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RESEARCH ARTICLE

DISPERSAL PATTERN OF CORAL LARVAE IN KUANTAN COASTAL WATERS, MALAYSIA

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ABSTRACT

Understanding source and sink pattern of coral larvae is among the key elements for effective ecosystem management and future habitat restoration. This study examined dispersal pattern of coral larvae among three known inshore reefs (Pulau Ular, Balok Reef and Raja Muda reef) in Kuantan coastal waters by simulating virtual larvae trajectories during spawning event in 2018. Dispersal pathways were modelled and constructed by incorporating biological traits (timing of spawning and pelagic larvae duration) using Langragian particle tracking module integrated with 2-dimensional, hydrodynamic, flexible network model (MIKE 21 FM). Results indicated that Acroporid larvae moved in southward direction throughout dispersal period. Source and sink dynamic suggested that Pulau Ular has high larvae retention (70%) in which most of larvae originated from natal reef. Balok reef was dominant source of larvae for Raja Muda reef. Results also indicated that patches reefs near Raja Muda was ideal sink site for coral larvae and should be prioritized for future ecosystem management action.

KEYWORDS

Coral larvae dispersal, Source-sink dynamic, Ecosystem management, Kuantan coastal waters.

1. INTRODUCTION

Kuantan coastal waters has relatively unknown patches of inshore reefs which are less documented compared to popular island reefs such as those in Tioman Island Archipelago. These reefs may serve as nursery and breeding ground for fish and other marine organisms. They also provide income for small scale fishermen by catching fish using 'bubu' trap and fishing rods along this area. Recent study in five shallow reef sites (less than 20 m depth) in Balok reef has indicated that this inshore reef has 'fair' coral cover with overall coral cover of 39 % and has relatively 4.78 mean coral recruitment densities (Hanapiah et al., 2019; Rani et al., 2015).

Ecosystem conservation and habitat restoration planning within this region involve deployment of artificial reefs which were meant for increasing fish population density. Considering that coral reef is protected ecosystem which rely heavily on constant larval input from connectivity framework, it is imperative for us to understand how these reefs may connect in term of dispersal pattern of coral larvae. Identifying source and sink region is essential for future conservation planning and management actions from the authority. Understanding the dispersal pattern of coral larvae is an integral key element in conservation action. A description on the pattern of coral larvae dispersal in this coastal region is currently unavailable. Therefore, this important element was often disregarded for sustainable marine ecosystem management.

Recently, there is increasing attention given in incorporation of physical models and the biological variables of the larvae which better known as biophysical models. The inclusion of certain biological processes during dispersal such as pelagic larval duration, larval release from source reef, larval mortality and larvae settlement onto reef habitat in the models give an explicit picture on reef connectivity. Even though information on these biological processes are still limited especially among coral reef species, larval dispersal virtual simulation has been proven to be able to forecast population connectivity with adequate precision for conservation and management purpose (Tilburg et al., 2010).

In this study, dispersal of larvae particles was investigated by applying the Langrangian particle tracking module integrated with 2-dimensional, hydrodynamic, flexible network model (MIKE 21 FM). The primary objective for this study is to describe the dispersal patterns of coral larvae

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in Kuantan coastal waters. It is assumed that inshore reefs in Kuantan coastal waters might be connected in source-sink dynamic population connectivity.

2. Materials and Methods

2.1 Study Area

Kuantan coastal waters encompassed area spanning from Cherating in the north until Cherok Paloh in the south (Figure 1). The present study simulated the dispersal pattern of coral larvae from three reef locations namely Pulau Ular (in the North), Balok reef (in the middle) and Raja Muda (in the South). Based on the recent analysis of local hydrodynamic regime, the local circulation in this region was dominated by tidal forcing which influence the current flow pattern (Hanapiah et al., 2020).

