PEMETAAN PENGGUNAAN MODEL NUMERIK PADA PERAIRAN INDONESIA : SEBUAH TINJAUAN SISTEMATIS

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ABSTRACT

Indonesian waters exhibit highly complex characteristics due to interactions among various oceanic, atmospheric, and terrestrial dynamics, leading to diverse problems that require in-depth understanding, ranging from current patterns, wave propagation, to pollutant dispersion. This complexity demands the use of scientific approaches capable of providing predictive insights, one of which is numerical modeling. This study aims to systematically review the development of numerical model applications in Indonesian waters research within the publication period from 2009 to 2024. The research methodology was conducted through literature review using a Systematic Literature Review approach. Data search was performed using scientific article search software and the Scopus database. Initial steps yielded 711 relevant publications, which after duplicate removal decreased to 614 articles, and following screening based on title, first author, and abstract, 206 articles were obtained that met the inclusion criteria of studies with first authors from Indonesia and research locations within Indonesian waters. Literature review results indicate that numerical models are extensively used to study ocean current dynamics, wave simulation, and pollutant dispersion analysis. Although the frequency of numerical model usage continues to increase year by year, several limitations are still encountered, particularly related to long-term field data constraints, model application in remote areas, and integration with practical needs in coastal and marine management. Based on these findings, it can be concluded that numerical models have become important instruments in Indonesian waters research, however, their future development direction still needs to consider strengthening observational data foundation, integration with other disciplines, and utilization to support more sustainable marine resource management policies.

Keywords: *Numerical Model, Systematic Literature Review, Indonesia Waters, Hydrodynamic, Oceanography*

ABSTRAK

Perairan Indonesia memiliki karakteristik yang sangat kompleks akibat interaksi berbagai dinamika laut, atmosfer, dan daratan sehingga menimbulkan beragam permasalahan yang perlu dipahami secara mendalam, mulai dari pola arus, perambatan gelombang, hingga penyebaran pencemar. Kompleksitas tersebut menuntut penggunaan pendekatan ilmiah yang mampu memberikan gambaran prediktif, salah satunya adalah pemodelan numerik. Penelitian ini bertujuan untuk meninjau secara sistematis perkembangan penggunaan model numerik dalam kajian perairan Indonesia dengan periode publikasi tahun 2009 hingga 2024. Metode penelitian

dilakukan melalui telaah literatur dengan pendekatan Tinjauan Literatur Sistematis. Pencarian data dilakukan menggunakan perangkat lunak pencari artikel ilmiah dan menggunakan basis data Scopus. Langkah awal memperoleh 711 publikasi yang relevan, kemudian setelah dilakukan proses penghapusan artikel ganda jumlah artikel berkurang menjadi 614, dan setelah penyaringan berdasarkan judul, penulis pertama, serta abstrak, diperoleh 206 artikel yang sesuai dengan kriteria inklusi yaitu penelitian dengan penulis pertama berasal dari Indonesia dan lokasi penelitian berada pada wilayah perairan Indonesia. Hasil peninjauan literatur menunjukkan bahwa model numerik banyak digunakan untuk mempelajari dinamika arus laut, simulasi gelombang, dan analisis penyebaran polutan. Meskipun frekuensi penggunaan model numerik terus meningkat dari tahun ke tahun, beberapa keterbatasan masih dihadapi, terutama terkait keterbatasan data lapangan jangka panjang, penerapan model di wilayah terpencil, serta integrasi dengan kebutuhan praktis dalam pengelolaan pesisir dan laut. Berdasarkan temuan tersebut dapat disimpulkan bahwa model numerik telah menjadi instrumen penting dalam penelitian perairan di Indonesia, namun arah pengembangannya ke depan masih perlu memperhatikan penguatan basis data observasi, integrasi dengan disiplin lain, serta pemanfaatan untuk mendukung kebijakan pengelolaan sumber daya laut secara lebih berkelanjutan.
Kata Kunci :   Model Numerik, Review Literatur Sistematis, Perairan Indonesia, Hidrodinamika, Oseanografi

1. PENDAHULUAN

Perairan Indonesia memainkan peran penting secara global karena fungsi ekologis, klimatologis, dan ekonominya. Wilayah ini dicirikan oleh dinamika yang sangat kompleks akibat interaksi berbagai faktor fisik, geografis, sirkulasi laut [1], [2], variabilitas iklim dan pengaruh global [2], [3], serta keanekaragaman hayati dan ekosistem [4], [5]. Kompleksitas ini menjadikan kawasan ini sebagai area yang menarik untuk diteliti namun juga menantang untuk dikelola secara berkelanjutan.

Interaksi dinamika tersebut menimbulkan beragam permasalahan praktis yang mendesak untuk dipahami dan diantisipasi, mulai dari pola arus untuk navigasi dan keselamatan pelayaran, perambatan gelombang dan tsunami untuk sistem peringatan dini bencana, hingga penyebaran polutan dan sedimentasi yang berdampak pada kesehatan ekosistem dan sumber daya pesisir. Untuk mempelajari wilayah luas yang kompleks tersebut, model numerik hadir sebagai alat yang indispensable. Model numerik mampu merepresentasikan dinamika laut skala besar [6], [7], [8], memiliki fleksibilitas untuk menguji berbagai skenario [6], serta dapat mencapai resolusi spasial dan temporal yang tinggi untuk menangkap detail proses seperti arus pesisir, upwelling, dan stratifikasi [9], [10].

