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Performance Evaluation of IDSL for Tsunami Early Warning Systems at Bungus Port

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Abstract

Indonesia is highly vulnerable to near-field tsunamis due to its tectonic setting along active subduction zones. Rapid detection of sea-level anomalies is therefore critical for the effectiveness of Tsunami Early Warning Systems (TEWS). This study evaluates the performance of an Inexpensive Device for Sea Level (IDSL) installed at Bungus Port, West Sumatra, with particular emphasis on its suitability for real-time tsunami monitoring. The performance assessment includes sea-level measurement accuracy, data gaps, transmission latency, alert functionality, and webcam-based verification. IDSL observations show strong agreement with predicted tidal data from the Geospatial Information Agency (BIG), with a correlation coefficient of 0.98 and a root mean square error (RMSE) of 0.10 m. The average data transmission latency ranges between 3 and 10 seconds, indicating near-real-time capability suitable for early warning applications. Data gaps were generally short (3–5 minutes) and were primarily caused by communication disturbances. Webcam imagery also provided reliable visual validation, with more than 90% of the images classified as good quality. Overall, the results demonstrate that the IDSL system provides reliable, low-latency sea-level monitoring and represents a promising complementary instrument for strengthening Indonesia's TEWS, particularly in tsunami-prone coastal regions.

Keywords*—IDSL, Tsunami Early Warning System, sea level monitoring, latency, tsunami detection*

I. INTRODUCTION

Owing to its location at the convergence of the Eurasian, Indo-Australian, and Pacific tectonic plates, Indonesia is one of the most tsunami-prone countries in the world. Coastal regions facing active subduction zones, particularly along western Sumatra, are exposed to frequent seismic activity capable of generating destructive tsunamis (Sieh & Natawidjaja et al., 2000; Subarya et al., 2006). Historical events have shown that near-field tsunamis in this region can reach coastal communities within tens of minutes, leaving limited time for evacuation and emergency response. Effective early tsunami warning systems must rely not only on rapid earthquake detection but also on real-time sealevel observations to confirm tsunami generation and improve warning reliability. (Lauterjung et al., 2017). The western coast of Sumatra, the southern coast of Java, Nusa Tenggara, northern Papua, Sulawesi, Maluku, and parts of eastern Kalimantan are vulnerable coastal regions in Indonesia (BMKG, 2012).

West Sumatra is one of the most susceptible Indonesian provinces to earthquake and tsunami hazards (Sandy, 2018). The offshore region is characterized by high seismicity associated with the Sunda Subduction System, where the Indo-Australian Plate converges beneath the Eurasian Plate (Yudichara et al., 2010). The distribution of earthquake epicenters shows increasing focal depths toward the east, reflecting the subducting slab’s geometry (Natawidjaja et al., 2006). Geological evidence from coral microatolls further indicates that past megathrust earthquakes have generated significant vertical seafloor deformation, producing tsunamis that impacted the western coast of Sumatra and the Mentawai Islands (Natawidjaja & Triyoso, 2007). These characteristics highlight the importance of reliable coastal monitoring systems capable of detecting tsunami-associated rapid sea-level anomalies.

Despite significant technological progress, the exact timing of earthquakes and tsunami generation remains inherently unpredictable. Therefore, disaster risk reduction efforts primarily focus on minimizing potential impacts through effective monitoring and early warning mechanisms (Nanang, 2000; Baeda, 2010). Arrival times for nearfield tsunamis may be less than 30 minutes after the triggering earthquake, requiring extremely rapid dissemination of early warning information to support timely evacuation procedures (Husrin et al., 2013). In Indonesia, the Geospatial Information Agency (BIG) tide gauge network largely supports coastal sea-level monitoring. Although conventional tide gauges provide reliable long-term sea-level observations, their sampling intervals and transmission latency may limit their ability to detect rapid sea-level changes associated with near-field tsunamis. Furthermore, the spatial density of monitoring stations in several high-risk coastal regions remains limited.

