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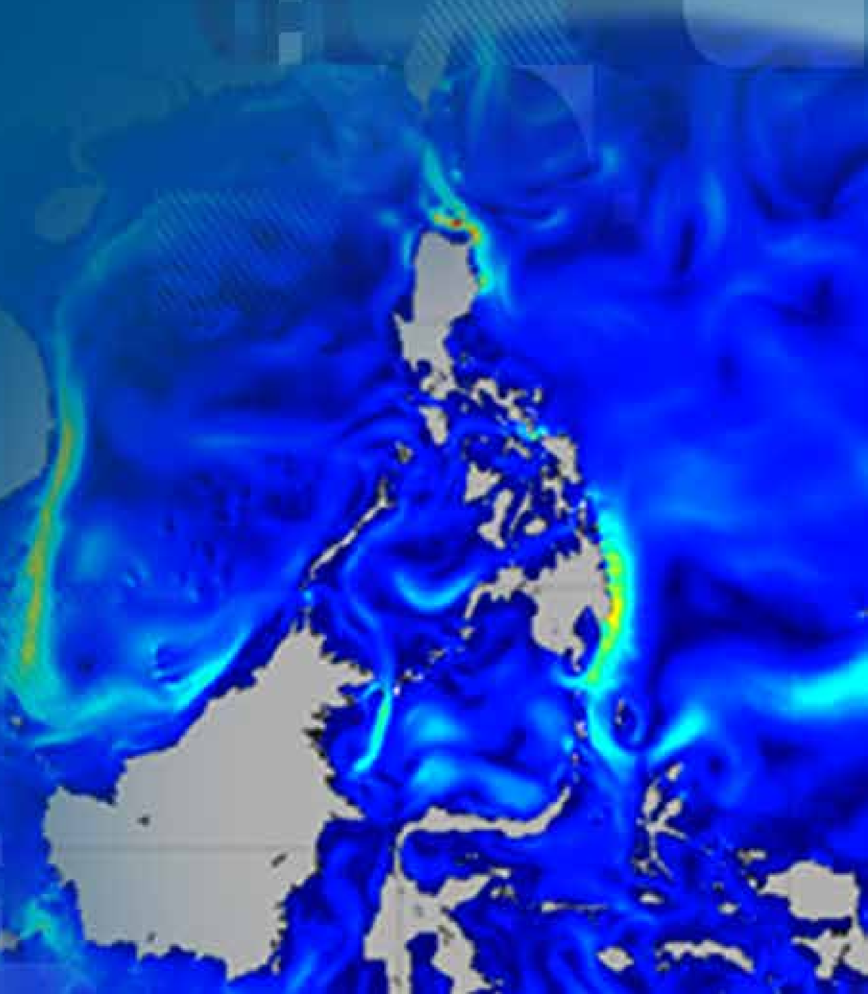
Larval Connectivity in Large Marine Ecosystems of South and Southeast Asia



