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Research Article

Estimating Economic Losses due to Coastal Flooding in Medan Belawan, Indonesia

Hafiza Fikri Naipospos [1*], Taryono [2], Zairion [3], Fery Kurniawan [4]

[1] Coastal and Marine Resources Management Study Program, Department of Aquatic Resources Management, Faculty of Fisheries and Marine Sciences, Institut Pertanian Bogor, Indonesia
[2] Centre for Coastal and Marine Resources Studies, Institut Pertanian Bogor, Indonesia
* Corresponding Author: fizanaipospos@apps.ipb.ac.id

Abstract: Coastal flooding is a recurring environmental hazard in Medan Belawan, driven by sea-level rise, land subsidence, and extreme tidal conditions. This study analyses the spatial distribution of coastal inundation in July 2025 and estimates the resulting economic losses across three affected sectors: households, business units, and public facilities. Spatial inundation mapping was conducted using DEMNAS elevation data combined with Highest High Water Level (HHWL) measurements, revealing that 79.5% of the study area (2,266 ha) was inundated. Primary data were collected through proportional random sampling involving 229 respondents and business/facility units across six urban villages. The estimated total economic loss reached IDR6.05 billion per month, consisting of IDR4.75 billion from household losses, IDR291 million from business units, and IDR1.01 billion from public facilities. Household losses were dominated by asset damage and income reduction, while business units experienced operational disruptions and decreased revenue. Public facilities faced structural damage and interruptions to basic services. These findings high-light significant economic impacts associated with the spatial extent and intensity of coastal flooding in low-lying coastal neighbourhoods of Medan Belawan.

Keywords: Economic Loss; Household Impact; Medan Belawan; Coastal Flooding; Spatial Inundation Analysis.

1. Introduction

Coastal flooding has become an increasingly prevalent environmental hazard in many coastal regions of Indonesia. Rising sea levels driven by global climate change, land subsidence, and inadequate drainage systems have exacerbated this condition (Hallegatte et al., 2016; Nicholls et al., 2021). The impacts of coastal flooding extend beyond physical damage to infrastructure, affecting the economic and social stability of coastal communities (Marfai & King, 2008).

Studies conducted in northern coastal Java, including Semarang, Demak, and Jakarta, demonstrate that tidal flooding causes substantial economic losses for households, small-scale entrepreneurs, and public facilities (Widiyanto et al., 2019; Abidin et al., 2020). In Medan Belawan District, a significant flooding event in 2021 inundated approximately 15,000 houses and affected more than 70,000 residents (Muhari, 2021). These conditions highlight the district's high vulnerability to the combined effects of sea-level anomalies, extreme rainfall, and persistent land subsidence (Putra et al., 2022). Additionally, recurrent flooding frequently disrupts port operations, fisheries, and logistics services, intensifying economic pressures on the local population.

Although numerous studies have examined the physical and spatial dimensions of coastal flooding in Indonesia (Marfai et al., 2011; Rosenzweig et al., 2019), comprehensive cross-sector assessments of economic losses in Medan Belawan remain limited. Economic valuation approaches are essential for quantifying the financial and social impacts of flooding,

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thereby providing a scientific basis for designing mitigation and adaptation strategies and for evidence-based coastal development planning (Dosi, 2001; IPCC, 2022).

Therefore, this study aims to estimate the economic losses from coastal flooding in Medan Belawan District by examining three sectors: households, businesses, and public facilities. Using an environmental damage assessment framework and proportional random sampling, this research provides a comprehensive overview of loss magnitude, types of damages, and levels of socioeconomic vulnerability among coastal communities facing increasingly frequent flood hazards driven by climate change and coastal environmental dynamics.

2. Materials and Method

2.1. Study Area: Medan Belawan District

Field data collection was conducted in July 2025 in Medan Belawan District. Geographically, Medan Belawan is located along the eastern coast of North Sumatra, bordered by the Malacca Strait to the north, Medan Labuhan District to the south, and Deli Serdang Regency to the east and west.

