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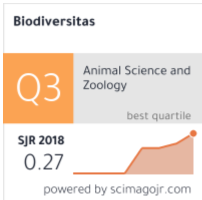

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Larval dispersal model of coral *Acropora* in the Karimunjawa Waters, Indonesia

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Abstract. *Indrayanti E, Zainuri M, Sabdono A, Wijayanti DP, Pranowo WS, Siagian HSR. 2019. Larval dispersal model of coral* Acropora *in the Karimunjawa Waters, Indonesia. Biodiversitas 20: 2068-2075.* Identification of connectivity patterns through the larval dispersal dynamics is urgently needed to support the sustainable larval supply. Many studies on the larval coral distribution have been reported. However, no study of coral larval dispersal has been conducted in Karimunjawa. The purpose of this research was to build a model of coral larval dispersal in Karimunjawa waters. Modeling was carried out by using a 2-dimensional hydrodynamic current approach with a particle tracking module. The larval release was conducted during the full moon in the first transition period (April) and the second transition period (October). The larval source was assumed from around Sambangan waters. Modeling validation was done by comparing the model results to the direct of current measurements with Acoustic Doppler Current Profiler (ADCP). The results of larval dispersal model showed that both the transition seasons I and II were similar in the direction of movement towards the west. This result indicated that currents, tides, and winds influenced the larval dispersal process. Also, the model results showed that Sambangan, Tengah, Cilik, Sintok, the west site of Karimun, Menjangan Kecil, and Menjangan Besar Islands were identified as the location of the larval settlement.

Keywords: Connectivity, coral larvae, Karimunjawa, larval dispersal, numeric model

INTRODUCTION

Karimunjawa archipelago, consists of 27 islands, is located in the Java Sea. This archipelago was designated as a marine reserve area through the Minister of Forestry Decree No. 123 / Kpts-II / 1986 on April 9, 1986. Based on Minister of Forestry Decree No. 78 / Kpts-II / 1999 dated February 22, 1999, Karimunjawa's status changed to Karimunjawa National Park (KNP). This park includes marine and terrestrial components with specifically 1101 km^2 of the sea, 13 km^2 of tropical lowland forest and 3 km^2 of mangrove forests. KNP is one of the first maritime areas that recognized as a marine biodiversity conservation area in Indonesia (Nababan et al. 2010; Campbell et al. 2013).

Coral reef ecosystem of Karimunjawa is approximately 713,11 hectares that consist of 69 scleractinian genera. These genera are dominated by genus *Acropora* and *Porites* (Nababan et al. 2010). In this study, *Acropora* was chosen as subject research due to a dominant role in species composition and abundance of many Indonesian coral ecosystems (Suharsono 2008). Acroporid is an excellent example of studying reef connectivity because they have much genetic information available for all coral genes throughout the world. Moreover, this genus has a more extensive geographical range compared to other coral families (Ladner and Palumbi 2012). Reproductive activities of 21 *Acropora* species in the Karimunjawa islands had been observed for five consecutive years (2008-2012) (Wijayanti et al. 2019). The observations showed that multi-specific spawning occurred during the first transition period and the second transition period (Permata et al. 2012; Wijayanti et al. 2019). Furthermore, DKP Central Java (2016) reported that Sambangan, Genting, and Seruni Islands of Karimunjawa were identified as excellent larval sources due to their high coral cover (>50%).

Coral larvae are simple, uniform ciliates and limited mobility that swim at speeds less than 0.4 cm s^{-1}. They are highly dependent on ocean currents for their dispersal and distribution (Gleason et al. 2009; Hata et al. 2017). The wide-ranging study area, the length of time required for observation and insufficient means of transportation were obstacles during conducting of this research. Therefore, hydrodynamic modeling of current flow and particle tracking could be used to predict larval routes and attachment patterns (Siegel et al. 2003; Wood et al. 2014; Fitriadi et al. 2017; Storlazzi et al. 2017). This approach was used as a basis for the assumption that coral larvae were in the planktonic phase. In this phase, coral larvae are particles that float, neutral, and passively carried by the mass of water. The larvae can spread several kilometers until they find a suitable place to attach (Siegel et al. 2003; Tay et al. 2012; Wood et al. 2014).