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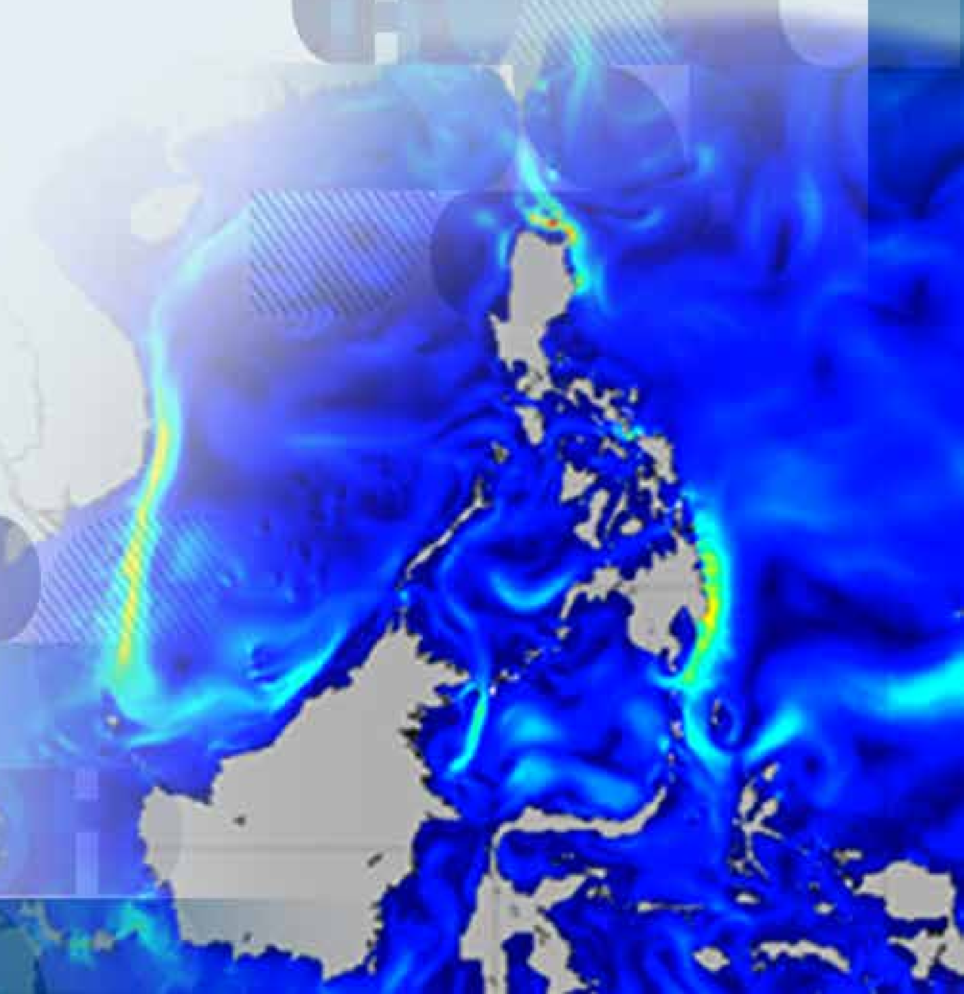


Introduction

Large Marine Ecosystems (LMEs) in South and Southeast Asia host some of the most biologically diverse and productive marine habitats globally, particularly coral reef systems that support fisheries, biodiversity, and coastal livelihoods. However, these ecosystems face increasing threats from overfishing, habitat degradation, and climate change. A critical but insufficiently understood process influencing the resilience and sustainability of these ecosystems is **larval connectivity** or the movement and exchange of larvae among spatially separated marine populations.

Larval connectivity governs population replenishment, genetic diversity, and ecosystem recovery following disturbances. Despite its importance, connectivity patterns across LMEs in the ASEAN region remain poorly quantified, especially at scales relevant for marine spatial planning and marine protected area (MPA) network design. This study addresses this gap by modelling larval dispersal and connectivity across four major LMEs: the **Indonesian Seas**, **Sulu-Celebes Seas**, **South China Sea**, and **Bay of Bengal**, with a focus on selected MPAs and pilot sites.

Scientific Context and Knowledge Gaps

Previous studies indicate that larval dispersal distances for reef-associated species typically range between 10 and 100 kilometres, suggesting that connectivity is often localised. Self-recruitment, where larvae settle near their origin, plays a major role in sustaining populations. However, long-distance dispersal events also occur and can be critical for maintaining genetic diversity and replenishing degraded populations.

Larval dispersal is influenced by complex oceanographic processes, including monsoon-driven currents, eddies, and upwelling systems. In the Coral Triangle and surrounding regions, these dynamics create a mosaic of connectivity patterns, with some reefs acting as strong sources of larvae and others as sinks. Despite this understanding, few studies have systematically examined connectivity across multiple LMEs using a consistent modelling framework, particularly in relation to MPA networks.

Objectives of the Study

The study aimed to:

1. Model ecological connectivity across four LMEs at a spatial resolution of 1/12°.
2. Simulate larval dispersal using biophysical models that integrate ocean circulation and larval behavior.
3. Identify connectivity patterns among key marine protected areas within each LME.
4. Develop higher-resolution models for selected pilot sites to examine fine-scale connectivity dynamics.

Pilot sites include prominent conservation areas such as Wakatobi National Park, Tubbataha Reef Natural Park, Turtle Islands Wildlife Sanctuary, and several protected areas in the South China Sea and Bay of Bengal.