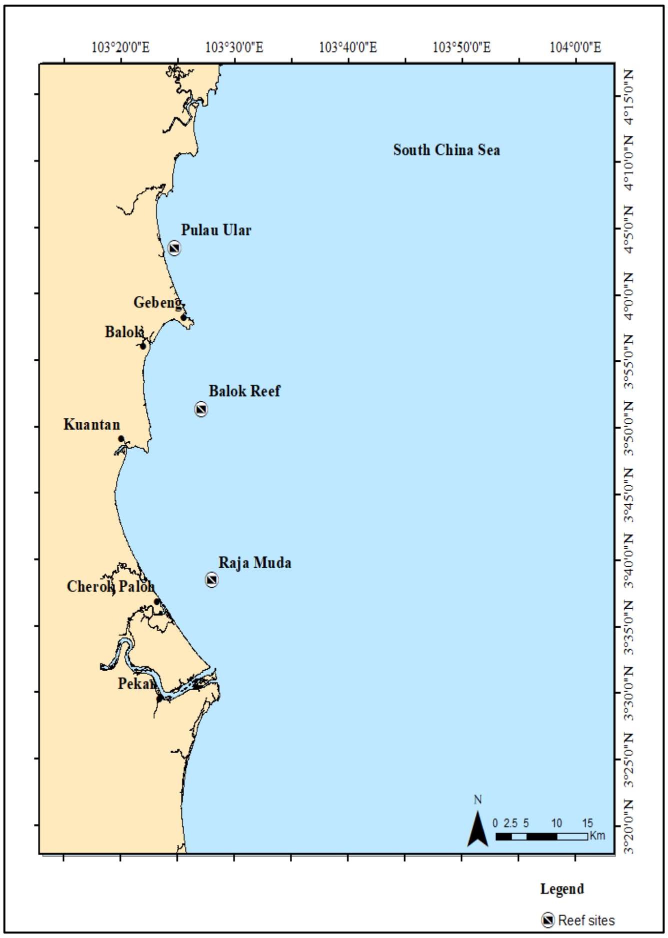

Figure 1: Map of study area of larvae dispersal in Kuantan coastal waters. Three source reefs were considered in this study namely Pulau Ular (4º3.482'N, 103º24.754'E) in the North, Balok Reef (3º51.377'N, 103º27.147'E) in the middle and Raja Muda (3º38'28.36"N, 103º28'3.22"E) in the South.

2.2 Coral larvae dispersal model

2.2.1 Lagrangian particle tracking module

The primary based model for this hydrodynamic simulation was validated and described in detail using MIKe 21 Flow Model FM (Hanapiah et al., 2020). To simulate virtual larvae trajectories, Lagrangian add-on particle tracking module from MIKE 21 FM was used. MIKE 21 FM has been used to simulate larvae dispersal pattern in Southern Singapore and Kapoposang, Indonesia (Afandy et al., 2017; Tay et al., 2012). This model was governed by depth-integrated incompressible Reynolds averaged Navier Stokes equations. The details of governing equations for this model can be found in MIKE 21 flow Model FM manual (DHI, 2017). The particle tracking implies a random walk model which use a Lagrangian discrete parcels approaches to simulate distance increment of the virtual larvae due to drift and dispersion.

2.2.2 Model assumption and biological traits properties

There were several assumptions were made to describe dispersal pattern in this study. The virtual larvae particles were assumed to be neutrally buoyant and passive. Therefore, dispersal pattern was relied on ocean current since larval movement was very minimal during pelagic larvae duration as suggested (Gleason and Hoffman, 2014). In addition, the location of larvae release was based on the previously documented survey coral distribution in inshore reef area of Balok, Kuantan (Hanapiah et al., 2019). Additionally, Pulau Ular was also selected as source point of larvae since it has substantial amount of reef area as reported (Sidek, 2016).