A better understanding on the period and larval dispersal pattern in the conservation area will increase the understanding of recruitment and connectivity among reefs (Kool and Nichol 2015; van der Meer et al. 2015; Storlazzi et al. 2017). Then, the research on modeling of larval dispersal is urgently needed to be conducted. The study results are expected to contribute to an understanding of local population dynamics and determining the coral reef conservation strategy in Karimunjawa. The coral larval dispersal is influenced by the number of gametes released, the success of fertilization and mortality (Tay et al. 2012). The mortality was assumed to be zero in the simulation model due to unavailable mortality data in Karimunjawa. However, the validation of the current hydrodynamic model showed good correspondence between the model and the *in situ* data, and this model indicated that the island identified as a larval settlement area showed a high coral cover and a relatively close genetic relationship (Wijayanti et al. 2018).

MATERIALS AND METHODS

Study area and model domain

The study was conducted in Karimunjawa Islands in 2018 which is located about 45 nautical miles or 83 km northwest of the city of Jepara, Central Java (5^o40 '-5^o57' LS; 110.04-110.40 BT) (Figure 1). Karimunjawa is located in the Java Sea, which is categorized as shallow waters. Its current circulation pattern is influenced by monsoons, that cause Karimunjawa to experience four distinct seasons (Tomascik et al. 1997). The seasons are the southwestern season (November-February); northeastern season (May-August); the first transition period (March-April); and the second transition period (September-October). These seasons greatly influence the properties of the Karimunjawa waters, such as ocean currents flowing from west to east (southwest monsoon). This season is characterized by high wind speed and high ocean waves. On the contrary, ocean currents that flow from east to west (east season), is characterized by low wind speed and low ocean waves (Balitbang Jateng 2003). Research showed that the wind direction comes from the southeast and moves the current to the west, with higher wind speed in the second transition period compared to the first transition period.

Initial release locations are coral reefs around Sambangan, Genting, and Seruni islands, with live coral cover ≥ 50 % (DKP Central Java 2016). The eight-point locations of the coral larval sources represent Sambangan compass points can be seen in Table 1 and Figure 1.

The model domain consists of large and small domains. The large model domain covers the Karimunjawa waters with 34 km x 17 km areas and the maximum size of 100,000 m^2 element area with the smallest angle of 30º (Figure 2a). The small model domain assumed to be the source area of larvae that covers the waters around Sambangan, Genting and Seruni Islands with a maximum element area of 10 m^2, the smallest angle of 30º and 5 m mesh size (Figure 2b). The triangular mesh was used as a design model with a higher resolution in the larval source area.

Table 1.. The 8 locations of the coral larval sources that represent around Sambangan compass point

Source	Longitude	Latitude
North source (N)	110.5849	-5.8420
Northeast source (NE)	110.5901	-5.8420
East source (E)	110.5881	-5.8460
Southeast source (SE)	110.5860	-5.8474
South source (S)	110.5849	-5.8480
Southwest source (SW)	110.5801	-5.8495
West source (W)	110.5787	-5.8459
Northwest source (NW)	110.5805	-5.8428

Table 2. Data and coefficient used in the model

Data/ coefficient	Source	Information
Bathymetric data	Indonesian map, Java North Coast, Karimunjawa Islands, Central Java, from the Navy's Hydro-oseanography Service (2013)	Scale 1: 75000. Bathymetric data is recorded as an input model with the format. XYZ
Tidal data (open boundaries conditions)	MIKE Prediction (Global Tide Model)	The provided elevation data is one year with 1-hour intervals, i.e., from January 1, 2018, to December 31, 2018, starting at 00.00
Wind data (friction condition)	Wind data obtained from http://ogimet.org	The one-year representative data with a 3 h time interval, and the soft start interval in the model area is 600 sec.
Time step	600 s	
Number of time step	4319	
Wind friction	0.0025	Varying in time, constant in domain
Initial surface level	0.3 m	
Horizontal eddy viscosity	Smagorinsky formula 0.28	
Bed resistance	Chezy number 38	