<table>
<tr><th>LME</th><th>Pilot Site</th><th>No. of Downscaled Models (Resolution)</th></tr>
<tr><td rowspan="2">South China Sea</td><td>Agoo - Damortis Protected Landscape and Seascape</td><td rowspan="2">1 (1/36°)</td></tr>
<tr><td>Bani-Bolinao-Burgos-Infanta-Dasol-Agno Marine Protected Area Network</td></tr>
<tr><td rowspan="3">Sulu-Celebes</td><td>Tubbataha Reef Natural Park (ASEAN Heritage Park)</td><td></td></tr>
<tr><td>Ticao-Burias Pass Protected Seascape</td><td>1 (1/48°)</td></tr>
<tr><td>Turtle Islands Wildlife Sanctuary</td><td>1 (1/36°)</td></tr>
<tr><td rowspan="2">Indonesian Sea</td><td>Kepulauan Togean National Park</td><td>1 (1/36°)</td></tr>
<tr><td>Wakatobi National Park (ASEAN Heritage Park)</td><td>1 (1/36°)</td></tr>
<tr><td rowspan="4">Bay of Bengal</td><td>Tarutao National Park (ASEAN Heritage Park)</td><td rowspan="4">1 (1/24°)</td></tr>
<tr><td>Ranong Biosphere Reserve (RAMSAR Site)</td></tr>
<tr><td>Muko Surin National Park (ASEAN Heritage Park)</td></tr>
<tr><td>Muko Similan National Park (ASEAN Heritage Park)</td></tr>
</table>

Methodological Approach

Biophysical modelling framework

The study employed a biophysical modelling approach, combining hydrodynamic data with particle-tracking simulations. Ocean circulation data were derived from the Copernicus Marine Environment Monitoring Service, which provides high-resolution information on currents, temperature, and salinity. These data drive the movement of simulated larvae within the Connectivity Modeling System.

Larvae are represented as particles released from coral reef areas mapped using the Allen Coral Atlas. The number of particles corresponds to reef extent, ensuring ecologically realistic source distributions. A spatial grid (1/12° resolution) is used to define reef “source” and “sink” areas, which are aggregated into manageable units for analysis.

Larval dispersal parametres

Simulations assume a planktonic larval duration of 30 days, with a settlement competency window between 5 and 30 days. Larvae can settle if they encounter suitable reef habitats during this period. Simulations were conducted for peak monsoon months (February and July) to capture seasonal variability.

Connectivity matrices were generated by tracking the probability of larvae moving from source reefs to sink reefs. These matrices form the basis for identifying key connectivity patterns, including self-seeding and inter-reef exchange.

High-resolution downscaling

To capture fine-scale dynamics, selected pilot sites were modelled using higher-resolution grids (up to 1/36°). These models are nested within the global circulation model using the SURF-NEMO platform, allowing detailed analysis of local hydrodynamics and connectivity patterns.

Oceanographic Circulation Patterns

Monsoon-driven dynamics

Across all LMEs, circulation patterns are strongly influenced by the Southwest (SW) and Northeast (NE) monsoons, resulting in seasonal reversals of currents. Western basin boundaries tend to exhibit stronger flows, while interior regions are characterised by weaker currents and eddy activity.

Regional circulation characteristics

- **Indonesian Seas:** Dominated by the Indonesian Throughflow, which transports water from the Pacific to the Indian Ocean. Complex topography and multiple straits create highly variable circulation patterns.
- **Sulu-Celebes Seas:** Circulation is shaped by monsoonal winds and constrained passages such as the Sibutu Passage, which facilitate water and larval exchange between basins.
- **South China Sea:** Exhibits basin-scale gyres that reverse seasonally, influenced by monsoons and interactions with the Kuroshio Current.
- **Bay of Bengal:** Characterised by strong seasonal variability, river inputs, and stratification, with cyclonic circulation during the SW monsoon and anticyclonic flow during the NE monsoon.

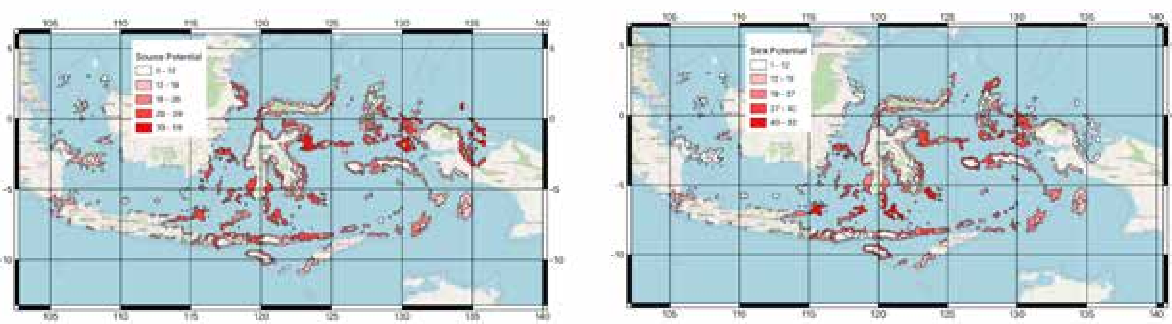
Larval Connectivity Patterns Across LMEs