Namun, penerapan model numerik juga tidak lepas dari keterbatasan, seperti ketergantungan pada kualitas data input dan asumsi yang digunakan [11], [12], keterbatasan resolusi dan parameterisasi [13], [14], serta kebutuhan akan kurva pembelajaran yang tinggi terkait penguasaan matematika, pemrograman, dan interpretasi hasil [15], [16]. Keterbatasan ini seringkali diperparah oleh kondisi di Indonesia, seperti kurangnya data lapangan jangka panjang dan resolusi tinggi untuk validasi, serta tantangan dalam memodelkan wilayah kepulauan terpencil. Oleh karena itu, pemetaan secara sistematis terhadap perkembangan dan penerapan model numerik di Indonesia menjadi langkah kritis untuk mengidentifikasi

capaian, tantangan, dan peluang pengembangannya di masa depan.

Berdasarkan latar belakang tersebut, penelitian ini bertujuan untuk melakukan tinjauan sistematis (SLR) terhadap perkembangan penggunaan model numerik dalam kajian perairan Indonesia dalam 16 tahun terakhir (2009-2024). Pemetaan ini tidak hanya penting secara akademis untuk melihat tren penelitian, dominasi model, dan sebaran geografisnya [17], [18], [19], tetapi juga crucial untuk memberikan landasan bagi penguatan kebijakan pengelolaan sumber daya laut yang berbasis sains. Hasil review ini diharapkan dapat menunjukkan bagaimana temuan-temuan pemodelan dapat diintegrasikan ke dalam perencanaan tata ruang pesisir, strategi mitigasi bencana, konservasi ekosistem, dan kebijakan eksploitasi sumber daya yang berkelanjutan.

2. MATERI DAN METODE

Metode penelitian yang digunakan adalah review literatur sistematis (*Systematic Literature Review*/SLR). SLR merupakan pendekatan terstruktur, transparan, dan dapat direplikasi untuk mengidentifikasi, mengevaluasi, dan mensintesis semua studi yang relevan dengan pertanyaan penelitian tertentu [20], [21]. Tujuan utama SLR ini adalah untuk mengidentifikasi, menganalisis, dan memetakan secara komprehensif penggunaan model numerik dalam studi perairan Indonesia, dengan fokus pada studi yang penulis pertamanya berafiliasi di Indonesia dan dipublikasikan antara tahun 2009 hingga 2024.

2.1 Identifikasi Pertanyaan Riset (RQ)

Pertanyaan riset (Research Questions/RQ) yang dirumuskan untuk memandu studi ini adalah:

1. Model numerik apa saja yang paling sering digunakan untuk memodelkan fenomena di perairan Indonesia?
2. Bagaimana distribusi spasial (geografis) penelitian yang menggunakan model numerik di berbagai wilayah perairan Indonesia?
3. Bagaimana tren perkembangan penggunaan model numerik dalam studi perairan di Indonesia dari waktu ke waktu.
4. Fenomena oseanografi apa saja yang disimulasikan pada penelitian menggunakan model numerik di perairan Indonesia?

2.2 Pencarian dan Pengumpulan Artikel

Pengumpulan data primer dilakukan dengan menelusuri artikel ilmiah pada database Scopus, yang terindeks secara internasional dan terpercaya. Pencarian dilakukan untuk publikasi antara 2009 hingga 2024 (rentang 16 tahun). Strategi pencarian menggunakan kombinasi kata kunci Boolean (AND/OR) yang dikelompokkan menjadi lima kategori untuk memastikan cakupan yang luas:

1. Kombinasi umum.
   a. ("*numerical model*" OR "simulasi numerik") AND ("perairan indonesia" OR "Indonesian waters")
   b. ("*hydrodynamic model*" OR "*ocean model*") AND (Indonesia OR "Indonesian sea" OR "perairan Indonesia")
   c. ("pemodelan air" OR "*water modeling*") AND (Indonesia) AND (laut OR sungai OR estuari OR teluk)
2. Kombinasi fokus model dan lokasi.
   a. DELFT3D OR ROMS OR "MIKE 21" OR MOHID OR SWAN) AND (Indonesia OR "*Indonesian waters*" OR "perairan Indonesia")
   b. ("*numerical model*" OR "simulasi numerik") AND ("Laut Jawa" OR "Java Sea" OR "Selat Makassar" OR "Makassar Strait" OR "Teluk Jakarta" OR "Jakarta Bay")
   c. ("*oceanographic model*" OR "*physical oceanography model*") AND ("Indonesia") AND ("*current*" OR "*wave*" OR "*tide*")
3. Kombinasi fokus aplikasi atau fenomena.

a. ("kualitas air" OR "*water quality*") AND ("model numerik" OR "*numerical model*") AND (Indonesia)
b. ("*sediment transport*" OR "*transport* sedimen") AND ("*numerical model*" OR "simulasi numerik") AND (Indonesia)
c. ("*storm surge*" OR "banjir rob" OR "tsunami") AND ("*numerical model*" OR "simulasi numerik") AND (Indonesia)
d. ("gelombang" OR "*wave*") AND (SWAN OR ROMS OR "MIKE 21") AND (Indonesia)
4. Kombinasi spesifik.
a. DELFT3D AND ("Teluk Jakarta" OR "*Jakarta Bay*") AND ("kualitas air" OR "*water quality*")
b. ROMS AND ("Selat Sunda" OR "*Sunda Strait*") AND ("arus" OR "*current*")
c. ("MIKE 21" OR "MIKE 3") AND ("Sungai Mahakam" OR "Mahakam River" OR "estuari Indonesia")
d. FVCOM AND (Indonesia) AND (pasang-surut OR "tidal")
5. Kombinasi menggunakan kata kunci lain.
a. ("ocean circulation" OR "sirkulasi laut") AND ("*numerical simulation*") AND (Indonesia)
b. ("*marine pollution*" OR "pencemaran laut") AND ("model" OR "simulasi") AND (Indonesia)
c. ("*coastal dynamics*" OR "dinamika pesisir") AND ("*numerical model*") AND (Indonesia)

Proses pencarian dilakukan pada 29 Juli 2025. Hasil awal pencarian menghasilkan 711 artikel.