Furthermore, pelagic larvae duration was categorized as minimum (4-5 DAS) and optimum (6-8 DAS) as suggested by who observed dispersal capacity of *Acropora cerviconis* in Florida Reef Tract, USA (Drury et al., 2018). Apart from that, erosion, settling rates and decay for virtual coral larvae were not included in the simulation due to lack of existing data. This approach has been applied in several coral larvae dispersal studies across the reef regions such as those reported (Tay et al., 2012). Drift profiles for virtual larvae was determined by hydrodynamic data from the model with 600s (10 minutes) time step interval and a minimum particle mass of 1 x 10-11 µg was applied with maximum particle age of 14 days.

2.2.3 Coral larvae dispersal model simulation

Virtual larvae were released 10 nights after full moon between 8.00 pm and 11.00 pm in April 2018 to represent larvae dispersal of *Acropora* in this region. To estimate connectivity pattern and source-sink dynamic between inshore reefs, about 10,000 larvae particles were released at each time steps (10 minutes interval) between 8:00 pm and 11:00 pm for each release date. In total, 570,000 virtual larvae were released throughout the simulation. Virtual larvae were initially released from three sources; Pulau Ular, Balok reef and Raja Muda. Simulation were made until eight days after predicted coral spawning during full moon in April 2018. Dispersal pathways were illustrated using MIKE Zero Plot from the simulation output to demonstrate larvae dispersal pattern from all three source reefs.

2.3 Data extraction

Based on larval dispersal pathways from the model, three potential sink regions were identified for data extraction as shown in Figure 2. Sink region I was chosen to determine self-recruitment pattern of coral larvae originated from Pulau Ular. Sink region II was designated to observe source-sink dynamic between Pulau Ular and Balok reef apart from observing self-recruitment pattern in Balok reef. Sink region III was chosen based on the pattern of larval plume trajectories during optimum pelagic larvae duration (6 – 8 DAS).

The initial assumption was that this area might receive substantial number of coral larvae based on our dispersal range simulated. For each sink region, data on larvae concentration (particle per volume of water) were extracted along the vertical lines (approximately 10 km length with 500 m interval) which consist of 100 extraction points per line. The output of simulation calculated as larvae concentration in $\mu g/m^3$. Therefore, to estimate the arriving larvae at each time steps, the larvae concentration was multiplied by average depth. In addition, the particle concentration was multiplied by 1.5×10^6 as suggested by who stated that the source reef should produce at least 1.5×10^6 viable planule than the number of particles released in the model (Hughes et al., 2000). The estimation for number of larvae, n per m^2 is as follows:

Number of larvae per m^2,

$$\frac{\text{Larvae concentration}, L\rho \times \text{Depth} \times 1.5 \times 10^6}{\text{Mass of larvae, g}}$$

Whereby mass of larvae is 1×10^{-11} µg as suggested (Tay et al., 2012).

