Mangrove land cover and coastline changes in Indramayu Regency in 1991 – 2021

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Abstract. The Indramayu Regency, located on the northern coast of West Java, has experienced mangrove loss and dynamic shoreline changes, largely due to the conversion of mangrove areas into aquaculture ponds. This study quantifies the changes in mangrove cover and shoreline position from 1991 to 2021 and assesses their relationship. Landsat imagery for 1991, 2001, 2011, and 2021 was classified in Google Earth Engine using a Random Forest algorithm, whereas shoreline change rates were derived in ArcGIS with the Digital Shoreline Analysis System (DSAS). Total mangrove extent declined from 1,443.74 to 833.07 ha between 1991 and 2001 (−610.67 ha) with an average shoreline retreat of −15.98 m/year. From 2001 to 2011, mangroves increased slightly to 844.24 ha (+11.17 ha) as the shoreline advanced at 13.69 m/year, and from 2011 to 2021, mangrove cover expanded to 1,521.27 ha (+677.03 ha), while the mean shoreline change reverted to retreat at −1.49 m/year. Linearity tests and the low coefficient of determination ($R^2 = 0.191$) indicated that there was no significant linear relationship between mangrove change and shoreline dynamics, suggesting that effective erosion mitigation requires an integrated coastal management approach that combines mangrove rehabilitation, coastal protection, and sediment management.

Keywords: Coastline, DSAS, Indramayu, Landsat, mangrove, remote sensing

1 Introduction

Mangroves are vital coastal ecosystems with significant ecological, economic, and social functions. They provide breeding grounds, feeding areas, and nurseries for finfish, shellfish,

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and crustaceans, and support commercial and subsistence fisheries [1]. In Indonesia, mangrove conservation is increasingly mainstreamed through restoration and coastal management agendas [3,24]. However, sustaining mangrove conservation remains challenging, as noted in global assessments [2]. Global assessments also report substantial mangrove loss over recent decades, with strong pressures in Southeast Asia, where conversion to aquaculture and agriculture remains a dominant driver [2,3,25].

The presence of mangroves along the coastline influences the physical and biological conditions of the coast. Extensive land-use changes and the degradation of mangrove forests can increase coastal vulnerability through the loss of natural protective barriers [4,26]. Such changes are often reflected in shoreline dynamics characterized by erosion (abrasion) and sediment accumulation (accretion) [5]. These processes can negatively affect communities and infrastructure, but they also reshape coastal landforms and habitats; for example, accretion may create new intertidal substrates that can be colonized by mangroves when conditions are suitable [6]. When intact and sufficiently dense, mangrove stands can contribute to shoreline protection by damping wave energy and stabilizing sediments [6].

In the Indramayu region, coastal mangrove ecosystems have experienced a significant decline, characterized by high rates of erosion and land conversion [8-11]. Local assessments indicate that mangrove degradation in Indramayu is substantial; approximately 50% of the 17,792 ha of mangrove forests have been classified as severely damaged [12,13]. This degradation has been associated with accelerated shoreline retreat, with reported erosion rates on the order of 9–10 m/year in affected stretches [5,12]. The primary causes include conversion to aquaculture ponds, settlements, and agricultural land, often undertaken without adequate rehabilitation [12]. Since 1962, aquaculture expansion has been a major factor in reducing mangrove coverage, leading to profound ecological changes in coastal environments [12].

The overexploitation of coastal areas without sustainable management can exacerbate environmental degradation. The ongoing reduction in the extent of mangroves influences shoreline dynamics, with shoreline changes manifesting as either erosion or sedimentation. These processes have both negative and positive implications for local communities; erosion threatens infrastructure and livelihoods, whereas sedimentation can lead to the silting of estuaries and land disputes. Natural sedimentation processes driven by river-mouth dynamics can increase land area, but human activities such as dam construction and urbanization can disrupt sediment supply and intensify coastal vulnerability [21,22]. Therefore, understanding the relationship between mangrove cover change and shoreline dynamics is crucial for developing effective coastal management strategies.

2 Materials and methods

2.1 Study area

The Indramayu Regency is situated along the northern coast of Java Island and comprises 11 sub-districts. The region features low-lying coastal plains with elevations ranging from sea level to 100 m, making it susceptible to coastal hazards, including tidal inundation, storm surges, and shoreline erosion [13]. The climate follows the Schmidt-Ferguson Type D classification, characterized by humidity levels between 70% and 80%, with temperature variations from 22.9°C to 30.0°C, influenced by proximity to the sea [14]. For a detailed analysis, the focus was placed on coastal zones directly bordering the ocean, divided into 35 grid cells, each measuring 4 km × 4 km.