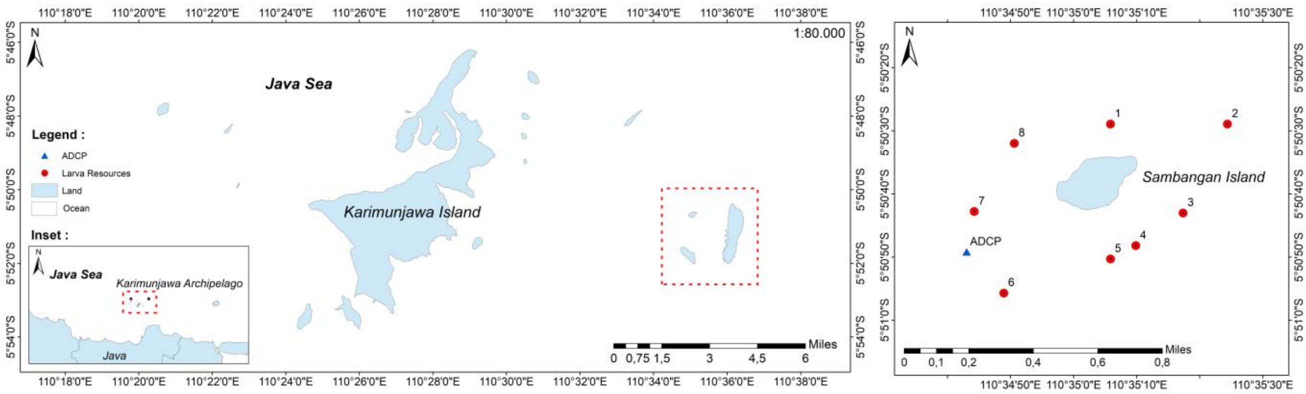
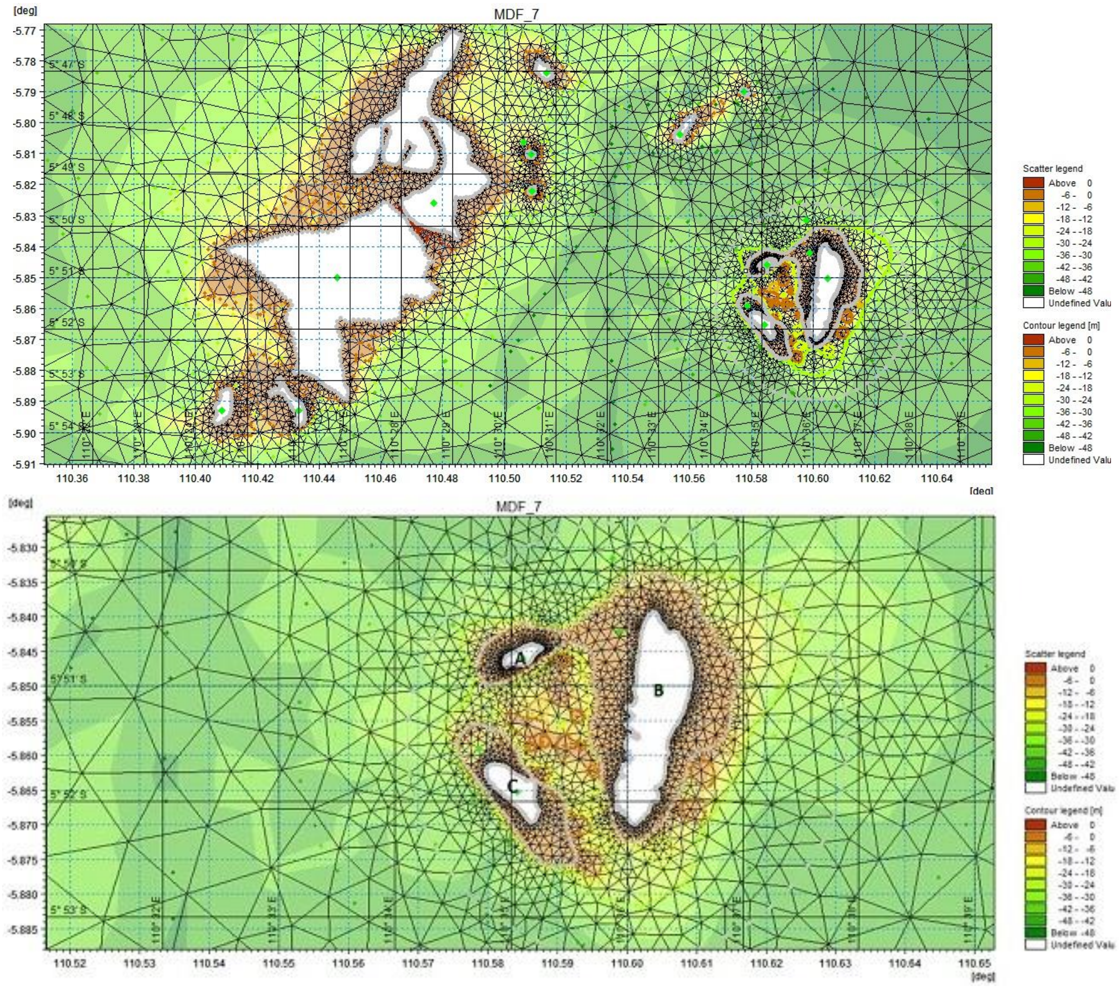