To address these limitations, additional real-time monitoring technologies must complement the existing tsunami observation networks. The Inexpensive Device for Sea Level (IDSL), developed by the Joint Research Center of the European Commission, is designed to provide high-frequency sea-level measurements with automated anomaly detection and rapid data transmission (Annunziato et al., 2019). Its relatively low cost and autonomous operation enable deployment in remote or underserved coastal areas, supporting the development of denser monitoring networks. Since 2019, IDSL sensors have been installed at eight locations across West Sumatra and southern Java since 2019 (Husrin et al., 2022). However, despite their increasing deployment, comprehensive evaluations of IDSL operational performance under real-world coastal conditions remain limited.

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Therefore, this study aims to evaluate the operational performance of the IDSL instrument deployed at Bungus Port (IDSL 305), West Sumatra (Figure 1) and assess its suitability as a supporting component of Indonesia’s tsunami early warning infrastructure. Through integrated webcam observations, the evaluation focuses on key operational parameters, including measurement accuracy, data transmission latency, data reliability, alert system behavior, and visual verification capability. The results of this study provide important insights into the potential role of low-cost realtime sea-level monitoring systems in strengthening early warning capabilities in Indonesia’s tsunami-prone coastal regions.

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II. RESEARCH METHOD

The analysis focuses on the IDSL-305 station located at Bungus Port, Padang City, West Sumatra, Indonesia. Operational since August 1, 2020, the instrument facilitates continuous coastal monitoring by capturing highresolution sea-level data at precise 15-second intervals. These empirical datasets were systematically retrieved from the centralized IDSL monitoring server (https://webcritech.jrc.ec.europa.eu/TAD_server/Device/483) to conduct a detailed performance analysis covering the initial observation period from August 1 to August 31, 2020. The evaluation encompasses a multifaceted assessment protocol, which includes validating the accuracy of the sea-level measurements, analyzing data continuity through gap identification to determine operational reliability, assessing data transmission latency, verifying the responsiveness of the automated alert system, and evaluating the integrated webcam imagery for visual validation. The location of the IDSL-305 installation can be seen in Figure 1.

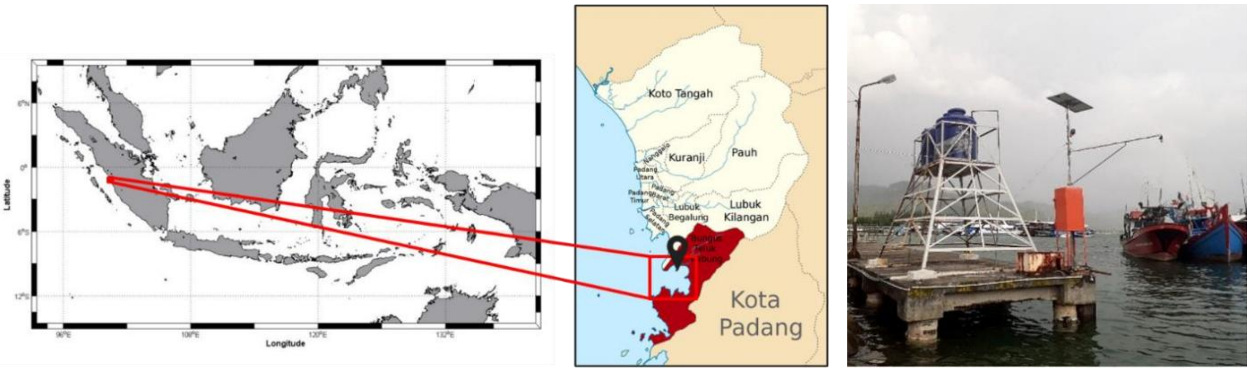


Figure 1 IDSL-305 installation location

To rigorously ascertain the observational accuracy of the IDSL-305 station, the recorded sea-level measurements were validated against authoritative tidal prediction data sourced from the Indonesian Geospatial Information Agency (Badan Informasi Geospasial, BIG). The statistical robustness of this validation was subsequently quantified utilizing established metrics, specifically the Correlation Coefficient (CC) to measure the strength of the linear relationship, the Root Mean Square Error (RMSE) to evaluate the standard deviation of the measurement errors, and the Mean Absolute Percentage Error (MAPE) to determine the overall measurement precision relative to the predicted models.