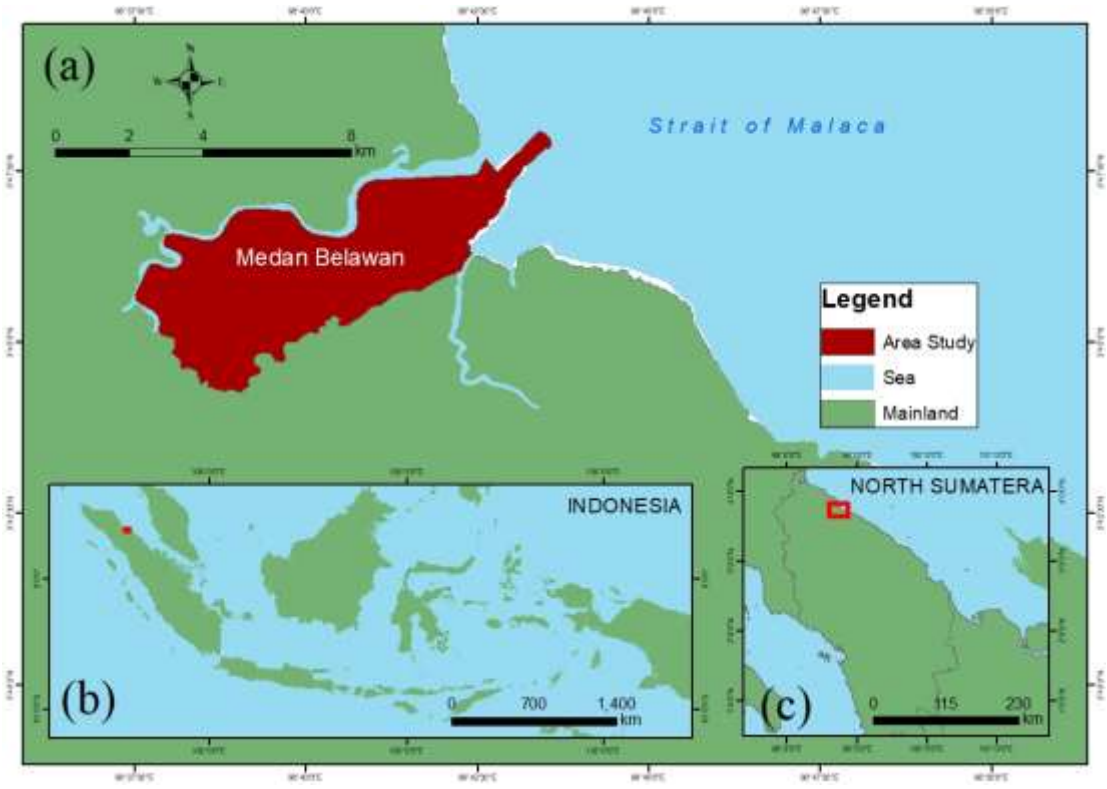

Figure 1. Research Location in the coastal district of Medan Belawan.

2.2 Data

This study employed a proportional random sampling method to ensure that the selected sample accurately reflected the proper distribution and characteristics of the target population (Taluke et al., 2019). The method involved dividing the population into strata based on specific variables, such as the number of households (HH), business units (BU), and public facilities (PF) in each subdistrict. From each stratum, samples were randomly selected in proportion to the stratum's size within the overall population. This approach aligns with principles discussed in the statistical literature, such as those of Yanagawa (1975), who emphasised that stratification with proportional allocation increases precision and reduces estimation variance.

Table 1. Number of Respondents in the Study Area.

Sub-district	community unit	Hausehold	Elected HH 1%	Business unit	Elected BU 10%	Public facilities	Elected PF 10%
Belawan Sicanang	20	3972	40	127	13	70	7
Belawan Bahagia	20	2711	27	29	3	45	5
Belawan Bahari	13	2187	22	56	6	45	5
Belawan II	44	5615	56	65	7	78	8
Bagan Deli	15	3356	34	93	9	55	6
Belawan I	31	5001	50	491	49	70	7
Total	143	22842	228	861	86	363	36

Using this proportional sampling approach, the study selected 1% of households (HH), 10% of business units, and 10% of public facilities within each subdistrict in Medan Belawan District. These percentages were chosen to obtain a representative sample while remaining efficient in terms of time and resources. In total, the sample consisted of 197 RTs, 86 business units, and 36 public facilities.

In the local administrative system, a community unit (CU) refers to the neighbourhood head, nominated by the village head but not formally part of the village government. Respondents in the business unit category included those engaged in retail trade, service provision, entertainment, food stalls, and financial institutions. Public facilities included schools, health centres, sports facilities, places of worship, energy facilities, offices, and port facilities.

3. Proposed Method

3.1. Existing Flood Conditions

Flood inundation modelling was conducted to identify the spatial extent of affected areas. Because DEMNAS uses Mean Sea Level (MSL) as its vertical datum, flood inundation can be calculated directly by comparing ground elevations with the Highest High Water Level (HHWL), which is also referenced to MSL. This eliminates the need to calculate HHWL–MSL differences. Spatial analysis was performed using the Raster Calculator based on a modified equation from Marfai et al. (2011):

$$WD = Con\,([DEM] \leq HHWL, 1, 0) \quad (1)$$

Where WD is Water depth/inundation presence(m); DEM is Digital Elevation Model (m); HHWL is Highest High Water Level (m); CON is Conditional function (in raster calculator); Binary raster output: 1 = inundated, 0 = not inundated

HHWL data for July 2025 were obtained from BMKG Belawan, while DEM data were sourced from DEMNAS through the official government portal.