2.3 Kriteria Inklusi dan Eksklusi

Artikel yang terkumpul kemudian disaring berdasarkan kriteria inklusi dan eksklusi yang ditetapkan secara ketat (Tabel 1). Kriteria ini menjamin bahwa hanya penelitian yang benar-benar relevan dengan fokus studi yang dianalisis.

Tabel 1 Kriteria Inklusi dan Eksklusi

Kriteria Inklusi	Kriteria Eksklusi
• Terindeks pada database scopus.	• Terbit di luar rentang kriteria inklusi.
• Terbit antara tahun 2009 hingga 2024.	• Fenomena yang disimulasikan tidak terkait dengan oseanografi.
• Lokasi penelitian di Indonesia.	
• Fenomena yang disimulasikan terkait dengan ilmu kelautan atau oseanografi.	• Penulis pertama bukan orang indonesia.
• Penulis pertama orang indonesia.	• Artikel berupa tinjauan (review).

2.4 Seleksi dan Pemilahan Artikel

Proses seleksi dilakukan secara bertahap mengikuti diagram alur PRISMA yang disajikan pada Gambar 1.
1. Identifikasi: Hasil pencarian dari Scopus (n=711) dikumpulkan dan dikelola menggunakan perangkat lunak manajemen referensi Zotero.
2. Deduplikasi: Artikel duplikat yang dihasilkan dari kombinasi kata kunci yang berbeda dihilangkan secara otomatis dan manual, menghasilkan 614 artikel unik.
3. Screening: Ke-614 artikel tersebut kemudian disaring berdasarkan judul dan abstrak.
4. Included: Sebanyak 206 artikel dinyatakan memenuhi syarat dan digunakan untuk analisis lebih lanjut.
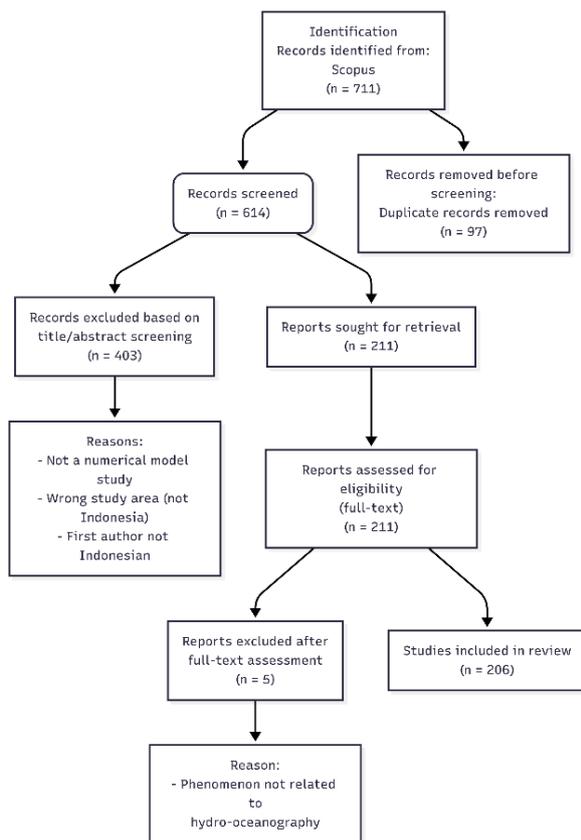
Gambar 1: Diagram Alur PRISMA

2.5 Ekstraksi dan Analisis Data

Data dari 206 artikel yang terpilih kemudian diekstraksi ke dalam lembar spreadsheets Excel untuk dianalisis. Meta-data yang diekstraksi untuk setiap artikel meliputi:

- Judul artikel
- Tahun publikasi
- Model numerik yang digunakan (jika lebih dari satu, semua dicatat)
- Lokasi penelitian (koordinat atau nama wilayah)
- Fenomena utama yang disimulasikan

Analisis data dilakukan secara kuantitatif dan kualitatif:

- Analisis Kuantitatif: Menghitung frekuensi dan tren penggunaan model, sebaran geografis penelitian, dan fenomena yang disimulasikan. Hasilnya divisualisasikan dalam bentuk grafik dan peta heatmap.
- Analisis Kualitatif: Mensintesis temuan dari artikel-artikel terpilih untuk

membahas pola, tantangan, dan implikasi dari penggunaan model numerik di Indonesia, yang akan disajikan dalam bagian hasil dan pembahasan.

3. HASIL DAN PEMBAHASAN
3.1 Tahun Publikasi

Berdasarkan tahun publikasi akan dilihat tren dan fokus utama penelitian secara garis besar berdasarkan periode 4 tahunan.