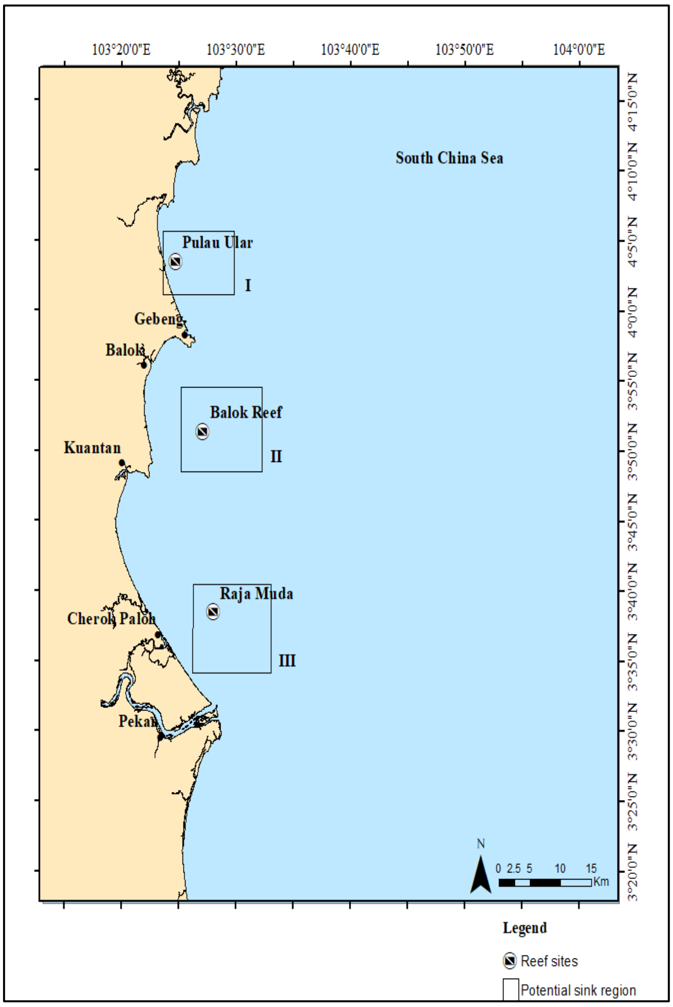

Figure 2: Map of potential sink region in the study area from three source reefs. The area considered for larvae dispersal data extraction is indicated by rectangle polygon and namely as sink region I, II and III respectively.

3. Results

In the present study, dispersal pattern of coral larvae was described based on the pelagic larvae duration of *Acropora* genus which have minimum competency period between 4 – 5 days after spawning (DAS) and optimum pelagic larvae duration (PLD) between 6-8 days after spawning (Nozawa and Harrison 2008; Ritson-Williams et al., 2010). Dispersal pathways plots indicated that Acroporids larvae moved in southward direction throughout the dispersal period. Larvae dispersal pathways from three source reefs (Pulau Ular, Balok reef and Raja Muda) were shown in Figure 3 to represent connectivity pattern within Kuantan coastal waters. Figure 4 – Figure 6 demonstrated virtual larvae arrival pattern based on the data extraction at each sink region. It can be noticed that most Acroporids larvae originated from Pulau Ular were retained locally (within sink region I) throughout the simulation.

Dispersal pathways plot indicate that most of larvae concentration remain high near Pulau Ular as shown in Figure 3a – Figure 3h. Data extraction for sink region I also indicated this retention pattern in which approximately 5000 larvae per m² were remained in this sink region throughout simulation (Figure 4). Most of Acroporid larvae from Balok reef were dispersed away from source reef right from the beginning of dispersal process (Figure 3a – Figure 3b). It can be noticed that low number of Acroporid larvae was retained in sink region II as shown in Figure 5. Acroporid larvae originated from Raja Muda were retained in sink region III while some of them dispersed southward on 3rd DAS as shown in Figure 3c. Sink region III received substantial number of larvae originated from Balok during 4th until 6th DAS with maximum larvae of 3174 larvae per m² (Figure 6).