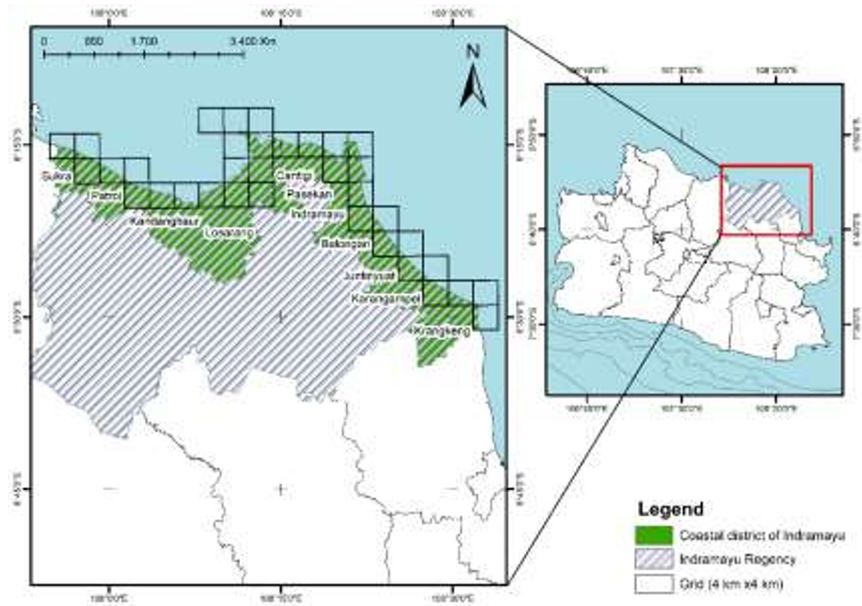

Fig. 1. Map of the study area.

2.2 Data processing

Changes in mangrove cover were analyzed using multitemporal Landsat imagery from 1991, 2001, 2011, and 2021 (Landsat 5 TM, Landsat 7 ETM+, and Landsat 8 OLI). Level-2 Surface Reflectance (SR) products provided by the USGS were used, which were atmospherically and geometrically corrected. To ensure that all images were comparable for multitemporal analysis, we applied a common preprocessing workflow in Google Earth Engine [27], which was clipped to the study area, reprojected to a uniform UTM coordinate system, and filtered using quality assurance bands to mask clouds, cloud shadows, and saturated pixels. Land cover classification was performed in the Google Earth Engine using a supervised Random Forest classifier. Training samples for mangrove and non-mangrove classes were derived from a combination of visual interpretation of Landsat composites, very-high-resolution basemaps, and existing ancillary maps/field information for the most recent year. Polygons representing homogeneous areas of each class were digitized across the study area and converted to point samples. The full set of reference samples was randomly split into 80% for training and 20% for independent validation to ensure that all classes were adequately represented in both subsets. This sampling and partitioning strategy was used to improve the classifier's generalization ability and provide an unbiased estimate of the classification accuracy. The classified data were then downloaded and analyzed using ArcGIS. The analysis involved overlaying classified images from different years to quantify changes in mangrove extent and calculating the area of loss or gain in hectares.

Coastline data were obtained from multitemporal Landsat Level-2 Surface Reflectance imagery (Landsat 5 TM, Landsat 7 ETM+, and Landsat 8 OLI) for 1991, 2001, 2011, and 2021. For each year, cloud and cloud-shadow pixels were masked using the QA band, and the scenes were cropped to the study area. To delineate the shoreline, we first enhanced the contrast between land and water by computing a band-ratio water index (green/SWIR), and then converted the result to a binary land–water mask using an empirically determined threshold. The land–water boundary was subsequently converted from raster to vector, and the resulting polylines were visually checked and edited to remove artifacts and ensure a continuous shoreline each year.

Shoreline change analysis was conducted using the Digital Shoreline Analysis System (DSAS) in ArcGIS. DSAS generates shore-normal transects and measures the intersection of these transects with shorelines in different years [15,28]. The rate of shoreline change was calculated using the end-point rate (EPR) method, expressed in meters per year, and Net Shoreline Movement (NSM), expressed in meters. The EPR provides a straightforward estimate of shoreline change, assuming linear movement over the observation period [16].

The correlation between the mangrove cover change and shoreline dynamics was assessed using Pearson's correlation analysis. Prior to this, linearity tests were performed to verify the appropriateness of the correlation analysis, with significance levels set at 0.05. The linearity test involves calculating the F-value and comparing it with the F-table value. Data analysis was conducted using the SPSS software.

3 Results and discussion

3.1 Mangrove area changes from 1991 to 2021

Analysis of Landsat imagery from 1991, 2001, 2011, and 2021 revealed that mangroves were distributed across five of the 11 coastal subdistricts in Indramayu. The total mangrove area decreased from 1,443.74 hectares in 1991 to 833.07 hectares in 2001, representing a significant reduction primarily due to deforestation and land conversion for aquaculture, especially in Cantigi and Pasekan subdistricts. The loss of approximately 610.67 hectares over this period reflects the impact of unregulated land use changes, with the expansion of shrimp ponds being a major factor [12]. Since 1962, aquaculture has been a primary driver of mangrove loss, leading to an ecological imbalance.