The statistical metrics were calculated using the following equations:

$$\text{CC} = \frac{\sum_{i=1}^{N}(x_i - x)(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{N}(x_i - x)^2 \sum_{i=1}^{N}(y_i - \bar{y})^2}} \tag{1}$$

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{N}(y_i - x_i)^2}{N}} \tag{2}$$

$$MAPE = \frac{1}{N}\sum_{i=1}^{N}\left|\frac{y_i - x_i}{y_i}\right| \times 100\% \tag{3}$$

Whwere:

n : the number of data

i : data order

X_i : model data

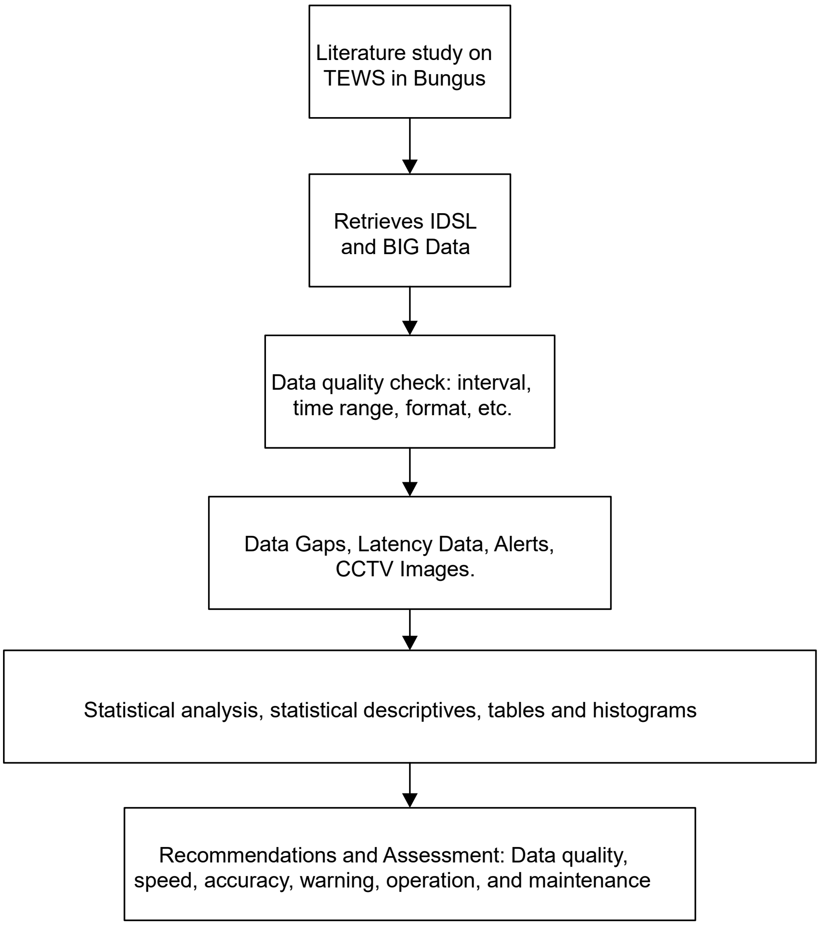
y_i : obsrvasi data

$\bar{x}$: mean ofmodel data

$\bar{y}$: average observation data

Data gaps were identified from the TAD server database, which can be accessed at https://webcritech.jrc.ec.europa.eu/TAD_server/Device/483. The data gap is then calculated descriptive statistics in the number of gaps, total gap duration, mode, median, average, minimum, maximum, and range of data gaps in the three stations.

The alert system is viewed by matching the alert data contained in the raw data with incoming sms/e-mail, validating with webcam captures, and considering the results of elevation measurements (whether there is an elevation spike that indicates a tsunami or not). Then image analysis is carried out by calculating the percentage of images with good quality (bright, sea-level elevation is visible), medium quality (less precise, sea-level height is still visual), poor quality (dark/blurry, not visible sea level elevation). As for the latency data, look at the graph on the interactive plot on the website and see the descriptive statistics of the current latency value. The workflow diagram can be seen in Figure 2 below.