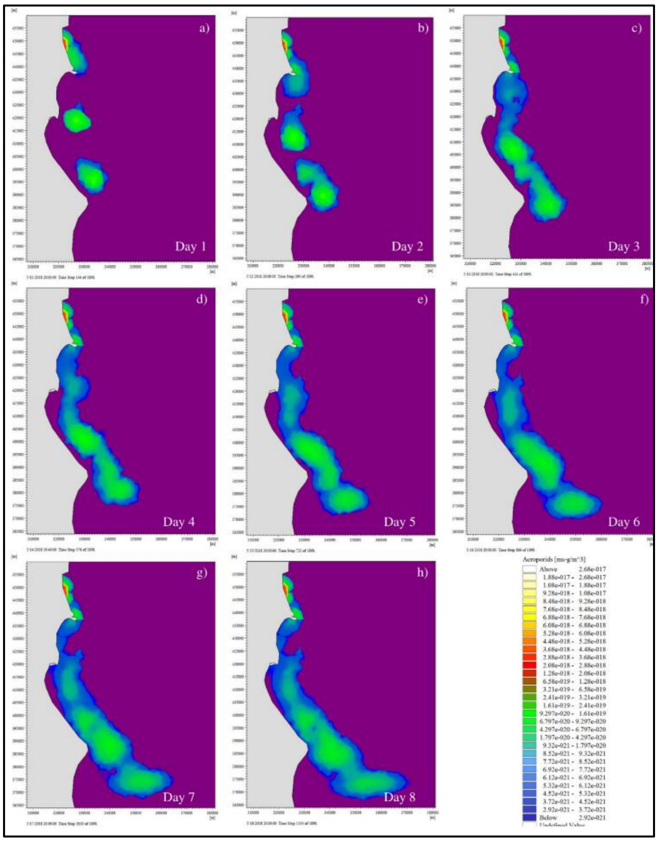

Figure 3: Dispersal pathways of Acroporid larvae originated from three source reefs (Pulau Ular, Balok reef and Raja Muda) during predicted coral spawning in April 2018. Dispersal pathways were plotted as larvae density per m3 (µgm-3) from 1st day after spawning (a) until 8th days after spawning (h). Colour legend indicate larvae concentration variation.

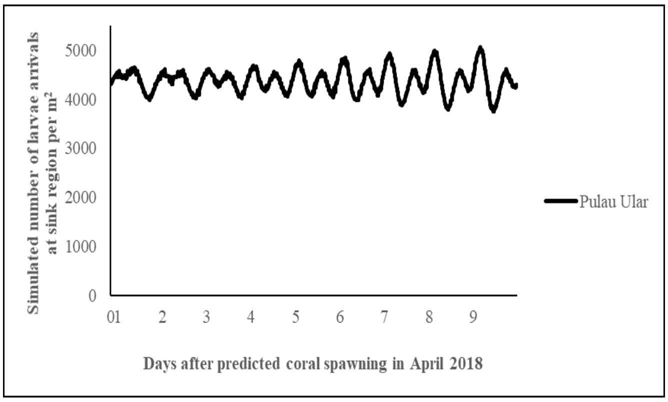

Figure 4: Simulated larvae arrival per m² from Pulau Ular to sink region I during predicted spawning event in April 2018.

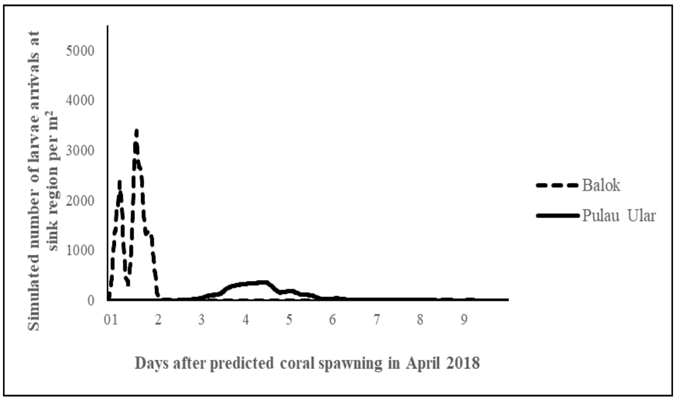

Figure 5: Simulated larvae arrival per m² from Pulau Ular and Balok to sink region II during predicted spawning event in April 2018.

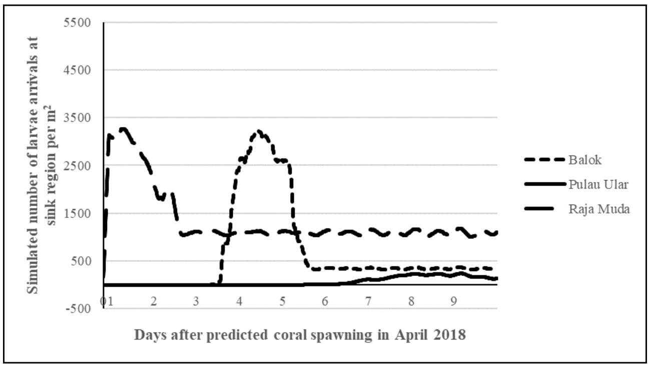

Figure 6: Simulated larvae arrival per m^2 from Pulau Ular and Balok to sink region III during predicted spawning event in April 2018.