Between 2001 and 2011, a slight recovery was observed, with mangrove coverage increasing marginally from 833.07 to 844.24 hectares, indicating initial rehabilitation efforts [17]. From 2011 to 2021, a substantial increase of 677.03 hectares was recorded, attributed to government and community-led restoration initiatives, including innovative planting techniques and collaborative management, which have contributed to ecosystem sustainability [18]. Local government and environmental reports also highlight Indramayu role as a focal area for mangrove development programs in western Indonesia [13].

Table 1. The extent of mangrove coverage across districts in Indramayu Regency for the years 1991, 2001, 2011, and 2021.

Regency	Mangrove area (ha)			
	1991	2001	2011	2021
Kandanghaur	7.29	1.73	2.21	1.13
Losarang	172.89	113.46	114.42	161.13
Cantigi	1,116.13	674.61	706.78	1,065.21
Pasekan	139.21	42.63	19.71	286.37
Indramayu	8.22	0.64	1.11	7.43
Total	**1,443.74**	**833.07**	**844.24**	**1,521.27**

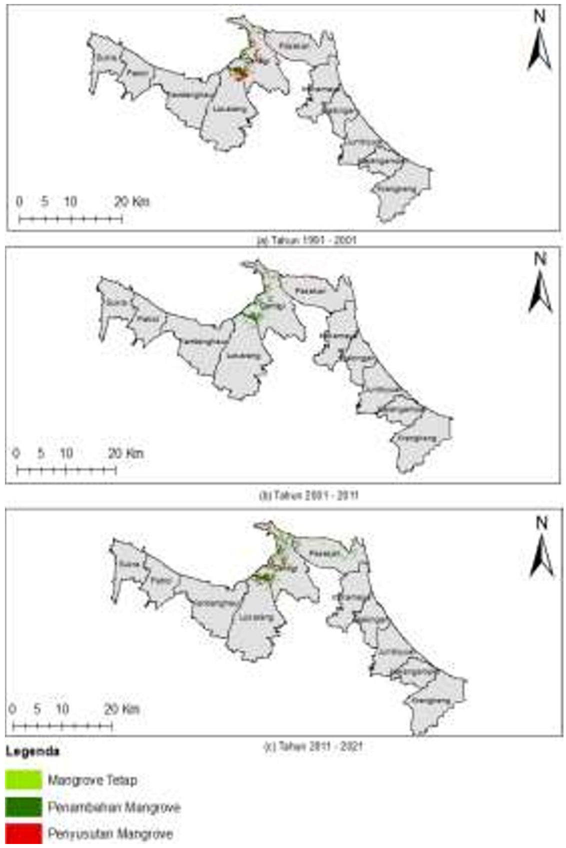

Fig. 2. Mangrove land cover change 1991 – 2021.

3.2 Coastline changes from 1991 to 2021

The coastline changes observed in Indramayu Regency over a thirty-year period (1991–2021) are illustrated in the accompanying figure. The black lines represent the coastline as it was in the earliest year, whereas the blue lines depict the most recent shoreline. The analysis of shoreline change rates between 1991 and 2021 is presented through the average annual distance (in meters per year) of the transects within each grid. The rates of erosion and accretion along the coast during this period are classified into eight categories: severe erosion (<-10 m/year), high erosion (-9.99 to -5 m/year), moderate erosion (-4.99 to -2 m/year), light erosion (-1.99 to 0 m/year), light accretion (0–2 m/year), moderate accretion (2-5 m/year), high accretion (5-10 m/year), and very high accretion (>10 m/year) [19]. To facilitate the analysis, the entire period was divided into three ten-year segments, allowing for a more detailed examination of shoreline dynamics over time.

Between 1991 and 2001, coastal erosion affected almost all districts bordering the Indramayu coastline, including Sukra, Patrol, Kandanghaur, Cantigi, Pasekan, Indramayu, Balongan, Juntinyuat, Karangampel and Krangkeng. Several grids in Cantigi and Pasekan experienced very high retreat rates, with shoreline recession exceeding 700 m and reaching more than 1,100 m in one grid in Pasekan (H1) (**Table 2**). Accretion was limited to a few locations in Kandanghaur, Cantigi, Pasekan, and Krangkeng, where the shoreline advance locally reached approximately 200 m/year, such as in grid G3 in Pasekan. Overall, this decade was dominated by erosion, with a mean shoreline retreat of approximately −15.98 m/year along the Indramayu coast.