III. RESULTS AND DISCUSSION

A. Sea-Level Accuracy

Based on one month of data, the tidal range, defined as the difference between the highest and lowest water levels during the observation period, is approximately 1.42 m**.** The minimum recorded tidal elevation is 0.64 m, while the maximum reaches 2.06 m, with a mean sea level of approximately 1.27 m**.**

Data validation was conducted by evaluating the correlation between observational data and tidal predictions obtained from the IDSL and BIG tide gauges. For the August 2020 observations at Bungus Port, the correlation coefficient between the IDSL and BIG datasets is 0.98, indicating a very strong agreement between the two datasets.

A correlation value approaching 1 signifies higher accuracy and consistency in the analysis results, while a positive correlation indicates a directly proportional relationship between the compared datasets.

The Root Mean Square Error (RMSE) between the two datasets is 0.10 m, representing the average magnitude of prediction errors. Lower RMSE values indicate better model performance. The Mean Absolute Percentage Error. (MAPE), which represents the average absolute error over a given period, is calculated to be 14% (0.14) for the IDSL and BIG data at Bungus Port.

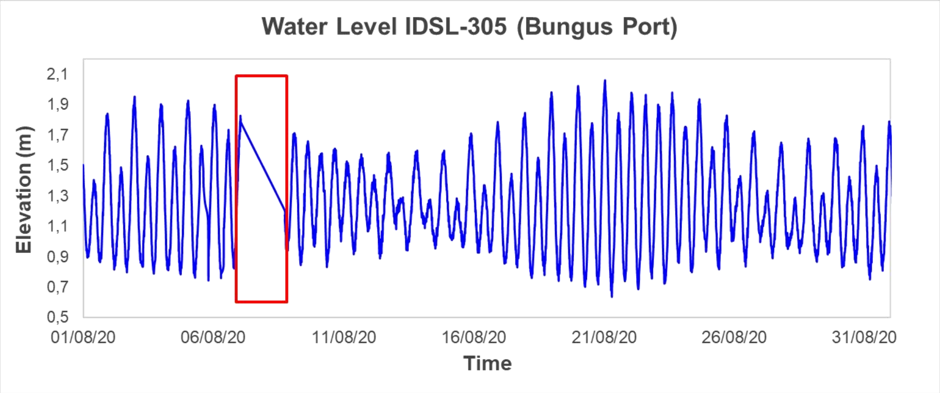


Figure 3 Tidal elevation from IDSL measurements, Bungus Port

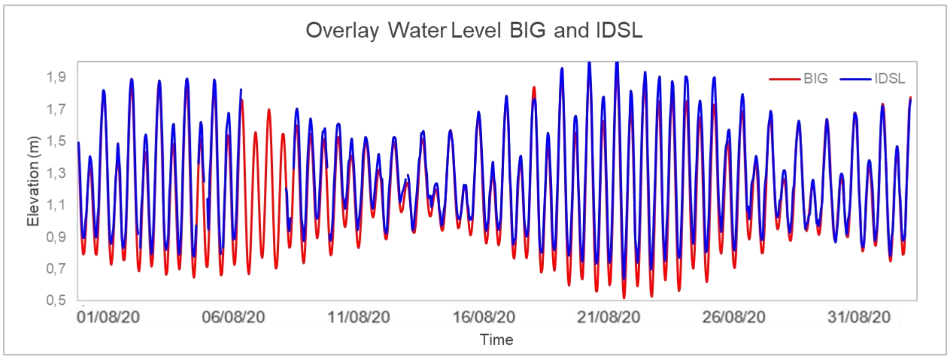
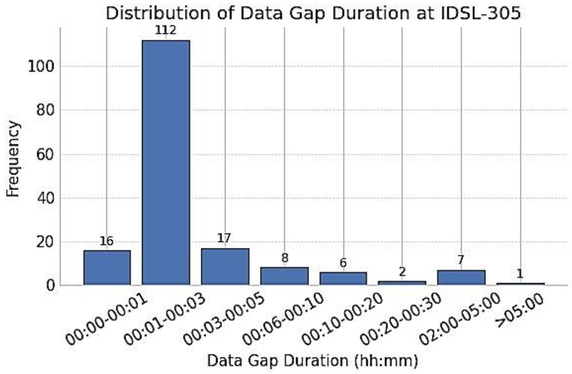