3.2. Estimation of Economic Losses

Economic losses experienced by households and business units were estimated using the environmental damage assessment method. According to Dosi (2001), environmental

damage assessment is a systematic process for identifying, evaluating, and determining recovery measures for ecological impacts caused by specific activities. A similar approach was applied by Simanjuntak (2010) in estimating total flood-related economic losses.

3.2.1. Identification of Affected Objects

This stage involved identifying various types of damage resulting from flooding. For households, the impacts were categorised into structural damage, property loss, vehicle damage, income loss, medical expenses, and educational disruption. For business units, impacts included structural damage, asset loss, vehicle damage, wage disruption, and reduced business income.

3.2.2. Damage Classification

Flood-related damage was classified to assess severity and corresponding repair needs

Tabel 2. classification of the level of damage.

Damage category	Description	Severity	Type of repair
Affected	Floodwater occurs outside the area without causing any damage	Low	Not required
Minor	Floodwater enters the area but does not damage goods or sub-merge buildings.	Moderate	Yes (repairable)
Mayor	Floodwater enters properties and damages structures such as walls	High	Yes (repairable)
Destroyed	Floodwater ≥ 4 meters, causing severe structural damage to build-ings	Very high	No (non-repair-able)

3.2.3. Loss Valuation

Flood-induced costs were categorised into replacement, repair, and disruption costs. Replacement costs refer to irreparable losses (e.g., damaged household goods or business assets). Repair costs represent expenditures needed to restore damaged items or structures. Disruption costs include losses in income, health, education, and labour productivity. The scope of the Damage and Loss estimation in this study is the losses caused by coastal flooding that occurred in July 2025.

Table 3. Methods for calculating damage and economic disruption.

No	Types of damage and disruption	Methods for calculating damage and economic disruption
1	Structural loss	Cost of loss and repair costs
2	Assets loss	Cost of loss and repair costs
3	Income loss	*Loss of Earnings*
4	work disruption	Total employees who are absent multi-plied by the number of days they are ab-sent multiplied by (wages/30 days)
5	Health impact	*Cost of Illness*

No	Types of damage and disruption	Methods for calculating damage and economic disruption
6	educational disruption	Total days of learning lost × educational cost per student per day

a. Income loss:

$$\Delta P = P_1 - P_2 \quad (2)$$

Where ΔP is income loss per household (IDR/ household); P_1 is pre-flood income (IDR/ household); P_2 is post-flood income (IDR/ household)

b. Health impact: cost of illness approach

$$KER = \frac{\sum KE}{n} \quad (3)$$

Where KER is the average economic loss (IDR/person); KE is the individual respondent's loss (IDR); n is the number of respondents (person)

c. Total population-level losses:

$$KER = \frac{\sum KE}{n} \times N \quad (4)$$

Where KET is the total economic loss (IDR), N is the total affected population (people)

In this study, economic losses were analysed across three main sectors: households, business units, and public facilities to capture sector-specific damage patterns and disruption levels. Each sector was assessed using its own analytical framework that linked damage types to economic loss components.

4. Results and Discussion

In this section, the author needs to explain the hardware and software used, dataset sources, initial data analysis, results, and results analysis/discussion. Presenting the results with pictures, graphs and tables is highly recommended. Formulas or evaluation measuring tools also need to be included here. There must be discussion/analysis, and you can't just rewrite the results in sentence form, but you need to provide an explanation of their relationship to the initial hypothesis. In addition, this section needs to discuss and elaborate on important findings.

4.1. Existing Coastal Flooding Map (2025)

The spatial distribution of coastal flood inundation in Medan Belawan during July 2025 was mapped by integrating DEMNAS elevation data with tidal records and administrative boundaries, and the classification distinguished between inundated and non-inundated areas to determine vulnerability levels across subdistricts.