Tabel 2 Periode Publikasi

Tahun	Jumlah Studi
2009-2012	**16**
Sitasi	
[22], [23], [24], [25], [26], [27], [28], [29], [30], [31], [32], [33], [34], [35], [36], [37]	
2013-2016	**18**
Sitasi	
[38], [39], [40], [41], [42], [43], [44], [45], [46], [47], [48], [49], [50], [51], [52], [53], [54], [55]	
2017-2020	**66**
Sitasi	
[56], [57], [58], [59], [60], [61], [62], [63], [64], [65], [66], [67], [68], [69], [70], [71], [72], [73], [74], [75], [76], [77], [78], [79], [80], [81], [82], [83], [84], [85], [86], [87], [88], [89], [90], [91], [92], [93], [94], [95], [96], [97], [98], [99], [100], [101], [102], [103], [104], [105], [106], [107], [108], [109], [110], [111], [112], [113], [114], [115], [116], [117], [118], [119], [120], [121]	
2021-2024	**106**
Sitasi	
[122], [123], [124], [125], [126], [127], [128], [129], [130], [131], [132], [133], [134], [135], [136], [137], [138], [139], [140], [141], [142], [143], [144], [145], [146], [147], [148], [149], [150], [151], [152], [153], [154], [155], [156], [157], [158], [159], [160], [161], [162], [163], [164], [165], [166], [167], [168], [169], [170], [171], [172], [173], [174], [175], [176], [177], [178], [179], [180], [181], [182], [183], [184], [185], [186], [187], [188], [189], [190], [191], [192], [193],	

[194], [195], [196], [197], [198], [199], [200], [201], [202], [203], [204], [205], [206], [207], [208], [209], [210], [211], [212], [213], [214], [215], [216], [217], [218], [219], [220], [221], [222], [223], [224], [225], [226], [227]

Berdasarkan tabel 2 penelitian menggunakan model numerik dapat dijabarkan sebagai berikut :

- Fase awal (2009-2012) 16 studi, dengan rata-rata 4 publikasi/tahun dan model didominasi oleh TUNAMI atau Shallow Water Equation. Studi berfokus kepada tsunami pasca 2004 dan sirkulasi dasar.

- Fase konsolidasi (2013-2016) 18 studi, dengan rata-rata 4,5 publikasi/tahun dan model didominasi oleh HAMSOM, FVCOM, dan COMCOT. Studi diversifikasi topik seperti sedimen dan polusi.

- Fase pertumbuhan (2017-2020) 66 studi, dengan rata-rata 16,2 publikasi/tahun dan model didominasi oleh Delft3D dan MIKE21. Fokus studi terhadap gelombang, sirkulasi dan early warning.

- Fase matang (2021-2024) 106 studi, 26,5 publikasi/tahun dengan dominasi model Delft3D, MIKE21, dan HYCOM. Terdapat studi rekeyasa mitigasi seperti *breakwater* dan *sea walls*.
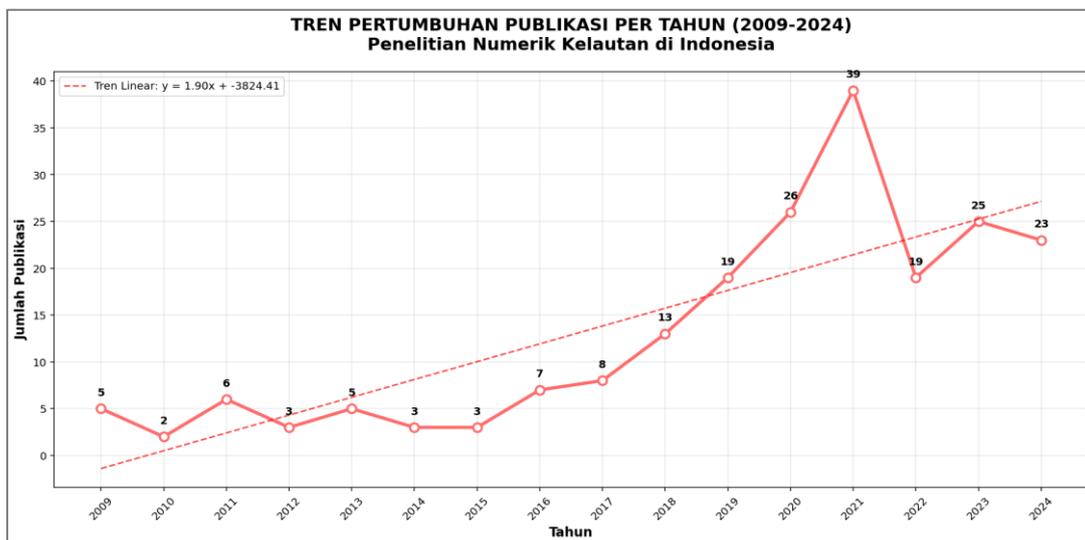