Figure 1. Map of the study area in Karimunjawa, including Sambangan Island that was selected as coral larval source for the model



A
B

Figure 2. A. The large model domain of Karimunjawa waters with triangular mesh. B. The small model domain of Sambangan (A), Genting (B), and Seruni Islands (C) with triangular mesh

Current model

The initial model to create larval coral dispersal was the Current Surface model. The Current Surface model was established by using a numerical model (MIKE 21) developed by the Danish Hydraulics Institute (DHI: www.mikepoweredbydhi.com). The equations used in this model included continuity equations and momentum equations (DHI 2012). This model has been used to track of coral larvae in Singapore (Tay et al. 2012), Kapoposang Marine Tourism Park, Indonesia (Afandy et al. 2017). Data input and coefficients used in this model were presented in Table 2.

Model validation

Validation was conducted to find out whether the model results were close to the actual measurement values in the field. Validation was carried out by comparing the water surface elevation of the modeling results with direct measurement results using Acoustic Doppler Current Profiler (ADCP), which was placed in the Sambangan waters at the coordinates of-5.8477 °S and 110,5784 °E (Figure 1). Observation of measurements was carried out for 7 x 24 hour (July, 14 to 21, 2018) with average time interval of 600 s and a sample rate of 300 s. The current velocity was measured at 6 depth layers (2 m, 4 m, 6 m, 8 m, 10 m, 12 m) with a total depth of ADCP was 14 m.

Larval dispersal model

The larval dispersal model was constructed by using the Particle-Tracking module in the MIKE 21 FM application (Flow Model). This module calculates the displacement of the particle position from the input speed of the hydrodynamic model output every time (DHI 2012). The *Acropora* larvae were used as the object research due to their dominance and the main component of reef builders in Karimunjawa (Nababan et al. 2010). Also, this coral genera spawning time was already known two times a year (Permata et al. 2012; Wijayanti et al. 2019). The larval dispersal corals was a complex process that involves external and internal factors.

Furthermore, there were limited information in the behavior and characteristics of coral larvae. Therefore, several assumptions were used in the model construction, such as:

i. Coral larvae are considered as particles that do not have a swimming force, so the particle swimming speed is not significant compared to the current (Tay et al. 2012; Hata et al. 2017).
ii. Spawning coral pattern in Karimunjawa likely follow the lunar cycle, split spawning occurred over an extended period, ranging from 8 days before full moon to 9 days after full moon in March 2009 and 7 days before full moon and 1 day after full moon in April 2012, 1 day before full moon and 2 days after full moon in October 2012 (Permata et al. 2012; Wijayanti et al. 2019). Based on the previous research, release time was assumed with 2 scenarios of release duration: the first transition period (time release April 12, 2018, 20:00 WIB) and the second transition period (time release 16 October 2018, 00:00 WIB).
iii. The density of larval number released at the spawning time was adjusted to the proportion of coral reef conditions at the source location. This study did not attempt to make a model of the real number larval deployment. Whereas, this study was focused on the representation of the spatial larval dispersal potency and the connectivity levels among locations
iv. In this study, the life duration of coral larvae was 19 days. Pelagic larval duration (PLD) varies in each coral species, for example in a short time between 4-7 days, medium about 30 days and length >100 days (Treml et al. 2008; Kool et al. 2011; Tay et al. 2012; Schill et al. 2015).
v. The movement of these particles was a conservative movement, where decay, erosion, and sediment velocity values were ignored. During the simulation, it assumed that there was no predation and death process for larvae (Sundelöf and Jonsson 2012; Tay et al. 2012).
vi. Model simulation results were presented on a time scale as long as the larval pelagic state moves in the sea. The coral larval movement was represented by the total of mass particles. The larval movement was divided into three stages, namely, the initial stage when the coral start spawning on April 12, 2018 (first transition period) and October 16, 2018 (second transition period); the medium stage occurred when the larvae entered the pelagic stage on April 16, 2018 (first transition period) and October 23, 2018 (second transition period); and the final stage occurred before the end of the larval phase on April 24, 2018 (first transition period) and October 28, 2018 (second transition period).