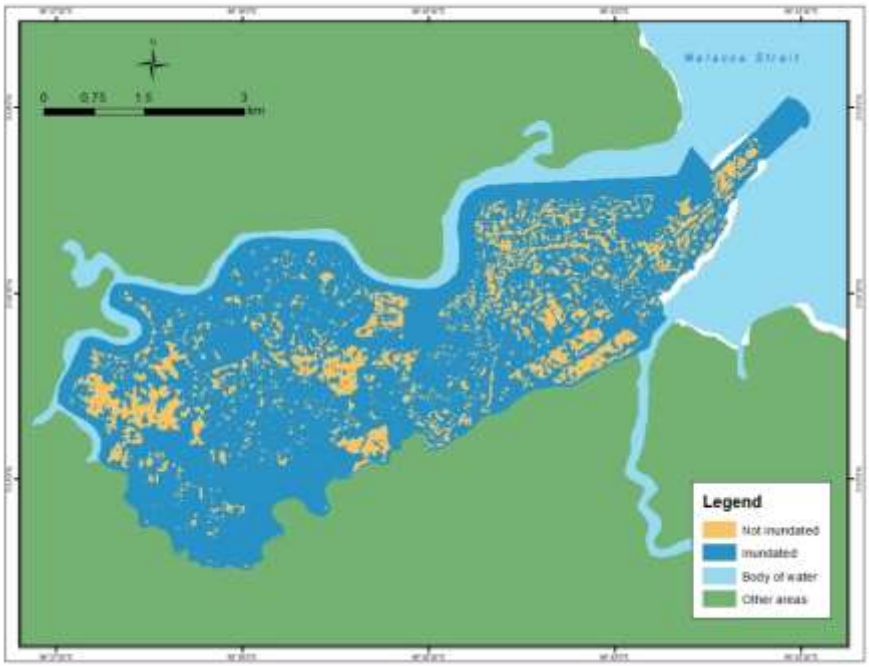

Figure 2. Flooding in July 2025.

Based on the spatial analysis, the inundated area in July 2025 reached approximately 2,266 hectares, while 583 hectares remained dry. This indicates that about 79.5% of the total study area was affected by coastal flooding, with varying depths and durations of inundation. The most severely inundated urban villages were Belawan Sicanang, followed by Belawan Bahagia, Belawan II, and Bagan Deli. These areas are situated at low elevations (< 1 m above mean sea level) and are located near river mouths and coastal zones that are highly exposed to tidal flooding.

The extent of inundation observed in 2025 is consistent with patterns observed in previous flood events documented through field observations. According to the Medan City Disaster Management Agency (BPBD, 2025), several urban villages in Belawan—particularly Sicanang and Bahagia—experienced flood depths of 30-80 cm, with inundation lasting 2–5 hours during spring tides. Findings by Marfai et al. (2018) also indicate that a combination of sea-level rise, land subsidence, and inadequate drainage performance drives coastal flooding in northern Sumatra.

Overall, both the simulation outputs and the observed conditions in 2025 indicate that Medan Belawan District is highly vulnerable to coastal flooding. Without intervention measures—such as improved water management systems and the implementation of grey and green infrastructure—the frequency and intensity of coastal flooding are projected to increase in the coming years (Hallegatte et al., 2016; Rosenzweig et al., 2019).

4.2 Economic Loss Estimation from Coastal Flooding

4.2.1. Households

Economic losses at the household level resulting from the July 2025 coastal flooding event in Medan Belawan District were assessed using survey data collected from 229 respondents across six affected urban villages. The analysis compares average household income before and during the flood event (Table 4). The difference between these values represents the magnitude of potential income loss experienced during the inundation period.

Table 4. Households' Income Loss Due to Coastal Flooding in July 2025.

Sub district	Respondent	Before flooding (IDR)	After flooding (IDR)	Losses (IDR)
Belawan Sicanang	40	57,450,000	51,725,000	5,725,000
Belawan Bahagia	27	38,500,000	30,800,000	7,700,000
Belawan Bahari	22	31,450,000	26,775,000	4,675,000
Belawan II	56	79,750,000	71,775,000	7,975,000
Bagan Deli	34	46,150,000	36,400,000	9,750,000
Belawan I	50	75,150,000	63,325,000	11,825,000
Total	229	328,450,000	280,800,000	47,650,000

Based on Table 4, the total household income loss due to coastal flooding in Medan Belawan amounted to approximately IDR47,650,000. This indicates an average income reduction of 14.5% compared to pre-flood conditions. The highest loss was recorded in Belawan I (IDR11,825,000), followed by Bagan Deli (IDR9,750,000), both of which are densely populated areas situated in low-lying zones frequently affected by tidal inundation. In contrast, Belawan Bahari experienced the lowest loss (IDR4,675,000), likely due to a larger share of households engaged in informal sectors with relatively flexible income sources.

Overall, these results demonstrate that coastal flooding significantly disrupts household economic stability in Belawan. Income reductions during flood periods highlight the economic vulnerability of coastal communities, many of whom rely on daily-wage livelihoods such as fishing, port labour, and small-scale trading. These findings align with Marfai *et al.* (2018) and Rosenzweig *et al.* (2019), who argue that coastal flooding reduces both physical assets and economic capacity in low-lying urban areas. Economic disruptions experienced by households include both physical damages (structural damage and asset losses) and non-physical impacts (interference with work, health, and education). Table 5 presents the total economic losses for the six affected urban villages—Belawan Sicanang, Belawan Bahagia, Belawan Bahari, Belawan II, Bagan Deli, and Belawan I.