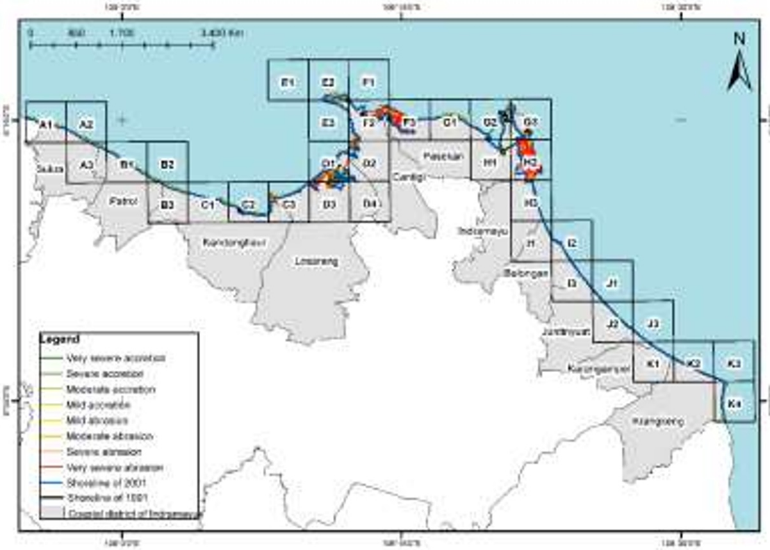

Fig. 3. Shoreline change 1991 – 2001.

From 2001 to 2011, the spatial pattern of shoreline change remained broadly similar to that of the previous decade, with persistent erosion along the coasts of Sukra, Patrol, Kandanghaur, Cantigi, Pasekan, Juntinyuat, Karangampel and Krangkeng. Erosion rates were generally lower than those during 1991–2001, but still reached approximately −335 m/year in parts of Cantigi (e.g., grid D2). In contrast, pronounced accretion developed in several grids in Cantigi and Pasekan, where the shoreline advance exceeded 1,500 m over the decade, particularly in grid E1 in Cantigi (**Table 2**). On average, shoreline change during this period was characterised by net accretion of approximately 13.69 m/year along the coastline.

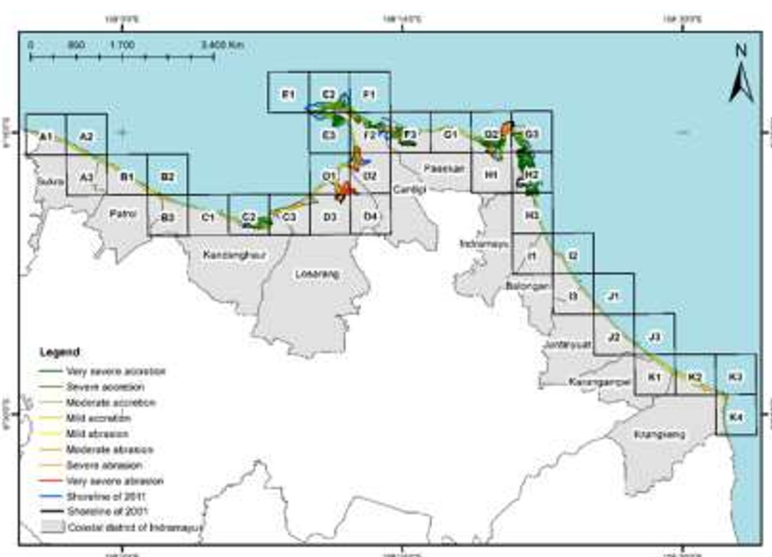

Fig. 4. Shoreline change 2001 – 2011.

The erosion observed from 2011 to 2021 showed a decreasing trend compared with earlier decades. Erosional sectors remain in Sukra, Patrol, Kandanghaur, Cantigi, Pasekan, and Karangampel, but retreat rates are generally below −200 m/year, with the highest values (around −193 m/year) occurring in Kandanghaur (grid C2). Simultaneously, accretion becomes more prominent in several grids in Cantigi, Balongan, Juntinyuat, and Krangkeng, where EPR locally exceeded 190 m/year, such as in grid E1 in Cantigi (**Table 2**). Based on this analysis, the 2011–2021 period still indicates overall erosion along the coast, but with a reduced mean retreat rate of approximately −1.49 m/year.