General connectivity trends

Connectivity matrices revealed that **self-seeding (local retention)** is a dominant feature across all LMEs. However, significant variability exists, with some reefs acting as major larval sources and others as sinks. Connectivity patterns are influenced by ocean currents, reef distribution, and larval behavior.

Indonesian Seas

Connectivity is highly complex due to extensive reef coverage and intricate circulation. Numerous reefs function as both sources and sinks, supporting widespread larval exchange. This highlights the region's importance as a connectivity hub within the Coral Triangle.

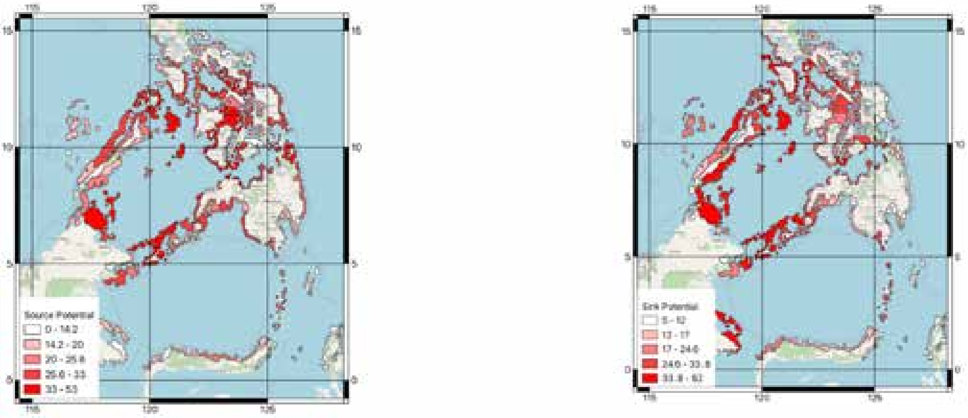


Source *Sink*

Figure 1. Source and sink potential maps for the reefs in the Indonesian Seas

Sulu-Celebes Sea

Connectivity is constrained by narrow passages, particularly the Sulu Archipelago, which acts as a critical corridor for larval dispersal. Reefs in this region serve dual roles as sources and sinks, while some areas exhibit limited connectivity due to prevailing currents.

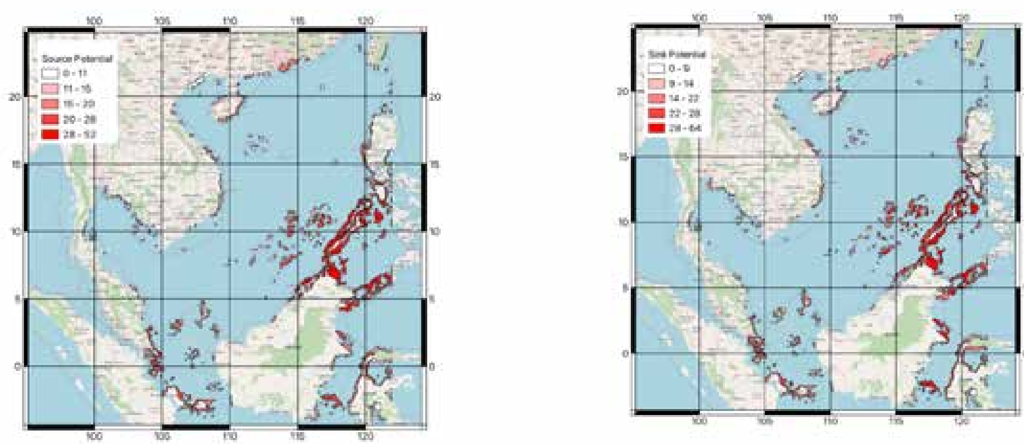


Source *Sink*

Figure 2. Source and sink potential maps for the reefs in the Sulu-Celebes Sea

South China Sea

High connectivity is observed in the southern portion, where reef density is greatest. The presence of numerous atolls enhances both source and sink potential, supporting extensive larval exchange across the basin.