The percentage of larvae settlement and directional dispersal pattern from each source reefs varies among sink regions and days after spawning as indicated in Table 1 and Table 2. It can be noticed that most of Acroporids larvae released from Pulau Ular were likely to settle in natal reef since about 76 % of them were retained in sink region I during both minimum and optimum PLDs (Table 1). Pulau Ular has 100 % local retention and self-recruitment since larvae only originated from Pulau Ular as shown in Table 2. Sink region II received relatively low percentage of Acroporid larvae settlement during both minimum and optimum PLDs (Table 1) with most of larvae originated from Pulau Ular. Local retention decreased from 9.78% on 4th DAS to only 0.02 % on 9th DAS for this sink region. Local retention of Acroporid larvae in sink region III was more than 100% at the beginning of minimum PLD period (4th DAS). This was partly due to arrival of larvae from Balok reef which encompassed 80% of total larvae release from this source combined with 30 % larvae retained from Raja Muda in sink region III as shown in Table 1. However, the number of larvae retained from this source was decreasing during 5th and 6th DAS since only 9% of larvae from Balok reef were retained in sink region III on 8th DAS. Figure 7 demonstrated the overall pattern of larvae dispersal and connectivity among source reefs and potential sink regions. The dispersal range during simulation period is estimated about 15-20 km width and approximately 100 km length (from Pulau Ular until the last dispersal pathways on 8th DAS).

Table 1: Relative settlement percentage pattern of Acroporid larvae from all three sources reef.

PLD (days)	Source	Percentage of larvae on settlement region, %		
		Sink region I	Sink region II	Sink region III
4	Pulau Ular	76.54	3.13	0
	Balok	0	0	80.95
	Raja Muda	0	0	30.62
5	Pulau Ular	76.61	0.55	0.04
	Balok	0	0	29.19
	Raja Muda	0	0	30.6
6	Pulau Ular	0	0.13	1.2
	Balok	0	0	9.5
	Raja Muda	0	0	30.6
7	Pulau Ular	76.74	0.04	4.27
	Balok	0	0	9.5
	Raja Muda	0	0	30.61
8	Pulau Ular	76.81	0.02	5.94
	Balok	0	0	9.51
	Raja Muda	0	0	30.62

Table 2: Directional dispersal pattern between populations. Relative dispersal percentages from source reefs during 4th until 9th DAS. Local retention was defined as percentage of settlers in region of origin/total particles from that region, and self-recruitment was percentage of particles settling in region of origin/total particles settling in that region.

PLD (days)	Source	Local retention (%)	Self-recruitment (%)
4	Pulau Ular	76.54	100.00
	Balok	9.78	0.00
	Raja Muda	111.57	27.44
5	Pulau Ular	76.61	100.00
	Balok	3.13	0.00
	Raja Muda	59.83	51.14
6	Pulau Ular	76.68	100.00
	Balok	0.55	0.00
	Raja Muda	41.30	74.09
7	Pulau Ular	76.74	100.00
	Balok	0.13	0.00
	Raja Muda	44.38	68.97
8	Pulau Ular	76.81	100.00
	Balok	0.04	0.00
	Raja Muda	46.07	66.48