Table 5. Household Damages and Economic Disruptions Caused by Coastal Flooding in July 2025.

Sub district	Damage (IDR)		Disturbance (IDR)			Total
	Structural	Assets	Work	Healt	Education	Loss(IDR)
Belawan Sicanang	1,719,000	1,703,000	750,000	1,000,000	553,000	5,725,000
Belawan Bahagia	2,240,000	2,370,000	795,000	1,350,000	945,000	7,700,000
Belawan Bahari	1,625,000	1,567,000	310,000	770,000	403,000	4,675,000
Belawan II	2,220,000	2,227,000	1,400,000	1,400,000	728,000	7,975,000
Bagan Deli	2,755,000	2,985,000	1,700,000	1,360,000	950,000	9,750,000
Belawan I	3,020,000	4,320,000	1,750,000	1,735,000	1,000,000	11,825,000
Total	13,579,000	15,172,000	6,705,000	7,615,000	4,579,000	47,650,000

Table 5 indicates that household losses from the July 2025 coastal flooding were substantial, with the most significant burden arising from asset damage and disruptions to daily activities. The highest losses occurred in densely populated areas such as Belawan I, Bagan Deli, and Belawan II, where many assets and infrastructures are situated in flood-prone zones. At the same time, Belawan Bahari recorded the lowest losses due to its lower residential density. Health-related disruptions represented the most considerable non-structural impact, reflecting increased medical expenses and reduced productivity during flood events. Overall, these results highlight that coastal flooding imposes multidimensional pressures on household welfare, affecting both physical conditions and socio-economic stability.

Table 6. Average Household Economic Losses Due to Coastal Flooding in July 2025.

Sub district	Loss cost (IDR)	Responden	Average loss (IDR)	Population	Total loss (IDR)
Belawan Sicanang	5,725,000	40	143,125	3,972	568,492,500
Belawan Bahagia	7,700,000	27	285,185	2,711	773,137,037
Belawan Bahari	4,675,000	22	212,500	2,187	464,737,500
Belawan II	7,975,000	56	142,411	5,615	799,636,161
Bagan Deli	9,750,000	34	286,765	3,356	962,382,353
Belawan I	11,825,000	50	236,500	5,001	1,182,736,500
Total	47,650,000	229	1,306,486	22,842	4,751,122,051

Based on Table 6, the total estimated household loss across the six urban villages amounted to IDR 4.75 billion. This value illustrates the substantial economic burden borne by coastal communities due to flood-induced damage to homes, assets, and household activities. The highest average losses occurred in Bagan Deli (IDR 286,765) and Belawan Bahagia (IDR 285,185), indicating that, although these areas have smaller populations, the value of assets and the intensity of economic activity contribute to higher per-household losses.

These findings align with global research indicating that low-income households are the most severely affected by coastal flooding. Hallegatte *et al.* (2020) emphasise that hydrometeorological disasters in coastal urban areas impose a disproportionate economic burden on vulnerable groups due to their limited access to insurance, savings, and adaptive assets. This condition is evident in Belawan, where a large proportion of residents work in informal sectors that rely on daily income generation; thus, even a 4–12-hour inundation can substantially reduce monthly earnings. The high economic losses observed in densely populated areas further reflect the limited adaptive capacity of local communities and their high exposure to flood risk (Hallegatte *et al.*, 2016; Marfai *et al.*, 2018).

4.2.2. Business Units

Coastal flooding also significantly affects local economic activities, particularly in the business sector, which serves as a primary livelihood for many residents in Belawan. The flooding event in July 2025 led to a decline in business revenue due to operational disruptions, damage to goods and equipment, and reduced customer demand. Table 7 compares business

income before and during the flood, along with the estimated loss in each affected urban village.

Table 7. Business Income Loss Due to Coastal Flooding in July 2025.

Sub district	Before flooding (IDR)	After flooding (IDR)	Loss (IDR)
Belawan Sicanang	37,443,103	35,570,948	1,872,155
Belawan Bahagia	11,710,134	9,953,614	1,756,520
Belawan Bahari	42,724,682	40,588,448	2,136,234
Belawan II	52,400,822	49,780,781	2,620,041
Bagan Deli	58,954,222	53,058,800	5,895,422
Belawan I	265,144,588	250,403,115	14,741,473
Total	468,377,551	439,355,705	29,021,845

As shown in Table 7, total income losses across business units amounted to IDR29,021,845. The highest losses occurred in Belawan I (IDR14,741,473), followed by Bagan Deli (IDR5,895,422) and Belawan II (IDR2,620,041). These substantial losses reflect the high concentration of economic activity in these locations and their dependence on the trade and service sectors, which are highly sensitive to mobility constraints and physical disruptions during flood events.

