvae observed in the simulations aligns with prevailing current patterns in the region, which are influenced by the monsoonal cycles. Notably, the study found that larvae from nearshore reefs, such as Balok and Raja Muda Reefs, predominantly recruited in Sink Region I within the optimal PLD of 6-8 days. This finding is consistent with previous research indicating that local currents and eddies play a critical role in nearshore larvae retention [12].

One of the significant implications of these findings is the identification of nearshore reefs in the southern part of Kuantan coastal waters as ideal sink sites for coral larvae. The study highlighted that under prolonged PLD conditions (up to 20 days), larvae from the Pulau Tioman Marine Park (Pulau Tioman, Pulau Seri Buat and Pulau Tokong Burung) could reach nearshore reefs near Sink Region IV. The extended PLD simulations, showing potential larvae dispersal from Pulau Tioman Marine Park to nearshore reefs near Rompin, emphasize the critical role MPAs play as larvae sources. This connectivity is crucial for the replenishment and genetic diversity of coral populations, enhancing their capacity to withstand environmental stresses [13]. Effective management strategies should consider these sink regions as priority areas for conservation efforts.

The analysis of larvae arrival in different sink regions provides a deeper understanding of source-sink dynamics in the Pahang coastal region. In sink region I, the substantial recruitment of larvae from both nearshore and MPA reefs highlights the importance of this region as a critical recruitment area. The significant presence of larvae from Balok and Raja Muda reefs in this region emphasizes their role as major larvae sources. This finding suggests that conservation efforts should prioritize these nearshore reefs to ensure continuous larvae supply and ecosystem resilience. In Sink Region II, the patterns of larvae arrival mirrored those in Region I, with contributions from Pulau Berhala and other MPA sources. This redundancy in larvae sources is beneficial, providing a buffer against localized disturbances and enhancing overall ecosystem stability. The strong connectivity with Sink Region III, supported by substantial larvae input from Pulau Tioman and other MPA reefs, further underlines the interconnectedness of these reef systems. Such connectivity is vital for maintaining genetic diversity and enabling recovery from bleaching events and other stressors [14]. The potential for larvae from Tioman Marine Park to reach Sink Region IV under prolonged PLD conditions highlights the extended reach of larvae dispersal. This finding is particularly significant in the context of climate change, where increased water temperatures and altered current patterns could extend larvae PLD and dispersal ranges. Understanding these dynamics allows for better prediction of future changes in reef connectivity and informs adaptive management strategies [2].

The insights gained from this study have profound implications for the management and conservation of coral reef ecosystems in the Pahang Coastal Region. The identification of key sink sites, such as the nearshore reefs in southern Kuantan, highlights their critical role in larvae recruitment and ecosystem resilience. Prioritizing these areas in conservation strategies can enhance the overall health and sustainability of coral reef systems. Additionally, the significant connectivity between MPAs and nearshore reefs highlights the importance of protecting and maintaining MPAs as essential sources of larvae. Effective management should thus focus on both preserving these protected areas and ensuring the health of adjacent nearshore reefs to foster a resilient and interconnected reef network [1].

CONCLUSION

In conclusion, the research provides valuable insights into the dispersal dynamics of coral larvae in the Pahang Coastal Region, emphasizing the importance of connectivity between protected and non-protected areas. These findings can inform future conservation strategies and habitat restoration efforts, ensuring that both source and sink reefs are adequately protected to support the long-term viability of coral populations. The integration of hydrodynamic models with biological data in this study offers a robust framework for understanding and managing marine ecosystems effectively.

ACKNOWLEDGEMENT

The authors would like to thank Kulliyyah of Science, International Islamic University Malaysia for technical assistance such as scuba diving equipment and logistic during field data collection. This project was funded by Research Management Centre Grant (RMCG20-004-0004).