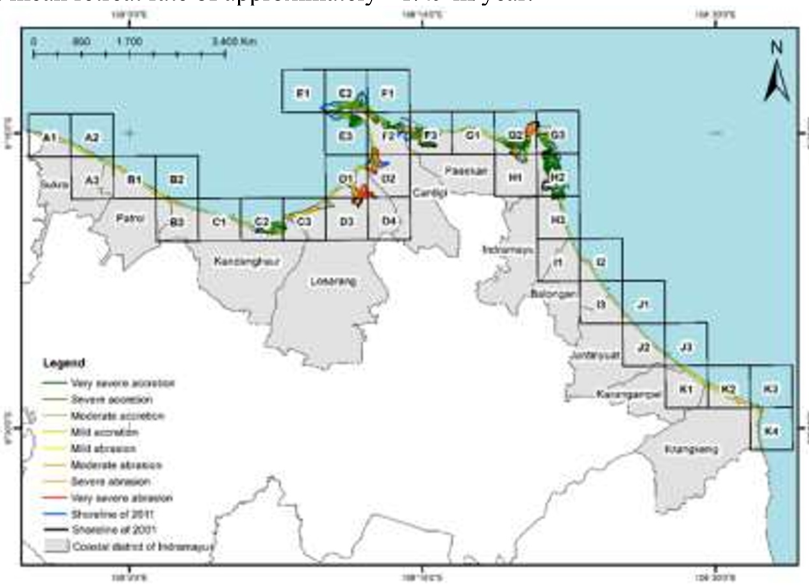

Fig. 5. Shoreline change 2011 – 2021.

The primary cause of the expansion of coastal areas in this region is believed to be the sedimentation processes. The rate of sedimentation along the coast depends on the number of river estuaries in the area [20]. Human activities such as dam construction and urbanization can disrupt sediment supply and intensify shoreline change [21,22]. Regions with very high vulnerability were observed in several districts, including Sukra, Patrol, Kandanghaur, Cantigi, Pasekan, Juntinyuat, Karangampel, and Krangkeng.

Based on the grid-averaged shoreline change rates for 1991–2021 (**Table 2**), most cells along the Indramayu coast experienced long-term erosion, while only a smaller proportion showed persistent accretion. The mean shoreline change over the 30-year period is approximately −2.2 m/year, indicating that, at the regional scale, the northern coastal zone of Indramayu Regency is predominantly erosional rather than accretional.

Table 2. Shoreline change rate in Indramayu Regency from 1991 to 2021.

Grid	Shoreline change (m)				
	1991 - 2001	2001 – 2011	2011 - 2021	The average (m/year)	District
A1	-119.40	-86.17	-72.47	-9.87	Sukra
A2	-127.07	-127.24	-42.16	-9.14	Sukra
A3	-126.62	-94.59	-16.74	-8.03	Sukra
B1	-98.31	-111.51	-59.27	-9.05	Patrol
B2	-145.84	-167.22	-6.00	-11.26	Patrol

Grid	Shoreline change (m)				
	1991 - 2001	2001 – 2011	2011 - 2021	The average (m/year)	District
B3	-134.38	-67.18	-13.31	-7.53	Kandanghaur
C1	-50.57	-28.60	-20.09	-4.14	Kandanghaur
C2	44.62	260.02	-192.58	6.03	Kandanghaur
C3	-99.38	9.93	-113.16	-2.28	Cantigi
D1	-105.01	-207.27	-24.96	-9.80	Cantigi
D2	-247.17	-335.21	-38.50	-14.08	Cantigi
D3	-445.33	-91.30	-23.75	-27.57	Cantigi
D4	0.70	0.00	0.00	0.02	Cantigi
E1	11.64	1556.97	199.27	34.01	Cantigi
E2	-9.46	655.74	131.28	23.78	Cantigi
E3	-244.44	622.64	-13.16	17.87	Cantigi
F1	-286.16	591.19	99.26	19.90	Cantigi
F2	-722.81	256.54	160.00	4.37	Cantigi
F3	-135.49	570.79	-156.07	-7.15	Pasekan
G1	41.21	-103.87	-106.91	-11.45	Pasekan
G2	-204.08	447.03	-142.93	9.80	Pasekan
G3	217.57	708.04	25.52	16.38	Pasekan
H1	-1136.78	70.62	25.45	0.73	Pasekan
H2	-38.03	1294.80	-119.31	0.71	Pasekan
H3	-49.62	163.19	-9.64	5.21	Indramayu
I1	-25.19	-19.88	26.74	-1.46	Balongan
I2	-25.75	-20.42	26.43	-1.27	Balongan
I3	-50.01	-13.18	32.10	-0.22	Juntinyuat
J1	-31.32	-36.12	9.11	-2.56	Juntinyuat
J2	-10.83	-17.89	12.72	-1.27	Juntinyuat
J3	-33.54	-6.63	29.47	0.65	Juntinyuat
K1	-66.37	-124.83	-88.31	-8.31	Karangampel
K2	-2.16	-157.57	38.70	-6.31	Krangkeng
K3	81.57	-11.06	79.24	1.51	Krangkeng
K4	-28.11	-28.11	192.52	7.47	Krangkeng

3.3 The correlation between mangrove and coastline changes in Indramayu

The results of the mangrove overlay analysis with shoreline changes indicated that mangroves are present only in certain grid areas. To facilitate correlation analysis and enable regression analysis, shoreline change values (NSM, m) were converted into estimates of land area loss or gain (ha) for each grid cell, allowing shoreline change and mangrove change to be compared in the same units. A summary of the combinations between mangrove presence/absence and shoreline change classes is presented in **Table 3**, providing an overview of how shoreline erosion and accretion are distributed across grids with and without mangroves.