Gambar 2 Tren publikasi per tahun

Dari Gambar 2, terlihat bahwa pertumbuhan publikasi penelitian pemodelan numerik kelautan di Indonesia selama periode 2009–2024 menunjukkan tren positif yang signifikan. Jumlah publikasi mengalami peningkatan hampir delapan kali lipat, dari hanya 5 publikasi pada tahun 2009 menjadi 39 publikasi pada tahun 2021. Lonjakan pesat terjadi terutama pasca-2017, yang tidak hanya mencerminkan peningkatan kapasitas pemodelan peneliti Indonesia, tetapi juga merupakan respons terhadap meningkatnya frekuensi dan intensitas bencana hidrometeorologi serta tekanan pembangunan pesisir. Meskipun sempat mengalami penurunan pada tahun 2022, jumlah publikasi kembali stabil pada level tinggi di tahun 2023–2024. Kestabilan ini mengindikasikan bahwa bidang pemodelan numerik kelautan di Indonesia telah matang dan terus menjadi fokus penting dalam penelitian kelautan Indonesia. Tren ini selaras dengan urgensi nasional untuk mengembangkan sistem peringatan dini yang akurat dan perencanaan tata ruang pesisir yang berbasis risiko, sekaligus mencerminkan komitmen nasional dalam menjawab tantangan kelautan melalui pendekatan sains berbasis komputasi, sebagaimana diamanatkan dalam Rencana Induk Riset Nasional dan agenda pembangunan berkelanjutan.

3.2 Model yang Digunakan

Selain tren temporal, analisis juga dilakukan terhadap distribusi model numerik yang digunakan. Dari 206 artikel yang ditinjau, terdapat beberapa penelitian yang menggunakan lebih dari satu model. Untuk memberikan gambaran yang komprehensif tentang preferensi pemodelan, setiap penggunaan model dihitung secara independen. Dengan pendekatan ini, total data yang dianalisis menjadi 253 penggunaan model. Distribusi lengkapnya disajikan pada Gambar 3.
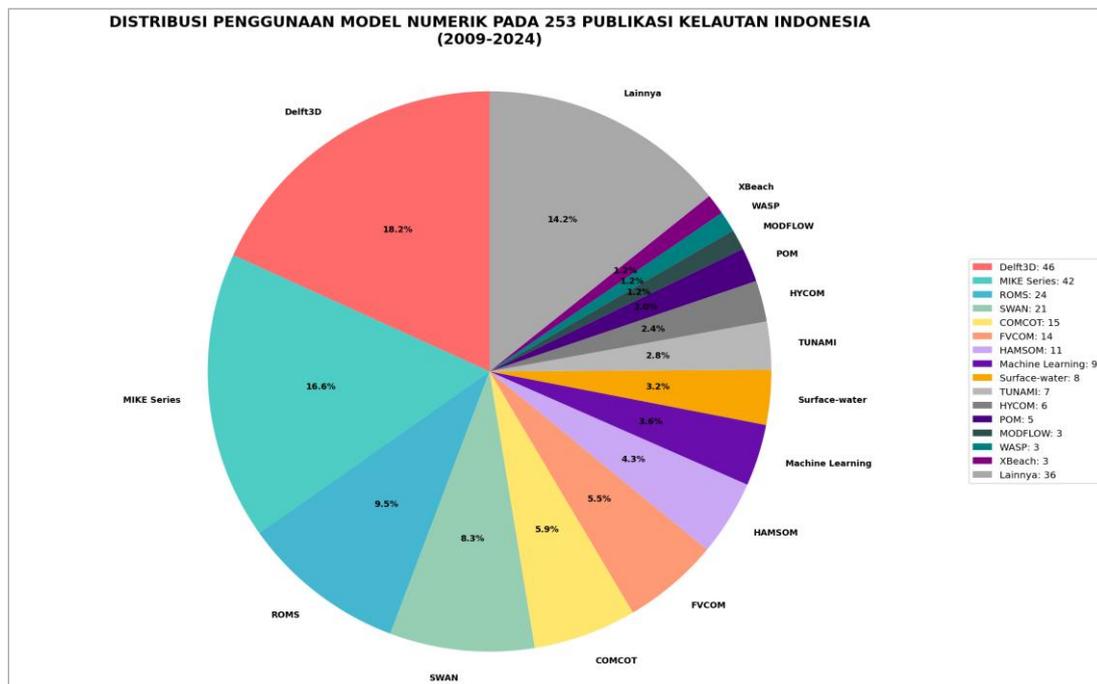
Gambar 3 Distribusi model

Berdasarkan Gambar 3, terlihat bahwa Delft3D (18,2%) [124], [125], [162],... dan MIKE Series (16,6%) [135], [139], [142],... mendominasi lanskap pemodelan. Dominasi ini mengindikasikan preferensi kuat para peneliti Indonesia terhadap platform komersial yang telah teruji, memiliki dukungan teknis yang komprehensif, dan antarmuka pengguna (Graphical User Interface/GUI) yang memudahkan, sehingga dapat mengatasi kendala kurva pembelajaran yang tinggi.

Di sisi lain, penggunaan signifikan dari model open-source seperti ROMS (9,5%) [56], [134], [195],... dan FVCOM (5,5%) [112], [127], [200],... mencerminkan kebutuhan untuk menangani kompleksitas dinamika perairan kepulauan Indonesia yang memerlukan model sirkulasi yang lebih fleksibel dan dapat dimodifikasi. Yang menarik, mulai bermunculannya adopsi model machine learning (3,6%) [79], [153], [156],... menunjukkan tren integrasi teknik komputasi modern dengan pendekatan hidrodinamika konvensional. Sementara itu, keragaman model dalam kategori "Lainnya" (14,2%) [113], [130], [146],... merepresentasikan diversifikasi metodologi yang adaptif, termasuk model-model khusus untuk simulasi tsunami, transport sedimen, dan kualitas air.