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

REFERENCES

[1] Sale, P. F., Cowen, R. K., Danilowicz, B. S., Jones, G. P., Kritzer, J. P., Lindeman, K. C. & Steneck, R. S. (2005). Critical science gaps impede use of no-take fishery reserves. *Trends in Ecology & Evolution*, 20(2), 74-80. doi: 10.1016/j.tree.2004.11.007.

[2] Randall, C. J., Giuliano, C., Stephenson, B., Whitman, T. N., Page, C. A., Treml, E. A., Logan, M., & Negri, A. P. (2024). Larval precompetency and settlement behaviour in 25 Indo-Pacific coral species. Communications Biology, 7(1), 1–15. https://doi.org/10.1038/s42003-024-05824-3

[3] Husaini, M. R., Saad, S., Khodzari, M. F. A., Ramli, R., & Yusof, M. H. (2015). Scleractinian coral recruitment density in coastal water of Balok, Pahang, Malaysia. *Jurnal Teknologi*, 25, 13–18.

[4] Hanapiah, M. F. M., Saad, S., & Ahmad, Z. (2020). Hydrodynamic Modelling in Inshore Reef Area within Kuantan Coastal Region. Journal CleanWAS, 4(1), 1–7.

[5] Kamarudin, N., Nik Asbullah, N. A. I., Azmi, A. N., Mustapa, M. Z., & Hanapiah, M. F. M. (2024). Benthic community structure and geomorphology of uncharted nearshore reefs in Kuantan coastal waters. Journal of Tropical Resources and Sustainable Science (JTRSS), 12(1), 1–6. https://doi.org/10.47253/jtrss.v12i1.1352

[6] Tilburg, C. E., Seay, J. E., Bishop, T. D., Miller III, H. L., & Meile, C. (2010). Distribution and retention of Petrolisthes armatus in a coastal plain estuary: The role of vertical movement in larval transport. Estuarine, Coastal and Shelf Science, 88, 260–266. doi: 10.1016/j.ecss.2010.01.001

[7] DHI. (2017). MIKE 21 FLOW MODEL FM. Denmark

[8] Tay, Y., Todd, P., Rosshaug, P., & Chou, L. (2012). Simulating the transport of broadcast coral larvae among the Southern Islands of Singapore. *Aquatic Biology*, 15, 283–297. doi: 10.3354/ab00435.

[9] Indrayanti, E., Zainuri, M., Sabdono, A., Wijayanti, D. P., Pranowo, W. S., & Siagian, H. S. R. (2019). Larval dispersal model of coral Acropora in the Karimunjawa Waters, Indonesia. *Biodiversitas*, 20(7), 2068–2075. doi: 10.13057/biodiv/d200738.

[10] Gleason, D. F., & Hofmann, D. K. (2011). Coral larvae: From gametes to recruits. *Journal of Experimental Marine Biology and Ecology*, 408, 42–57. doi: 10.1016/j.jembe.2011.07.025

[11] Drury, C., Paris, C. B., Kourafalou, V. H., & Lirman, D. (2018). Dispersal capacity and genetic relatedness in *Acropora cervicornis* on the Florida Reef Tract. *Coral Reefs*, 37, 585–596. doi: 10.1007/s00338-018-1671-y

[12] Cowen, R. K., & Sponaugle, S. (2009). Larval Dispersal and Marine Population Connectivity. *Annual Review of Marine Science*, 1 (1), 443-466. doi: 10.1146/annurev.marine.010908.163757.

[13] Jones, G. P., Srinivasan, M., Almany, G. R., & Riginos, C. (2009). Population Connectivity and Conservation of Marine Biodiversity. Oceanography, 20(3), 100-111. doi: 10.5670/oceanog.2007.30.

[14] Hughes, T. P., Baird, A. H., Dinsdale, E. A., Moltschaniwskyj, N. A., Pratchett, M. S., Tanner, J. E., & Willis, B. L. (2003). Detecting regional variation using meta-analysis and large-scale sampling: Latitudinal patterns in recruitment. *Ecology*, 84(6), 1601-1615.