Conversely, Belawan Bahagia and Belawan Sicanang reported lower income losses—IDR1,756,520 and IDR1,872,155, respectively—likely due to more minor business scales or local business owners' ability to adapt operations during flood conditions.

Beyond household impacts, coastal flooding significantly affects productive sectors, tiny and medium enterprises that play a crucial role in supporting the local economy. Business operations in trade, fisheries, and services were disrupted due to restricted mobility, damaged production facilities, and a decline in consumer purchasing power.

Tables 8 and 9 summarise the extent of physical damage and economic disruptions experienced by business units, as well as the estimated average economic loss extrapolated to the total business population in six affected urban villages.

Table 8. Structural Damages and Economic Disruptions to Business Units Caused by Coastal Flooding in July 2025.

Sub district	Damage (IDR)		Disturbance (IDR)		Total
	Structural	Assets	Work	Wages	Loss(IDR)
Belawan Sicanang	472,155	785,000	260,000	355,000	1,872,155
Belawan Bahagia	551,520	1,000,000	75,000	130,000	1,756,520
Belawan Bahari	716,234	930,000	210,000	280,000	2,136,234
Belawan II	795,041	1,300,000	175,000	350,000	2,620,041
Bagan Deli	1,805,422	3,190,000	450,000	450,000	5,895,422
Belawan I	5,996,473	5,070,000	1,225,000	2,450,000	14,741,473
Total	10,336,845	12,275,000	2,395,000	4,015,000	29,021,845

The total assessed loss for the business sector amounted to IDR29,021,845. This Fig. includes structural damage (IDR10,336,845), asset losses (IDR12,275,000), and economic disruptions related to health and worker wages, amounting to IDR2,395,000 and IDR4,015,000, respectively. Belawan I recorded the highest losses (IDR 14,741,473), followed by Bagan Deli and Belawan II. These findings indicate that areas with high concentrations of economic activity—particularly trade and fisheries in flood-prone zones—are more vulnerable to economic disruptions. Meanwhile, Belawan Bahagia and Belawan Sicanang recorded more minor losses, consistent with their fewer business units.

Table 9. Average Economic Losses of Business Units Due to Coastal Flooding in July 2025.

Sub district	Respondent's loss (IDR)	Respondent	Average Loss (IDR)	Populasi	Total business unit loss (IDR)
Belawan Sicanang	1,872,155	13	144,012	127	18,289,516
Belawan Bahagia	1,756,520	3	585,507	29	16,979,694
Belawan Bahari	2,136,234	6	356,039	56	19,938,185
Belawan II	2,620,041	7	374,292	65	24,328,953
Bagan Deli	5,895,422	9	655,047	93	60,919,363
Belawan I	14,741,473	48	307,114	491	150,792,981
Total	29,021,845	86	2,422,010	861	291,248,692

Based on Table 9, the total estimated economic loss for the business sector reached IDR291.25 million. Belawan I recorded the highest losses (IDR150.79 million), followed by Bagan Deli (IDR60.92 million) and Belawan II (IDR24.33 million), reflecting greater financial impacts in areas with more business units and denser economic activity. Meanwhile, Belawan Bahagia and Belawan Sicanang experienced lower losses due to their smaller business populations.

The vulnerability of these small business units is consistent with the findings of Widiyanto *et al.* (2019), who found that microenteIDRrises in port areas and coastal settlements are highly sensitive to flooding due to their low-lying locations and limited access routes. Furthermore, Vousdoukas *et al.* (2018) project that economic losses from coastal flooding in Southeast Asia could increase by up to fourfold by 2100 in the absence of structural and non-structural adaptation measures. These projections underscore the urgency of safeguarding small businesses in the Belawan area as an integral component of local economic sustainability strategies.

These results reinforce the conclusion that coastal flooding not only causes physical damage but also hinders the economic sustainability of coastal communities (Hallegatte *et al.*, 2016). Economic losses are strongly correlated with the intensity of local economic activities

and business density within affected areas. Therefore, disaster risk management strategies must incorporate economic-sector considerations, including protective measures for business assets and post-disaster recovery support (Marfai *et al*., 2018).

4.2.3. Public Facilities

The July 2025 coastal flooding event also had substantial impacts on the public facilities sector in Medan Belawan District. These impacts included structural damage to public buildings, asset losses, service delivery disruptions, and reduced productivity due to workforce interruptions. Table 10 presents the magnitude of damages and economic disruptions experienced by public facilities in each affected urban village.

Table 10. Structural Damage and Economic Losses of Public Facilities Due to Coastal Flooding in July 2025.