Table 3. Mangrove and shoreline's overlay.

Grid	District	Mangrove area change (Ha)			Shoreline change (Ha)		
		1991 - 2001	2001 - 2011	2011 - 2021	1991 - 2001	2001 - 2011	2011 - 2021
C2	Kandanghaur	-3.12	0.00	-0.98	0.00	0.03	-0.02
C3	Losarang	-15.80	0.00	36.54	-0.01	0.00	-0.01
D1	Losarang	-38.75	0.00	10.38	-0.01	-0.02	0.00
D2	Cantigi	-110.11	0.00	101.80	-0.02	-0.03	0.00
D3	Cantigi	-215.89	0.00	71.29	-0.04	-0.01	0.00
D4	Cantigi	-55.11	0.00	8.00	0.00	0.00	0.00
E1	Cantigi	0.00	0.00	44.79	0.00	0.16	0.02
E2	Cantigi	-0.67	27.95	2.17	0.00	0.07	0.01
E3	Cantigi	0.00	0.00	0.00	-0.02	0.06	0.00
F1	Cantigi	0.00	0.80	1.20	-0.03	0.06	0.01
F2	Cantigi	-42.68	0.07	129.93	-0.07	0.03	0.02
F3	Pasekan	-4.38	-2.65	38.10	-0.01	0.06	-0.02
G1	Pasekan	-38.91	-22.39	17.10	0.00	-0.01	-0.01
G2	Pasekan	-17.73	-0.87	56.65	-0.02	0.05	-0.01
G3	Pasekan	-5.83	0.12	39.32	0.02	0.07	0.00
H1	Pasekan	-3.85	0.00	61.03	-0.11	0.01	0.00
H2	Pasekan	-11.26	0.00	55.10	0.00	0.13	-0.01
H3	Indramayu	-5.15	0.00	6.42	0.00	0.02	0.00

Before conducting a correlation analysis, it was essential to perform a linearity test to determine whether the two variables were suitable for further analysis. The ANOVA for the linear regression between mangrove area change and shoreline area change yielded an F-value of 4.116 ($p > 0.05$), indicating that the slope of the regression line was not statistically different from zero.

ANOVA Table

			Sum of Squares	df	Mean Square	F	Sig.
GP * Mangrove	Between Groups	(Combined)	1.485E+16	15	9.899E+14	3.982	.219
		Linearity	5.238E+14	1	5.238E+14	2.107	.284
		Deviation from Linearity	1.432E+16	14	1.023E+15	4.116	.212
	Within Groups		4.971E+14	2	2.486E+14		
	Total		1.535E+16	17			

Fig. 6. ANOVA output for the linear regression between mangrove area change and shoreline area change.

The coefficient of determination (R^2) was calculated in addition to the linearity test. An R^2 value of 0.191 indicates that changes in mangrove extent explain less than 20% of the variability in shoreline area change among grid cells. In other words, the linear relationship between mangrove cover change and shoreline change was weak and far from deterministic. This suggests that shoreline dynamics in Indramayu are largely governed by other drivers, such as waves, currents, sediment supply, and local geomorphology, rather than by mangrove extent, highlighting the complexity of ecological interactions in the study area.

Measures of Association

	R	R Squared	Eta	Eta Squared
GP * Mangrove	.437	.191	.977	.954

Fig. 7. The results of R^2.

Based on the analysis of the table and linearity test results, it can be observed that even areas with a substantial presence of mangrove vegetation continue to exhibit high erosion rates. This phenomenon may be attributed to the dominance of oceanographic factors, such as currents, winds, waves, and tidal fluctuations, which significantly influence the erosion processes. Additionally, mangrove vegetation in these regions may be characterized by sparse density and suboptimal quality, thereby reducing its effectiveness as a natural barrier. Effective protection is contingent on the health and density of the mangrove forest; healthy, dense mangroves are more capable of mitigating wave energy and preventing erosion. The capacity of mangroves to serve as a buffer against wave action and erosion is primarily influenced by root and stem density as well as canopy diameter. In practice, coastal management may require complementary measures (e.g., hybrid or permeable structures) alongside restoration to manage erosion on mangrove–mud coasts [23].