Dominasi model komersial, meskipun memberikan kemudahan, menyoroti tantangan keberlanjutan jangka panjang, terutama terkait biaya lisensi dan ketergantungan pada vendor luar. Oleh karena itu, penguatan kapasitas pemodelan open-source menjadi solusi strategis yang tidak hanya menjamin kemandirian dan keberlanjutan penelitian di masa depan, tetapi juga mendukung prinsip keterbukaan sains (open science). Secara keseluruhan, distribusi

ini tidak hanya mencerminkan evolusi kapasitas pemodelan nasional, tetapi juga mengonfirmasi bahwa masalah kelautan Indonesia yang semakin kompleks ditangani melalui pendekatan multi-model dan interdisipliner.

3.3 Lokasi Penelitian

Hasil tinjauan literatur sistematis (SLR) mengungkapkan pola sebaran geografis penelitian pemodelan numerik yang tidak merata di perairan Indonesia. Dari total 206 artikel yang dianalisis, teridentifikasi 127 lokasi unik yang menjadi subjek studi, dengan konsentrasi penelitian tertinggi berada di wilayah Indonesia Barat.

Analisis frekuensi lokasi menunjukkan lima wilayah dengan produktivitas penelitian tertinggi:

- Teluk Jakarta (10 studi): Dominasi penelitian di wilayah ini didorong oleh tingginya aktivitas antropogenik dan tekanan lingkungan, menjadikannya studi kasus ideal untuk pemodelan kualitas air, sirkulasi, dan pencemaran [58], [134], [159],...
- Selat Makassar (6 studi): Sebagai jalur utama Arus Lintas Indonesia, wilayah ini menjadi fokus penelitian sirkulasi laut dan dinamika oseanografi [67], [131], [148],...
- Teluk Balikpapan (5 studi): Signifikansi penelitian di teluk ini mencerminkan pentingnya memahami dinamika perairan di kawasan industri dan pelabuhan [56], [157], [195],...
- Banda Aceh (5 studi): Fokus penelitian pada mitigasi bencana tsunami dan dinamika pesisir pasca tsunami 2004 [26], [29], [61],...
- Pangandaran (4 studi): Minat penelitian terkait dengan dinamika pesisir dan pengaruhnya terhadap sektor pariwisata dan konservasi [22], [126], [152],...

Wilayah penelitian lainnya yang signifikan meliputi perairan umum Indonesia, Laut Jawa, Selat Sunda, dan Selat Lombok [48], [66], [127], [193]. Beberapa penelitian berskala besar mencakup studi tentang Arus Lintas Indonesia (ITF) [202] dan wilayah pengelolaan perikanan (WPP) [130], sementara penelitian lain berfokus pada area spesifik seperti Cilacap dan Palu [141], [181].

Sebaran geografis penelitian yang tidak merata ini, seperti yang tervisualisasi dengan jelas pada Gambar 4, mencerminkan beberapa tantangan mendalam:

- Bias infrastruktur penelitian: Konsentrasi studi di Jawa-Bali, yang tampak jelas pada heatmap, merefleksikan ketimpangan infrastruktur penelitian dan kemudahan akses data.
- Kesenjangan kapasitas: Wilayah Indonesia Timur (Maluku, Papua, Laut Banda) yang secara oseanografi sangat kompleks justru menjadi "blank spot" dalam peta penelitian
- Implikasi kebijakan: Kesenjangan penelitian berpotensi menciptakan blind spot dalam pengambilan kebijakan pengelolaan wilayah laut Indonesia Timur

Rekomendasi untuk mengatasi kesenjangan ini meliputi:

- Pengembangan kolaborasi penelitian nasional-internasional untuk wilayah terpencil
- Pemanfaatan data satelit dan penginderaan jauh untuk mengatasi keterbatasan data lapangan
- Pengembangan model nested dengan downscaling dari model global

Ketimpangan distribusi lokasi penelitian ini menunjukkan adanya kebutuhan mendesak untuk melakukan pemerataan riset pemodelan ke wilayah Indonesia Timur, seperti Maluku, Papua, dan Laut Banda yang saat ini masih menjadi blank spot. Secara oseanografi, wilayah Indonesia Timur memiliki kompleksitas yang sangat tinggi, namun keterbatasan infrastruktur dan akses data lapangan seringkali menjadi hambatan utama bagi para peneliti. Tanpa adanya basis data pemodelan yang kuat di wilayah ini, kebijakan pengelolaan laut dan mitigasi bencana di Indonesia Timur berisiko tidak didukung oleh bukti saintifik yang memadai (blind spot kebijakan). Oleh karena itu, diperlukan strategi nasional yang mendorong

kolaborasi riset dan penguatan infrastruktur komputasi di wilayah timur guna memastikan keberlanjutan pengelolaan sumber daya laut di seluruh pelosok tanah air secara berimbang.