Figure 4 Overlay of observation and prediction data in August 2020 at Bungus Port

B. Data Gaps

Gap analysis is used to evaluate the performance of the tool. This gap analysis is also intended to identify what actions are needed to reduce the gap to achieve the expected performance of the instrument. Currently, IDSL is claimed to have a reasonably good algorithm compared to other tide gauges in Indonesia in reducing the gaps that arise. The following data gap analysis calculates the number and percentage of gaps that occur from various causes.



Statistic	Value
Number of gaps	169
Total	1 d 17:41:44
Min	00:01:35
Max	1 d 16:22:31
Range	1 d 16:20:56
Mean	08:28:44
Median	00:02:03
Mode	00:01:54

Figure 5 Histogram graph of data gaps (left) and descriptive statistics (right) of IDSL data during August 2020 at Bungus Port.

C. Latency

Latency measures the time it takes for data to travel from a source (measurement instrument) to a destination (processing software). The greater the latency value, the slower the response is given so that this latency value can be used as an indicator of the quality of the tool. Long latency will take time between measurement and processing, making warnings significantly delayed (Husrin et al., 2020).

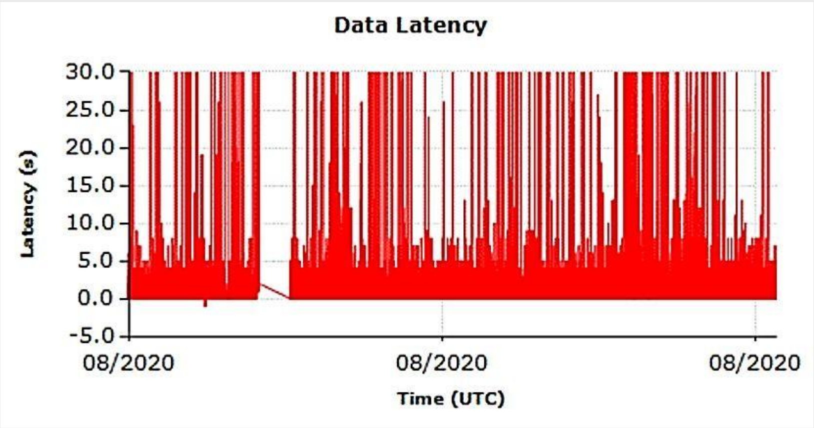


Figure 6 Graph of Bungus Port latency in August 2020

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The latency values recorded at Bungus Port during August 2020 are presented in Figure 6. The average latency at this station ranges between 3 and 10 seconds, indicating generally rapid data transmission performance. Nevertheless, several sporadic latency spikes were observed, with delays extending from minutes to several hours.These anomalies are primarily attributed to communication signal disturbances affecting data transmission between the instrument and the server.

Overall, the latency performance at Bungus Port can be considered satisfactory, as most latency values remain within the second-scale range. Such low latency is essential for real-time data processing, enabling faster dissemination of tsunami early warnings. However, detailed statistical analysis could not be performed because raw latency data are currently unavailable on the TAD server platform.

D. Alerts

On the IDSL instrument, the alert level is computed directly within the data logger using a detection methodology based on a Kalman filter**,** which evaluates the difference between the observed sea-level signal and the expected wave behavior. When this difference exceeds a predefined multiple of the signal's standard deviation, the alert level increases by one unit, with a maximum alert level set at 10.

Automatic notifications in the form of SMS and email are triggered when the alert level exceeds two units. If the detected anomaly persists and the alert level continues to increase, repeated notifications are issued at five-minute intervals. These warnings are transmitted to a predefined distribution list, including the Indonesian Agency for Meteorology, Climatology, and Geophysics (BMKG), where further verification of the detected event is conducted.

The overall alert mechanism is illustrated in Figure 7.