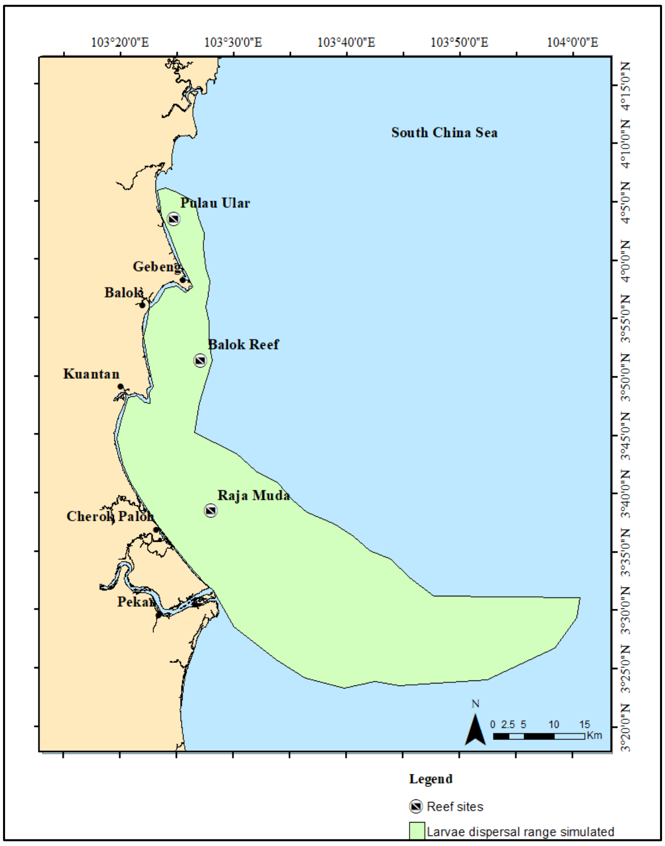

Figure 7: Larvae dispersal connectivity among the patches of inshore reefs within Kuantan coastal region. Green polygon indicated potential dispersal range of coral larvae within this region throughout simulation period.

4. Discussion

Present results clearly indicated larval exchange pattern from different source reefs towards sink regions during both minimum and optimum pelagic larvae durations. We found that both pelagic larvae duration and local hydrodynamic pattern influenced the dispersal dynamic and local retention pattern. In addition, we managed to identify ideal sink region for future conservation and ecosystem management plan in Kuantan coastal waters. The dispersal range simulated in this study was about 20 km width with 100 km length. Larvae plume move southward along the coastal region before curving eastward towards the offshore during 5th DAS. The longest dispersal distance within optimum PLD was approximately 40 km which was from Balok reef to sink region III. This was four times further than those virtual larvae simulated in southern part of Singapore during the same pelagic larvae duration (Tay et al., 2012). The large disparity between present study and their works might because of South China Sea circulation was more open and have stronger current flow compared with close circulation system in the Southern part of Singapore. Nevertheless, present findings provide important insights in designing future marine protected area zonation. It is suggested that the width of zonation shall be between 20 to 25 km to optimize larvae recruitment success in Kuantan coastal waters. There has been revival interest to include Kuantan coastal waters to be the part of Marine Protected Area (MPA) network by local authorities. Hence, to establish effective MPA network especially for sustainable coral reef ecosystem management, it is important for us to elucidate the dispersal pattern of coral larvae and population connectivity among each possible source reef within Kuantan coastal waters. An efficient marine ecosystem management can only be achieved when MPA zonation is greater than the dispersal range of coral larvae (Palumbi, 2003).

Finding dominant source reef is crucial in any population connectivity study. A group researchers suggested that, reef population will become isolated reproductively and susceptible to degradation without input source (Tay et al., 2012). In this case, Balok reef was dominant source reef for sink region III. Most of larvae originated from Balok reef arrived in sink region III during minimum PLD (4-5 DAS) as shown in Table 1. Some of these portions of larvae might settle within sink region III since most of them has already achieved competency. Hence, Balok reef should be protected since it plays important role in increasing local larvae supplies for adjacent reefs. On the contrary, dispersal simulation indicated that this reef received a smaller number of larvae compared to another sink region. Only small percentage of larvae (3 %) arrived from Pulau Ular as shown in Table 1. It can be postulated that there could be another unknown inshore reefs patches along Kuantan coastal waters which could supply larvae to this region since our previous finding indicate that this reef has fair coral cover percentage.