Temuan ini menyoroti perlunya strategi nasional yang lebih berimbang dalam pendistribusian sumber daya penelitian untuk mendukung pengelolaan sumber daya laut yang berkelanjutan di seluruh wilayah Indonesia.
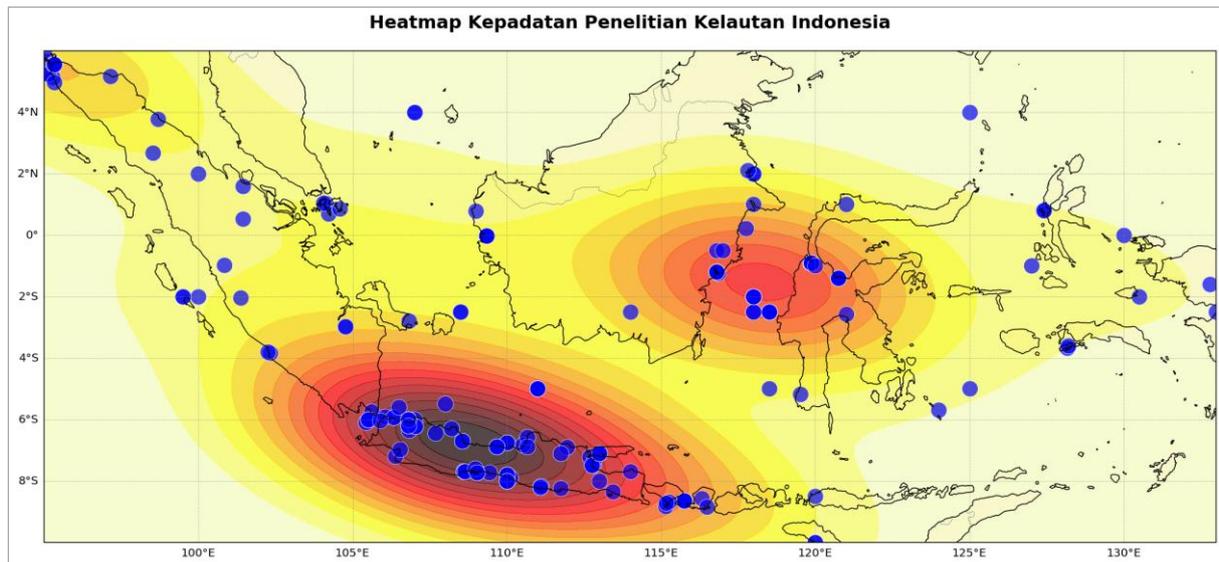

Gambar 4 *Heatmap* lokasi penelitian.

3.4 Fenomena yang Disimulasikan

Berdasarkan analisis terhadap 206 artikel penelitian pemodelan numerik di perairan Indonesia, fenomena yang disimulasikan dapat dikelompokkan ke dalam sepuluh kategori utama seperti terlihat pada Gambar 5.

Kategorisasi ini tidak hanya merefleksikan fokus dan tren penelitian, tetapi juga mengungkap prioritas dan kesenjangan dalam upaya memahami dinamika kelautan Indonesia melalui pendekatan komputasional.
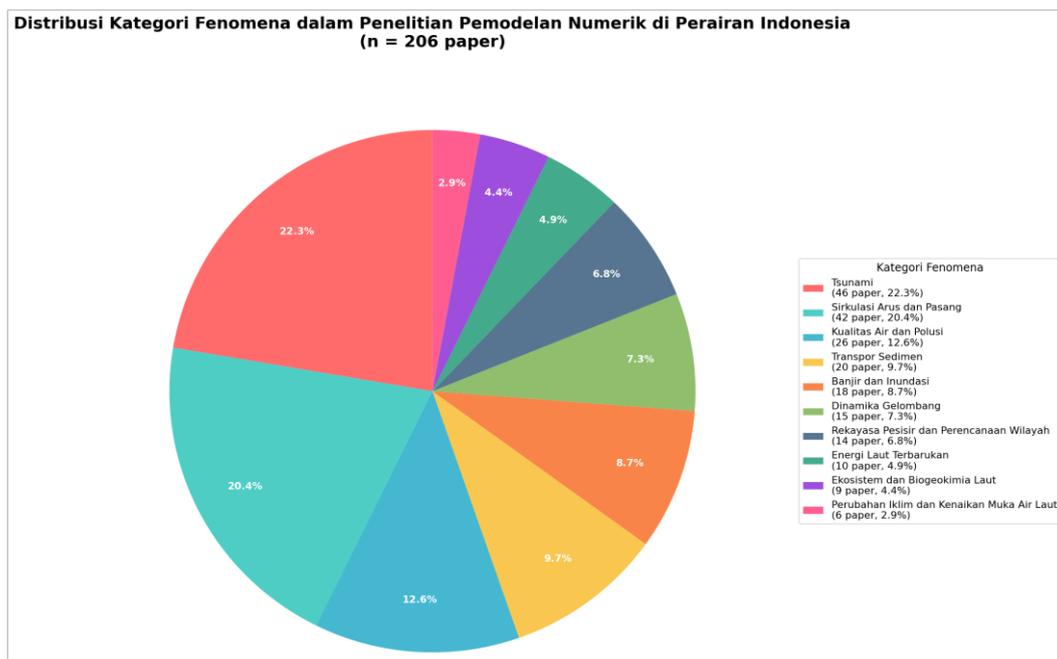
Gambar 5 Distribusi fenomena simulasi

Distribusi fenomena yang disimulasikan menunjukkan pola yang signifikan: Pemodelan tsunami mendominasi dengan 46 artikel (22,3%), diikuti oleh sirkulasi laut dan arus (42 artikel, 20,4%), serta kualitas air dan polusi (26 artikel, 12,6%). Kategori lainnya meliputi gelombang dan energi laut (25 artikel, 12,1%), transport sedimen (20 artikel, 9,7%), banjir dan inundasi pesisir (18 artikel, 8,7%), infrastruktur pantai (14 artikel, 6,8%), ekosistem dan lingkungan (9 artikel, 4,4%), perubahan iklim (6 artikel, 2,9%), dan kategori lain-lain.