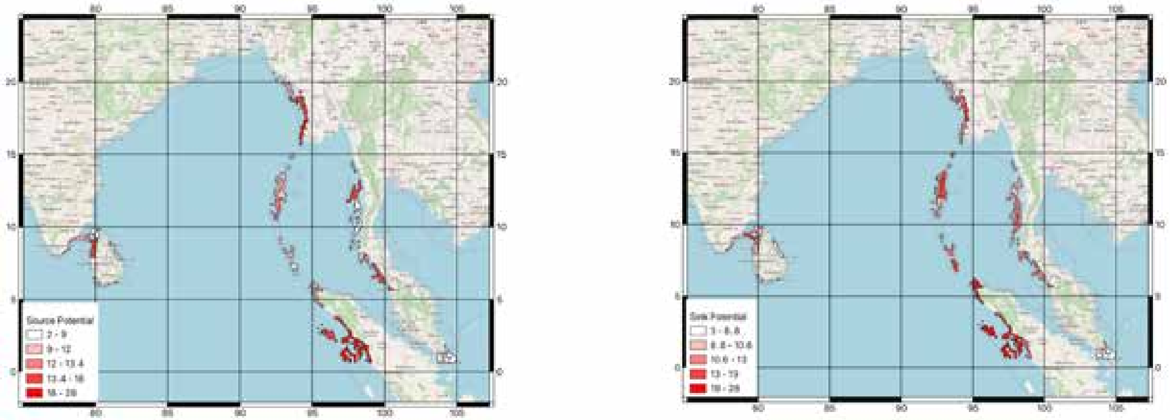


Source *Sink*

Figure 3. Source and sink potential maps for the reefs in the South China Sea

Bay of Bengal

Connectivity is limited due to sparse reef distribution. Most connectivity occurs along the Andaman and Nicobar Islands and the eastern coastline, with large areas of the basin lacking reef-mediated larval exchange.



Source *Sink*

Figure 4. Source and sink potential maps for the reefs in the Bay of Bengal

Connectivity in Pilot Sites

High-resolution models reveal distinct local dynamics:

- **Wakatobi National Park:** Exhibits relatively low connectivity due to larval dispersal into open waters.
- **Kepulauan Togean National Park:** Shows strong internal connectivity, with high source potential but limited external input.
- **Turtle Islands Wildlife Sanctuary:** Strong currents reduce self-seeding, leading to rapid larval export.
- **Ticao-Burias Pass Protected Seascape:** Highly complex connectivity due to strong currents and intricate geography, functioning as both a source and sink region.
- **Western Luzon MPAs:** Connectivity is linear along the coastline, with larval exchange occurring primarily between adjacent reefs.
- **Western Thailand Sites:** Connectivity modelling is constrained by complex bathymetry but indicates interconnected reef systems within the Andaman Sea.

Implications for Marine Conservation and Management

The findings underscore the importance of incorporating larval connectivity into MPA design and marine spatial planning. Key implications include:

- **Network Design:** MPAs should be configured to protect both source and sink reefs to ensure ecological resilience.
- **Regional Cooperation:** Connectivity across LMEs highlights the need for transboundary conservation strategies.
- **Climate Resilience:** Well-connected reef systems are more likely to recover from disturbances and maintain genetic diversity.
- **Adaptive Management:** Connectivity models can inform dynamic management approaches that account for seasonal and interannual variability.

Conclusions

This study comprehensively assessed larval connectivity across major LMEs in South and Southeast Asia using a consistent modelling framework. Results demonstrated that connectivity is highly variable and influenced by oceanographic processes, reef distribution, and model resolution.

While self-recruitment dominates many systems, inter-reef connectivity plays a crucial role in sustaining populations and enhancing resilience. The study also highlights the value of high-resolution modelling for understanding local dynamics within MPAs.

Importantly, the modelling framework and datasets developed in this study are transferable and can be used for further analysis, including advanced network metrics and scenario testing. These tools provide a strong scientific basis for improving marine conservation strategies and ensuring the long-term sustainability of the region's marine ecosystems.

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Graphic and Layout Artist:
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For more information, please contact the author
Dr. Cesar Villanoy
University of the Philippines Marine Science Institute
cesarv@msi.upd.edu.ph

/ASEANBiodiversity ASEAN_Biodiversity @aseanbiodiversity