RESULTS AND DISCUSSION

Hydrodynamic condition of Karimunjawa Island

The sea currents movement of Karimunjawa island is influenced by the tidal movement. The direction of sea currents in Karimunjawa Archipelago is bi-directional current which has two directions, east, and west-southwest. A range of velocity of sea currents are between 0.01-0.20 m/s in the first transition period (April) and a range is between 0.05-0.35 m/s in the second transition period (October). The tides off Karimunjawa Islands are mixed tide prevailing semidiurnal type with the Formzahl value is 2.89. Karimunjawa Islands have varying wind speed, and the direction of wind is predominantly from southeast, east and north, with higher wind speed in the second transition period (a range of speed between 1.0-7.9 m/s) compared to the first transition period (1.0-3.3 m/s).

The validation of model results showed that the water surface elevation of the modeling results and direct observation was similar (Figure 3). Also, the calculation result of tidal constituents was 88.5% of the correction value. Validation results indicated that the model results were close to the field measurement results.

Coral larvae dispersal model

The transition period

The dispersion of coral larvae on Karimunjawa Island was represented by the total of a mass particle in the first transition period and the second transition period can be seen in Figure 4. In the first transition (April 2018), coral larvae in the initial stages moved towards the west of Sambangan Island with a total mass approximately at 100 $\mu g/m^3$. After 12 hours the movement continues to the west with a total mass of 70 $\mu g/m^3$. In the medium stage, the total mass of larvae began to spread increasingly extending towards the west and the south to Tanjung Batulawang with a concentration of 0.14 $\mu g/m^3$, and Kemujan with a total mass of 0.07 $\mu g/m^3$.

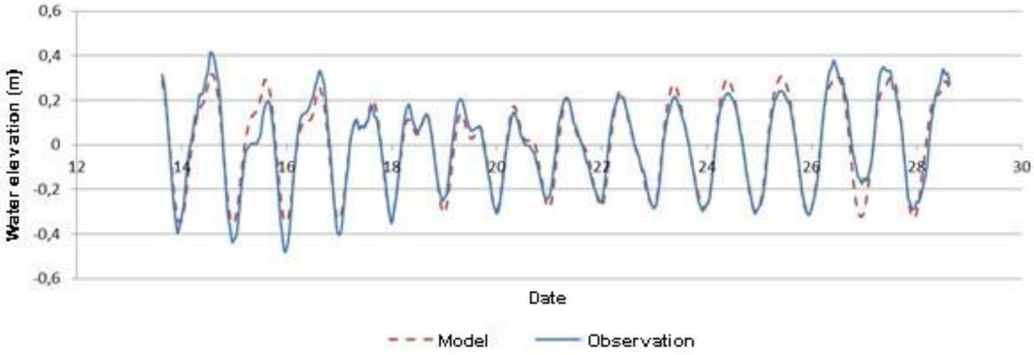


Figure 3. The validation of model by comparing the water surface elevation of the modeling results with direct measurement