Sub district	Damage and economic losses to public facilities (IDR)				Total Loss
	Structural	Asse	Wages	Inocome	
Belawan Sicanang	4,032,000	11,480,000	1,831,200	2,016,000	19,359,200
Belawan Bahagia	2,880,000	8,200,000	1,308,000	1,440,000	13,828,000
Belawan Bahari	3,456,000	9,840,000	1,569,000	1,728,000	16,593,000
Belawan II	2,880,000	8,200,000	1,308,000	1,440,000	13,828,000
Bagan Deli	3,456,000	9,840,000	1,569,000	1,724,000	16,589,000
Belawan I	4,608,000	13,120,000	2,093,000	2,560,000	22,381,000
Total	21,312,000	60,680,000	9,678,200	10,908,000	102,578,200

The table shows four major categories of losses: structural damage, asset losses, worker wage disruptions, and income loss. The highest total losses were recorded in Belawan I, where structural and asset-related damages exceeded IDR17 million, reflecting the high concentration of public facilities and service activities in the area. Meanwhile, Belawan II and Belawan Bahagia recorded the lowest damages, consistent with lower flood intensity and fewer public facilities. Overall, public facility losses across the six urban villages amounted to IDR102,578,200, indicating a considerable financial burden on the public sector in coastal Belawan.

Table 11. Average Economic Losses in the Public Facilities Sector Due to Coastal Flooding in July 2025.

Sub district	Total Losses of Respondents (IDR)	Respondents	Average losses (IDR)	Population	Total losses of public facilities (IDR)
Belawan Sicanang	19,359,200	7	2,765,600	70	193,592,000
Belawan Bahagia	13,828,000	5	2,765,600	45	124,452,000

Belawan Bahari	16,593,000	6	2,765,500	45	124,447,500
Belawan II	13,828,000	5	2,765,600	78	215,716,800
Bagan Deli	16,589,000	6	2,764,833	55	152,065,833
Belawan I	22,381,000	8	2,797,625	70	195,833,750
Total	102,578,200	37	16,624,758	363	1,006,107,883

This table estimates average losses based on the number of respondents and the total affected population in each urban village. The highest losses occurred in Belawan Sicanang (IDR 193.59 million), followed by Belawan I (IDR 195.83 million) and Belawan II (IDR 215.71 million). These values indicate that damage and service disruption levels are closely linked to the number of facility users and the intensity of public service activities. In total, public facility losses across the study area amounted to approximately IDR1.006 billion, underscoring the need to strengthen adaptive capacity and infrastructure resilience in the public sector.

4.3.4. Total Estimated Economic Loss Across Three Sectors

Economic losses from the July 2025 coastal flooding event in Medan Belawan were estimated by combining the three primary sectors: households, business units, and public facilities. This provides a comprehensive assessment of the economic impacts of tidal inundation and extreme high tides on coastal community activities. Table 12 summarises the total economic losses in each urban village.

Table 12. Total Estimated Economic Losses from Coastal Flooding in July 2025.

Sub district	Total Losses Household (IDR)	Total Losses business units (IDR)	Total Losses of public facilities (IDR)	Total Losses (IDR)
Belawan Sicanang	568,492,500	18,289,516	193,592,000	780,374,016
Belawan Bahagia	773,137,037	16,979,694	124,452,000	914,568,731
Belawan Bahari	464,737,500	19,938,185	124,447,500	609,123,185
Belawan II	799,636,161	24,328,953	215,716,800	1,039,681,914
Bagan Deli	962,382,353	60,919,363	152,065,833	1,175,367,549
Belawan I	1,182,736,500	150,792,981	195.833,750	1,529,363,231
Total	4,751,122,051	291,248,692	1,006,107,883	6,048,478,626

The table shows that total economic losses across the three sectors amounted to IDR6,048,478,626 per month. The highest losses were observed in Belawan I (IDR 1.53 billion), followed by Bagan Deli (IDR 1.17 billion). These figures reflect the high population

density, intensive economic activity, and a significant number of public facilities exposed to flooding.

In contrast, Belawan Bahari recorded the lowest losses (IDR609 million), suggesting lower flood intensity or less concentrated economic activity. Among sectors, household losses contributed the largest share, followed by public facilities and business units, highlighting that the direct impacts of flooding are most strongly felt at the household level.

Field observations further indicate that flooding occurred twice during the month—10–14 July and 23–27 July—with inundation frequencies of 1–2 times daily. Flood duration ranged from 4 to 12 hours, exacerbating economic disruptions in households and small enterprises. These recurring events illustrate that flooding affects not only physical assets but also daily economic activities and community productivity (Hallegatte *et al.*, 2016; Marfai *et al.*, 2018).