4 Conclusion

The analysis of mangrove land cover and shoreline dynamics in the Indramayu Regency from 1991 to 2021 revealed significant environmental shifts over a three-decade period. Initially, there was a notable decline in mangrove areas due to deforestation and habitat conversion for aquaculture, with a loss of approximately 610.67 hectares between 1991 and 2001. Subsequently, from 2001 to 2011, mangrove coverage slightly increased by about 11.17 hectares, and from 2011 to 2021, it expanded by roughly 677.03 hectares, indicating successful restoration efforts. Shoreline changes have been characterized mainly by erosion, although periods of sedimentation and accretion have also occurred and are influenced by both natural and human activities. During the first decade, the shoreline retreat averaged -15.98 meters annually, while from 2001 to 2011, there was a period of accretion at 13.69 meters per year. The latest decade saw a reduced retreat rate of -1.49 meters annually, suggesting some stabilization. Despite restoration efforts, the relationship between mangrove health and shoreline stability remains weak, primarily because of factors such as vegetation density, oceanographic conditions, and sediment dynamics. These findings emphasize the need for integrated coastal management strategies that combine ecological restoration with infrastructure support to mitigate erosion, improve mangrove resilience, and promote sustainable development. Developing comprehensive policies that address both the ecological and infrastructural aspects is vital for the long-term preservation of coastal ecosystems in the region.

References

1. A. Vincentius, M.N. Nessa, J. Jompa, A. Saru, M. Hatta, N. Rukminasari, The association of economically important fish with mangroves in Maumere Bay, Indonesia, in Proceedings of the ISMF2 2019, IOP Conference Series: Earth and Environmental Science, Makassar, Indonesia, 22 June 2019 (2019)

2. Food and Agriculture Organization of the United Nations, *The world's mangroves 2000–2020*, (FAO, Rome, 2023). https://doi.org/10.4060/cc7044en
3. Y. Rochmayanto, D. Priatna, K.L. Ginoga, J.N. Prihartini, A. Wibowo, M. Salminah, F.J. Salaka, N.S. Lestari, M.Z. Mutaqin, I. Samsoedin, U. Wiharjo, D. Suryadi, I. Afandi, Strategi dan teknik restorasi ekosistem hutan mangrove, (IPB Press, Bogor, 2021)
4. D.A. Friess, K. Rogers, C.E. Lovelock, K.W. Krauss, S.E. Hamilton, S.Y. Lee, R. Lucas, J. Primavera, A. Rajkaran, S. Shi, The state of the world's mangrove forests: past, present, and future. *Annu. Rev. Environ. Resour.* 44, 89–115 (2019). https://doi.org/10.1146/annurev-environ-101718-033302
5. Kusnanto, Perubahan garis pantai dan strategi pengelolaan wilayah pesisir di Kabupaten Indramayu, Master Thesis, Institut Pertanian Bogor, Bogor, 2022
6. R. Gijsman, E.M. Horstman, D. van der Wal, D.A. Friess, A. Swales, K.M. Wijnberg, Nature-Based Engineering: A Review on Reducing Coastal Flood Risk With Mangroves. *Front. Mar. Sci.* 8, 702412 (2021). https://doi.org/10.3389/fmars.2021.702412
7. Susiana, M.P. Suhana, Tingkat kerusakan mangrove di perairan Desa Berakit, Pulau Bintan, Indonesia. J. Akuakultur, Pesisir dan Pulau–Pulau Kecil. **3**, 73–79 (2019). https://doi.org/10.29239/j.akuatikisle.3.2.73-79
8. S.H. Nur, E. Hilmi, The correlation between mangrove ecosystem with shoreline change in Indramayu coast. IOP Conf. Ser.: Earth Environ. Sci. 819, 012015 (2021). https://doi.org/10.1088/1755-1315/819/1/012015
9. M. Ilman, P. Dargusch, P. Dart, Onrizal, A historical analysis of the drivers of loss and degradation of Indonesia's mangroves. *Land Use Policy* 54, 448–459 (2016). https://doi.org/10.1016/j.landusepol.2016.03.010
10. W.A. Gunawan, D.N. Handiani, Kerentanan pesisir di pantai utara Jawa Barat, in Proceedings of the FTSP Series 1 Seminar Nasional dan Diseminasi Tugas Akhir 2021, February 8 – 9 2021 (2021)
11. D.N. Handiani, A. Heriati, F. Suciaty, Coastal vulnerability assessment along the North Java coastlines - Indonesia. J. Segara **18**, 1–12 (2022). https://doi.org/10.15578/segara.v18i1.10664
12. Sodikin, Permodelan spasial dinamis perubahan hutan mangrove dan strategi rehabilitasinya di Kabupaten Indramayu, Ph.D. thesis, Institut Pertanian Bogor (2018)
13. DLH Indramayu, Daya dukung dan daya tampung lingkungan hidup Kabupaten Indramayu (Dinas Lingkungan Hidup Kabupaten Indramayu, Indramayu, 2018)
14. BAPPENAS, Kaji ulang RAN API: Kajian basis ilmiah bahaya perubahan iklim (Bappenas, Jakarta, 2018)
15. F. Istiqomah, B. Sasmito, F.J. Amarrohman, Pemantauan perubahan garis pantai menggunakan aplikasi Digital Shoreline Analysis System (DSAS) studi kasus: Pesisir Kabupaten Demak. J. Geod. Undip **5**, 78–89 (2016). https://ejournal3.undip.ac.id/index.php/geodesi/article/view/10559
16. E.A. Himmelstoss, R.E. Henderson, M.G. Kratzmann, A.S. Farris, Digital Shoreline Analysis System (DSAS) version 5.0 user guide. U.S. Geological Survey Open-File Report 2018–1179 (2018). https://doi.org/10.3133/ofr20181179
17. E. Riane, Kajian perubahan luasan dan kerapatan mangrove menggunakan citra satelit di Indramayu, Jawa Barat, Undergraduate Thesis, Institut Pertanian Bogor, Bogor, 2021