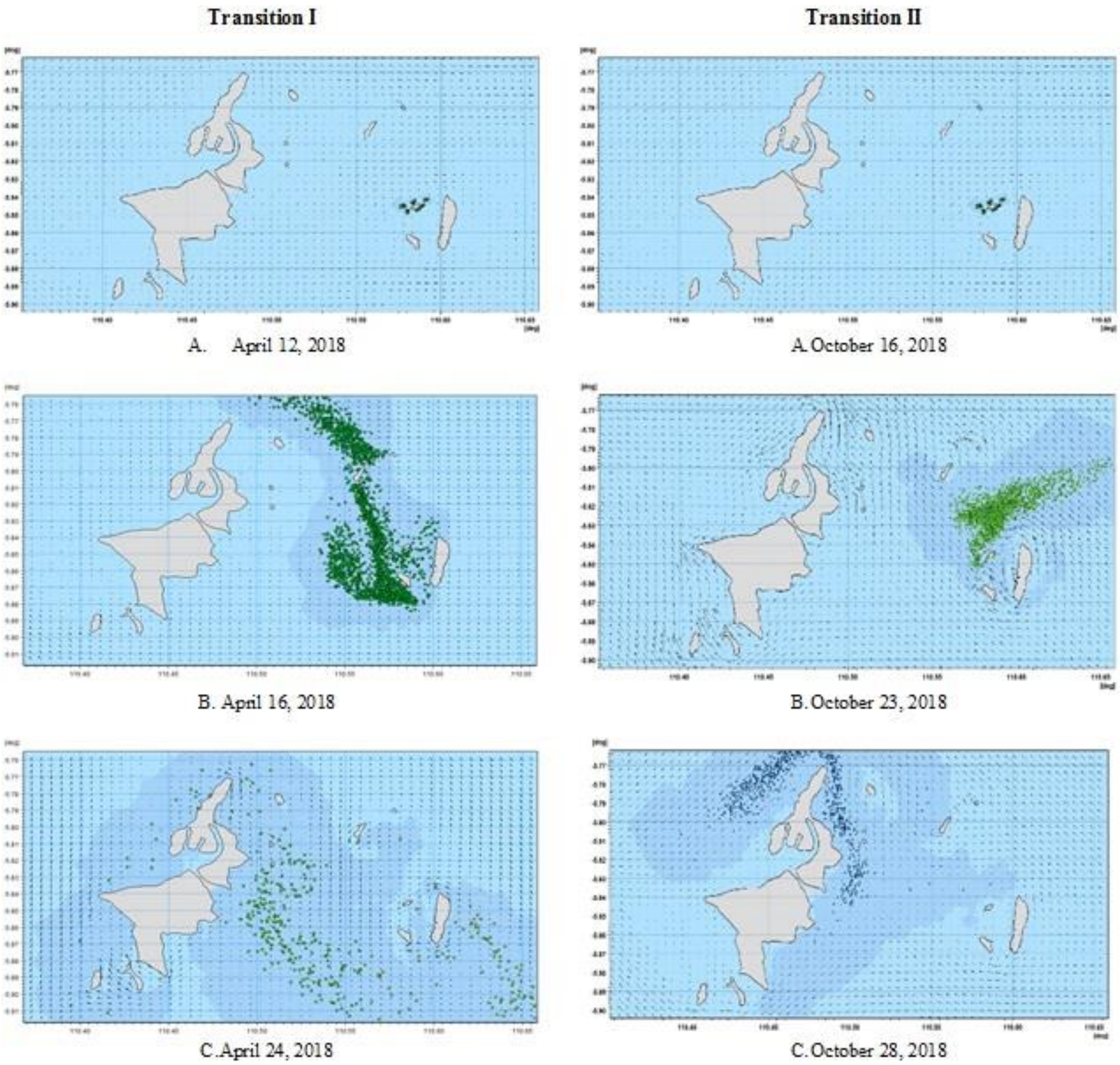


Figure 4. The coral larval dispersal model in Karimunjawa in the first transition period (April) and the second transition period (October) was displayed in 3 stages which represent (A) the initial stages (coral release egg or coral spawning), (B) the medium (coral larval entered their pelagic stage) and (C) before the end of the larval phase