Repeated coastal flooding in Medan Belawan also caused substantial structural damage to houses, corrosion of vehicles due to saltwater, temporary loss of agricultural land, increased home renovation costs, and restricted mobility due to inundated roads. These conditions contributed to significant reductions in small-business income, consistent with previous studies that emphasise the dual economic impacts of damage and activity disruption (Hallegatte *et al.*, 2016; Marfai *et al.*, 2018).

a)

b)

c)

d)

e) f)

Figure 3. Economic losses felt by Medan residents: a) The wall cracked, and water got in, b) rusty vehicle, c) agricultural land submerged in floodwater, d) house elevation due to flooding, e) public roads affected by flooding, f) residents' businesses affected by flooding.

5. Comparison

Based on the spatial assessment, the inundated area in July 2025 reached 2,266 hec-tares, while 583 hectares remained unaffected, indicating that approximately 79.5% of the total study area experienced coastal flooding with varying depths and durations. The most extensively inundated areas were Belawan Sicanang, followed by Belawan Bahagia, Belawan II, and Bagan Deli, all of which are located at low elevations (<1 meter above sea level). These conditions significantly disrupted local socio-economic activities, with results indi-cating that total economic losses from coastal flooding in Medan Belawan during July 2025 amounted to approximately IDR 6.05 billion per month. The household sector contributed the largest share (IDR 4.75 billion), followed by small business units (IDR 291 million) and public facilities (IDR 1.01 billion).

In addition to the area's low topography, the extensive inundation in Medan Belawan is closely linked to land subsidence. A national-scale study by Ao et al. (2024) shows that many coastal regions in Asia, including Indonesia, are experiencing land subsidence at rates exceeding global sea-level rise, thereby amplifying the risk of extreme tidal flooding. Fang et al. (2022) further emphasise that the combined effects of land subsidence and relative sea-level rise (RSLR) constitute the dominant drivers increasing the frequency, depth, and duration of coastal flooding in densely populated urban areas.

This phenomenon is consistent with conditions in Belawan, where field measure-ments confirm ongoing annual land subsidence that exacerbates tidal inundation impacts. Consequently, the economic losses recorded across household, business, and public facility sectors are driven not only by the flood event itself but also by long-term geotechnical processes that diminish drainage capacity and weaken local infrastructure resilience (Fang et al., 2021).

Households accounted for the largest share of total losses, reflecting the high exposure of coastal communities whose livelihoods depend on daily income. The average economic loss per household reached 14.5% of total monthly income, consistent with Hallegatte et al. (2016), who highlight that low-income groups are the most vulnerable to coastal disasters due to their limited adaptive capacity.

In the business sector, losses amounted to IDR 291 million, with the highest con-centration in Belawan I and Bagan Deli. Damage to buildings, loss of merchandise, and reduced consumer purchasing power were the main factors suppressing small business revenues. These findings demonstrate that coastal flooding not only affects households but also disrupts the continuity of local economic activities (Widiyanto et al., 2019).

Meanwhile, losses in the public facility sector reached approximately IDR 1.006 billion, primarily driven by damage to public buildings and disruptions to essential services such as education and healthcare. These impacts indicate that coastal flooding imposes long-term

social consequences that may slow economic recovery and reduce overall community well-being (Rosenzweig et al., 2019).

Overall, the observed loss pattern suggests that areas with high population density, low elevation, and concentrated economic activities experience significantly greater impacts. This underscores the importance of risk-based spatial planning and the implementation of mitigation strategies such as flood-resilient infrastructure, integrated drainage systems, and ecosystem-based solutions (green infrastructure), as recommended by Scussolini et al. (2017).

6. Conclusion

The July 2025 coastal flooding in Medan Belawan resulted in substantial economic losses, amounting to approximately IDR 6.05 billion (~USD 364,000) per month across households, businesses, and public facilities. The inundation extent—covering nearly 79.5% of the study area—demonstrates the high vulnerability of this coastal district to the combined effects of sea-level rise, land subsidence, and extreme rainfall. Household losses constituted the largest share, reflecting the limited adaptive capacity of coastal communities facing recurring floods. Business activities and public facilities also suffered significant disruptions and damage to assets. These findings underscore the need for integrated adaptation strategies that strengthen physical infrastructure, enhance socio-economic resilience, and incorporate ecosystem-based approaches to reduce future coastal flood risks.

The findings of this study corroborate international evidence indicating that coastal flood risk is intensifying due to the combined effects of sea-level rise, land subsidence, and increasing extreme weather events (Vousdoukas et al., 2018; Fang et al., 2022). Consequently, coastal areas such as Medan Belawan require long-term adaptation strategies that extend beyond hard-engineering solutions, incorporating ecosystem-based approaches and strengthened socio-economic capacity as fundamental components of disaster resilience.

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