Pola distribusi ini mencerminkan beberapa insight penting: Dominasi penelitian tsunami secara jelas menunjukkan respons terhadap kerentanan Indonesia sebagai negara kepulauan yang terletak di Ring of Fire, dengan fokus pada mitigasi bencana dan penyelamatan jiwa. Tingginya minat pada sirkulasi laut dan arus mengindikasikan pentingnya memahami dinamika fisik dasar untuk aplikasi praktis seperti navigasi dan keselamatan pelayaran.

Namun, terlihat ketidakseimbangan yang mencolok antara fokus pada bencana dengan penelitian untuk pembangunan berkelanjutan. Jumlah artikel tentang perubahan iklim (6) dan ekosistem (9) yang sangat rendah merupakan kesenjangan yang mengkhawatirkan, mengingat kedua aspek ini merupakan inti dari komitmen Indonesia dalam Perjanjian Paris dan agenda pembangunan berkelanjutan.

Temuan ini memberikan arahan strategis bagi pengembangan penelitian ke depan:
1. Perlunya peningkatan signifikan dalam penelitian pemodelan untuk perubahan iklim dan ekosistem
2. Pentingnya integrasi pendekatan multi-fenomena dalam satu framework pemodelan
3. Perlunya kolaborasi interdisipliner untuk menjembatani kesenjangan antara ilmu dasar dan aplikasi kebijakan

Distribusi penelitian ini pada akhirnya mencerminkan tantangan ganda yang dihadapi Indonesia - antara kebutuhan mendesak untuk mitigasi bencana dan tuntutan jangka panjang untuk pembangunan berkelanjutan, dimana pemodelan numerik berperan sebagai jembatan penghubung yang krusial antara sains dan kebijakan.

4. Kesimpulan

Berdasarkan tinjauan sistematis terhadap 206 artikel penelitian yang memenuhi kriteria inklusi, dapat disimpulkan bahwa pemodelan numerik telah berkembang pesat dan menjadi pilar fundamental dalam ilmu kelautan terapan di Indonesia. Studi ini berhasil memetakan lanskap penelitian pemodelan numerik di perairan Indonesia selama periode 2009–2024, mengungkap beberapa temuan kunci.

Pertama, terjadi peningkatan signifikan dalam jumlah publikasi, didominasi oleh model software komersial seperti Delft3D dan MIKE Series yang dipilih karena kemudahan antarmuka dan dukungan teknisnya, diikuti oleh model open-source seperti ROMS dan FVCOM.

Kedua, sebaran penelitian secara geografis sangat tidak merata, dengan konsentrasi tinggi di kawasan Barat Indonesia (seperti Teluk Jakarta dan Selat Makassar) yang merefleksikan bias ketersediaan data dan infrastruktur, sementara kawasan Timur masih menjadi blank spot yang kritis.

Ketiga, dari segi fenomena, fokus penelitian masih sangat didominasi oleh pemodelan tsunami dan sirkulasi arus laut, yang menunjukkan respons terhadap kebutuhan mendesak dalam mitigasi bencana dan keselamatan pelayaran. Namun, fenomena seperti dampak perubahan iklim dan kesehatan ekosistem masih relatif kurang mendapat perhatian, padahal keduanya merupakan isu strategis nasional.

Keberhasilan penerapan pemodelan numerik ini masih terkendala oleh beberapa tantangan mendasar, yaitu (1) keterbatasan data observasi jangka panjang dan resolusi tinggi untuk validasi model, terutama di wilayah terpencil; (2) kesenjangan kapasitas dan infrastruktur komputasi di luar pusat-

pusat penelitian utama; serta (3) kesenjangan antara hasil penelitian dengan implementasi kebijakan.

Untuk mengatasi tantangan ini, dirumuskan beberapa solusi strategis:

- Penguatan Data dan Kolaborasi: Membangun jaringan observasi laut nasional yang terintegrasi dan berbagi data secara terbuka (open data), serta memanfaatkan teknologi remote sensing dan citizen science.
- Peningkatan Kapasitas: Menyelenggarakan pelatihan pemodelan yang berjenjang dan menyediakan akses ke infrastruktur komputasi awan (cloud computing) untuk peneliti di seluruh Indonesia.
- Translasi Pengetahuan ke Kebijakan: Peneliti perlu didorong untuk tidak hanya mempublikasikan di jurnal ilmiah, tetapi juga menghasilkan policy brief dan rekomendasi teknis yang dapat diadopsi oleh pemangku kepentingan di Kementerian Kelautan dan Perikanan (KKP), BAPPENAS, BMKG, dan pemerintah daerah.

Pada akhirnya, pemodelan numerik harus bertransisi dari sekadar alat akademik menjadi instrument operasional yang mendukung pengelolaan sumber daya laut yang berkelanjutan dan berbasis sains (evidence-based policy). Hasil pemodelan harus diintegrasikan ke dalam perencanaan tata ruang pesisir, sistem peringatan dini bencana, strategi konservasi, dan kebijakan ekonomi biru. Dengan demikian, penelitian ini tidak hanya memetakan keadaan yang ada, tetapi juga memberikan peta jalan untuk masa depan, di mana pemodelan numerik berperan aktif dalam membangun ketahanan maritime Indonesia menghadapi perubahan iklim dan tekanan pembangunan.

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