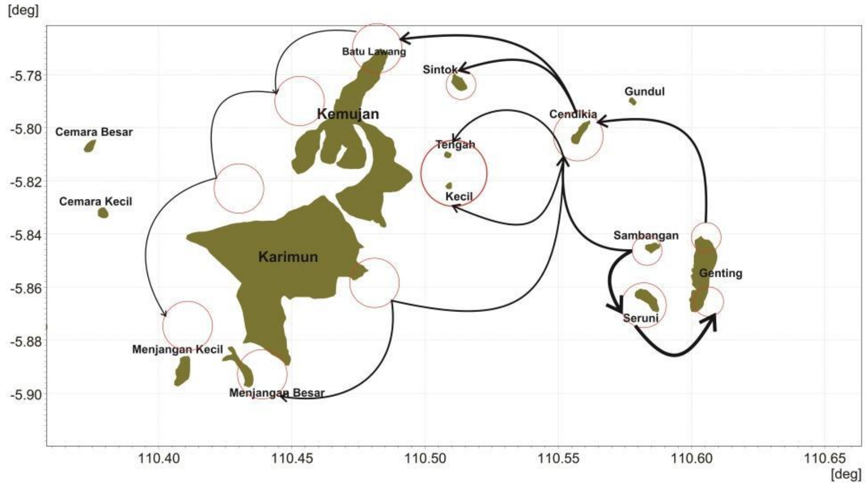


Figure 5. The areas were identified as the location of the larval settlement in the first transition period. Coral larvae originated from Sambangan waters spread around Sambangan, Genting and Seruni Islands. The larvae moved to the north towards the waters around Cilik, Tengah, Sintok, Tanjung Batulawang, and Kemujan Islands. The small portion of the larvae moved to the south through the eastern side of Karimun Island. The larval movement in the final stage moved to the west side of Karimun, Menjangan Kecil and Menjangan Besar

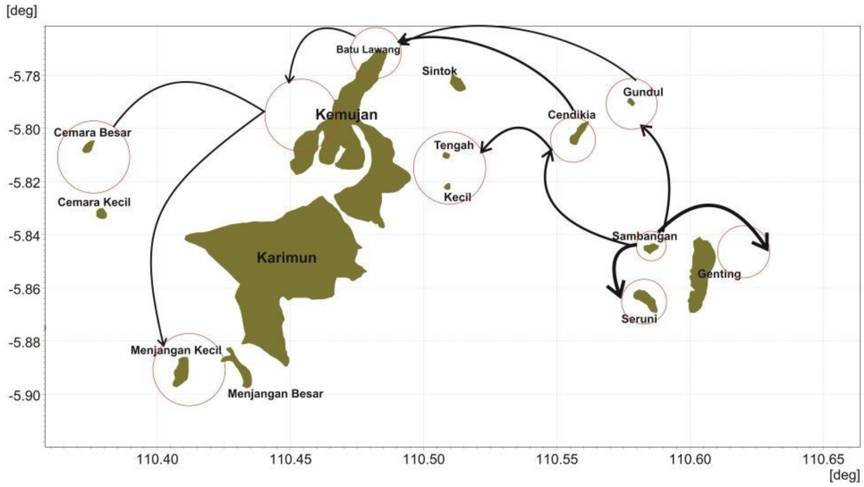


Figure 6. The areas were identified as the location of the larval settlement in the second transition period. Coral larvae originated from Sambangan moved towards the northeast and northwestern sides of Sambangan and Genting Islands. The larval movement began to spread into the larger areas, moving towards the north side of Cendikia, Tengah, Cilik, Batu Lawang. At the end of the stage, the larvae moved to the west side of Kemujan, Karimun and Menjangan Kecil Islands

In the second transition period, coral larvae moved from the east to the western area of Sambangan Island with a total mass concentration up to 146 µg/m^3. In the medium stage, the coral larvae moved towards the northeast, then to the northwest and spread around Cendikia Island, with a total mass concentration between 0.1-2.8 µg/m^3. In the final phase, the total coral mass decreases in the range between 0.01-1.9 µg/m^3, spread over Sintok, Cilik, and Tanjung Batulawang waters. Distribution of coral larvae in the first and second periods showed a decrease in the total mass concentration of coral larvae from the initial to the final stages, presumably while their disperse some larvae have sunk or settled.

The overall movement of coral larvae on Karimunjawa Island can be seen in Figure 4. The first transition period, where larval release around Sambangan waters occurred on April 12, 2018 at 18:00, moving towards the west side of Seruni Island. Following the current movement in the tidal phase, and the current direction was changed, the larvae moved towards the east side of Genting Island and spread in the waters around Sambangan, Genting and Seruni Islands. Furthermore, on April 16, 2018, the larvae moved to the north towards the waters around Cilik, Tengah, Sintok, Tanjung Batulawang, and Kemujan Islands. The larval movement in the final stage was on April 24, 2018. The larvae moved to the west side of Kemujan and Karimun Island. The small portion of the larvae moved to the southern regions of Karimun Island through the east side of Karimun.