Sink region III received the most larvae from adjacent reefs. Local retention in this sink region exceeded 100 % on the 4th DAS (Table 1) due to large number of larvae arrival from Balok reef. It is suggested that this sink region is more resilient towards future disturbance since larval replenishment from external source can recuperate any habitat loss. Other researchers suggested that distant dispersal could be vital as a natural recovery mechanism following disturbance (Gilmour et al., 2009). In addition, since this area is strong sink region within Kuantan coastal waters larvae connectivity, it could be an ideal site for future ecosystem management. Deployment of more artificial reefs could be increased in this region to provide more substrate for coral attachment which may contribute towards habitat restoration.

Fine scale biophysical modelling has also revealed extensive self-recruitment pattern of coral larvae in Pulau Ular which retained 76 % of larvae throughout dispersal period. Simulation indicated that virtual coral larvae moved back and forth between Pulau Ular and the shoreline. The same pattern can be observed for Acroporid larvae originated from Raja Muda in which about 30 % of larvae were retained within sink region III as shown in Table 2. It can be postulated that this retention mechanism might be caused by coastal topography which create region of reduced flow. Based on the bathymetry data, both sink region I and III has higher bottom topography which may increase retention potential due to higher bed friction. This may result in reduced nearshore flow especially in sink region I which may explain why high number of larvae remain within this area. Sink region III also has relatively high self-recruitment partly due to its bottom topography which has large number of shoals that further increase retention and possibly limits cross-shore dispersion of larvae.

Larvae connectivity pattern and source-sink dynamic in this study suggested that sink region I should be prioritized for protection and habitat management due to high larvae retention. High larvae retention indicate that the reefs are self-seeding and rely heavily with the larvae release from natal reef. Such condition might cause that reef to have low reef resilient as the number of larvae settlement will decrease if adult population facing coral degradation. In this case, reef within this region should be protected and anthropogenic release from nearby river should be monitored to avoid further reef degradation. Balok reef (sink region II) has high larvae flushing rate towards adjacent reefs and should be considered as important ecosystem for conservation. As for sink region III, it can be suggested that more artificial habitat being introduced such as artificial reef deployment to increase coral larvae settlement success. Being an ideal sink region in Kuantan coastal waters larvae network, sink region III could emerge as the center of coral biodiversity which serve as valuable marine resource.

There were several limitations in the study which should be addressed. The present larvae dispersal pattern simulations were designed to determine larvae dispersal pattern to identify potential source or sink region within Kuantan coastal waters. Several natural factors could affect larvae dispersal such as predation and larvae mortality. In this case, mortality was set to zero to estimate maximum dispersal pathways in which the larvae could travel and settle. Constant mortality rate could result in overestimation of larvae retention and underestimate long distance dispersal and larval exchange between reefs patches. In addition, we chose Acroporids larvae as the reference for larvae dispersal during optimum PLD rather than combinations of several other taxa which might have different PLD. This is because Acroporids has among the longest PLDs reported compared to other coral genera. Therefore, estimation of larvae dispersal based on Acroporids could give general dispersal range for larvae connectivity. Furthermore, since it is assumed that current pattern was the main driving force of dispersal, it is believed that other coral larvae shall follow the same dispersal pathways in Kuantan coastal waters.

5. Conclusion

The present findings have indicated larval exchange and connectivity pattern among inshore reefs within Kuantan coastal waters. Balok reef may serve as dominant source reef for larvae supplies towards adjacent sink region in Kuantan coastal waters larvae network. Sink region III was identified as an ideal sink region and has high potential to become important ecosystem. More attention should be given towards Pulau Ular due to high retention pattern observed throughout the study. This was only preliminary study to describe larvae connectivity using limited biological data input. Therefore, more study on population genetic could be proposed in the future to determine realized connectivity between reef patches within Kuantan coastal waters.

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