18. Oni, C. Kusmana, S. Basuni, Success story rehabilitasi ekosistem mangrove di Pantai Karangsong Indramayu. J. Nat. Resour. Environ. Manage. 9, 787–796 (2019). https://doi.org/10.29244/jpsl.9.3.787-796
19. O. Setyandito, J. Triyanto, Analisa erosi dan perubahan garis pantai pada pantai pasir buatan dan sekitarnya di Takisung, Propinsi Kalimantan Selatan. J. Teknik Sipil. **7**, 224–335 (2007)
20. G.A. Rahmawan, U.J. Wisha, W.A. Gemilang, Ilham, S. Husrin, Prediksi akumulasi sedimen berdasarkan survei batimetri dan hidrodinamika di pesisir Teluk Mandeh, Kabupaten Pesisir Selatan, Sumatera Barat. J. Kelaut. Trop. **23**, 105–116 (2020). https://doi.org/10.14710/jkt.v23i1.6076
21. C.D. Woodroffe, Y. Saito, River-dominated coasts. Treatise on Estuarine Coast. Sci. **3**, 117-135 (2011). https://doi.org/10.1016/B978-0-12-374711-2.00306-5
22. H.H. Nguyen, C. McAlpine, D. Pullar, S.J. Leisz, G. Galina, Drivers of coastal shoreline change: Case study of Hon Dat coast, Kien Giang, Vietnam. Environ. Manage. **55**, 1093–1108 (2015). https://doi.org/10.1007/s00267-015-0455-7
23. J.C. Winterwerp, T. Albers, E.J. Anthony, D.A. Friess, A.G. Mancheño, K. Moseley, A. Muhari, S. Naipal, J. Noordermeer, A. Ooost, C. Saengsupavanich, S.A.J. Tas, F.H. Tonneijck, T. Wilms, C. van Bijsterveldt, P. van Eijk, E. van Lavieren, B.K. van Wesenbeeck, Managing erosion of mangrove- mud coasts with permeable dams – lessons learned. Ecol. Eng. **158**, 106078 (2020). https://doi.org/10.1016/j.ecoleng.2020.106078
24. Government of Indonesia, Peraturan Presiden Republik Indonesia Nomor 18 Tahun 2020 tentang Rencana Pembangunan Jangka Menengah Nasional Tahun 2020–2024 (RPJMN 2020–2024) (2020). https://peraturan.go.id/id/perpres-no-18-tahun-2020
25. P. Bunting, A. Rosenqvist, L. Hilarides, R.M. Lucas, N. Thomas, T. Tadono, T.A. Worthington, M. Spalding, N.J. Murray, L.-M. Rebelo, Global Mangrove Extent Change 1996–2020: Global Mangrove Watch Version 3.0. Remote Sens. 14, 3657 (2022). https://doi.org/10.3390/rs14153657
26. D.N. Bryan-Brown, R.M. Connolly, D.R. Richards, F. Adame, D.A. Friess, C.J. Brown, Global trends in mangrove forest fragmentation. Sci. Rep. 10, 7117 (2020). https://doi.org/10.1038/s41598-020-63880-1
27. N. Gorelick, M. Hancher, M. Dixon, S. Ilyushchenko, D. Thau, R. Moore, Google Earth Engine: Planetary-scale geospatial analysis for everyone. Remote Sens. Environ. 202, 18–27 (2017). https://doi.org/10.1016/j.rse.2017.06.031
28. E.A. Himmelstoss, A.S. Farris, R.E. Henderson, M.G. Kratzmann, A. Ergul, O. Zhang, J.L. Zichichi, E.R. Thieler, Digital Shoreline Analysis System (DSAS) version 5.0 user guide. U.S. Geological Survey Open-File Report 2018–1179 (2018). https://doi.org/10.3133/ofr20181179