The second transition period, where the larval release occurred on October 16, 2018, at 00.00. The larvae moved following the current movement that experienced changes in the tidal phase from ebb to high tides. The coral larvae moved towards the northeast and northwestern sides of Sambangan and Genting Island. The next stage of larval dispersal occurred on October 23, 2018. The larval movement began to spread into the larger areas, moving towards the north side of Cendikia waters. The final movement was on October 28, 2018; the larvae moved to Sintok, Cilik and Tengah Islands, to the west side of Karimun and Kemujan Islands.

Based on the result and simulation of coral larval dispersal in April and October 2018, the larval movement pattern can be described and larval settlement location in the first transition period (Figure 5) as well as the second transition period (Figure 6) can be identified.

Discussion

Distribution of coral larvae in Karimunjawa depends on the current direction, velocity, and flow patterns. The hydro-oceanographic variability is influenced by the monsoon pattern that takes place during the first transition period and the second. Gaonkar et al. (2012) stated that western and eastern monsoons play an important role in the distribution of organisms in the tropics. The larval dispersal model in the first transition period and the second period indicated that the direction of larval movement tends to go to the westward. However, the larval dispersal pattern in the second transition period showed no larval coral disperse through the eastern side of Karimun Island. This result indicated that the distribution of coral larvae in Karimunjawa was influenced by both seasonal wind patterns and tidal currents. Moreover, Karimunjawa has specific geographical characteristics where the region of the water is surrounded by a group of large and small islands. Several previous studies reported that tidal currents in Karimunjawa flow eastward during high tide and flow west or northwest at low tide (BTNKJ 2010).

The farthest distance of larval dispersal in the first transitional period and the second in Karimunjawa were 23.3 and 24.62 km to the west from larval sources; respectively. Similar results were also reported in Biawak Island (Fitriadi et al. 2017) and the Kapoposang Marine Tourism Park, Sulawesi (Afandy et al. 2017), coral larvae could spread several kilometers until they find a suitable habitat to settle. The distribution of larvae depends on ocean currents, without active swimming simulation or vertical migration (Tay et al. 2012; Wood et al. 2014; Hata et al. 2017).

Some locations such as Sambangan, Tengah, Kecil, Sintok, the west side of Karimun, Menjangan Kecil and Menjangan Besar Islands were identified as a for coral larvae settlement originated from Sambangan island. These results indicated that coral reef existence in Karimunjawa is believed to originate from reef propagules in Karimunjawa itself. This study result is also supported by Wijayanti et al. (2018) stated that DNA analysis carried out on *Acropora hyacinthus* collected from five islands in Karimunjawa (Seruni, Sambangan, Genting, Cilik and Menjangan Kecil) showed a relatively close genetic relationship.

The coral larval dispersal is influenced by the number of gametes released, the success of fertilization and mortality (Tay et al. 2012). However, the mortality was assumed to be zero in the simulation model due to unavailable mortality data. The mortality of invertebrate larvae depends on many factors such as predation (Baird 2001), water temperature (Nozawa and Harrison 2007), salinity (Vermeij et al. 2006) and sedimentation (Humanes et al. 2017). Consequently, the connectivity among reefs in Karimunjawa was resulting in overestimation. However, the validation of the current hydrodynamic model showed good results, and this model indicated that the island identified as a larval settlement area showed a high coral cover and a relatively close genetic relationship.

The results of this study have important implications for the coral reef management and conservation efforts in Karimunjawa. The islands identified as the larval attachment area and have high coral cover need special attention. Fortunately, the Sambangan waters that were identified as sources of larvae was not the main tourist destination so far. The Sambangan, Genting, and Seruni waters have a substantial live coral cover and can be a robust coral source. A more complex model by extending the scope model, several larval sources, combining hydrodynamic conditions and biological properties of coral larvae might be possible in further studies to find out more about the potential larval coral resources and their connectivity.

In conclusion, the model showed that coral-larval dispersal in the first transition period and the second follows regional current patterns that were influenced by tides and seasonal wind patterns. Coral larvae originated from Sambangan waters were distributed to the west on adjacent islands including Sambangan, Tengah, Cilik, Sintok, west side of Karimun Island, Menjangan Kecil and Menjangan Besar.

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