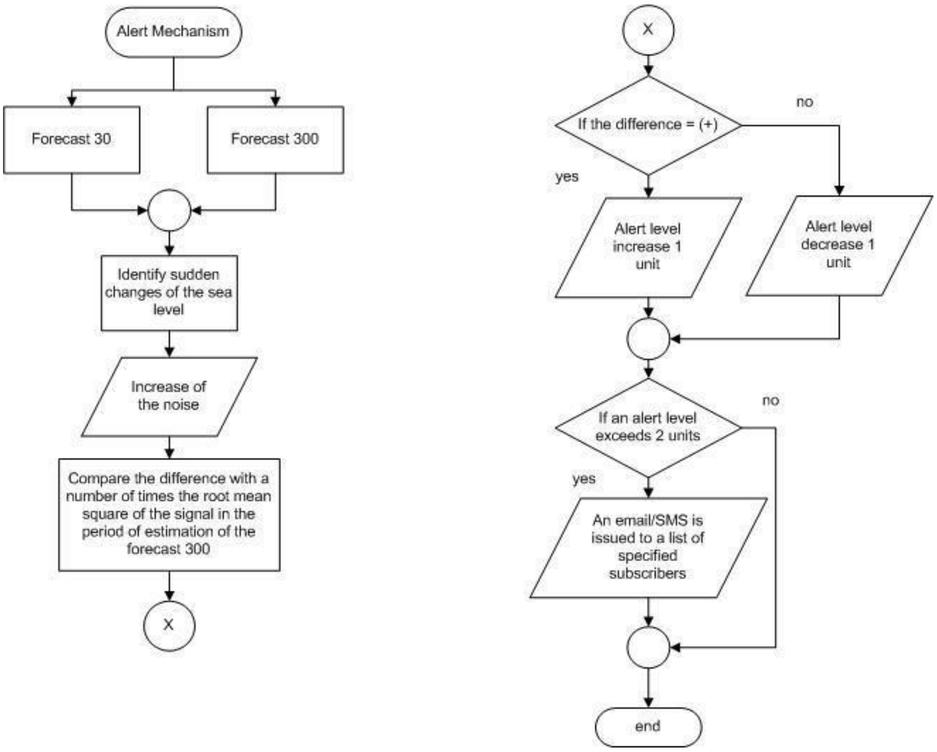

Figure 7 Mechanism of *alert*

Table 1 Occurrence of *alert* signals in August 2020

Time (UTC)	Alert	Elevation (m)
21/08/2020 13:52:33	1	1.76
21/08/2020 14:18:51	0	1.788
21/08/2020 14:26:01	10	1.71
21/08/2020 14:35:37	10	1.722

During August 2020, a total of three alert events were recorded at Bungus Port, as summarized in Table 1. To verify each alert signal, the detected events were cross-checked against the corresponding sea-level elevation measurements. The analysis showed no significant or sustained anomalous sea-level increase that would indicate the presence of high waves or tsunami activity.

Instead, the detected anomalies are likely associated with localized disturbances caused by vessel movements near the instrument sensors. Such disturbances can generate short-period fluctuations in sea level that temporarily trigger the alert system but do not represent tsunami-related signals.

E. CCTV *Webcam*

Table 2 presents the classification results of webcam images acquired from the IDSL-305 system. During the one-month observation period from August 01, 2021, to August 31, 2021**,** a total of 2,976 images were expected to be recorded. However, due to data gaps that temporarily interrupted IDSL operation, including webcam acquisition, only 2,587 images were successfully collected, resulting in 386 missing images. This corresponds to an image availability rate of 86.93%**.**

Table 2 Calculation of IDSL-305 *webcam* image quality classification

	Count	Percentage (%)
Poor Quality	59	2.28
Mid-Quality	28	1.08
Good Quality	2500	96.64

Image quality percentages were calculated based on the proportion of good-, medium-, and poor-quality images relative to the total number of available images. Most images recorded at Bungus Port were classified as good quality, accounting for 96.64% of the dataset (Figure 8). Good-quality images allow clear and bright visualization of sea-level conditions, enabling reliable visual verification.

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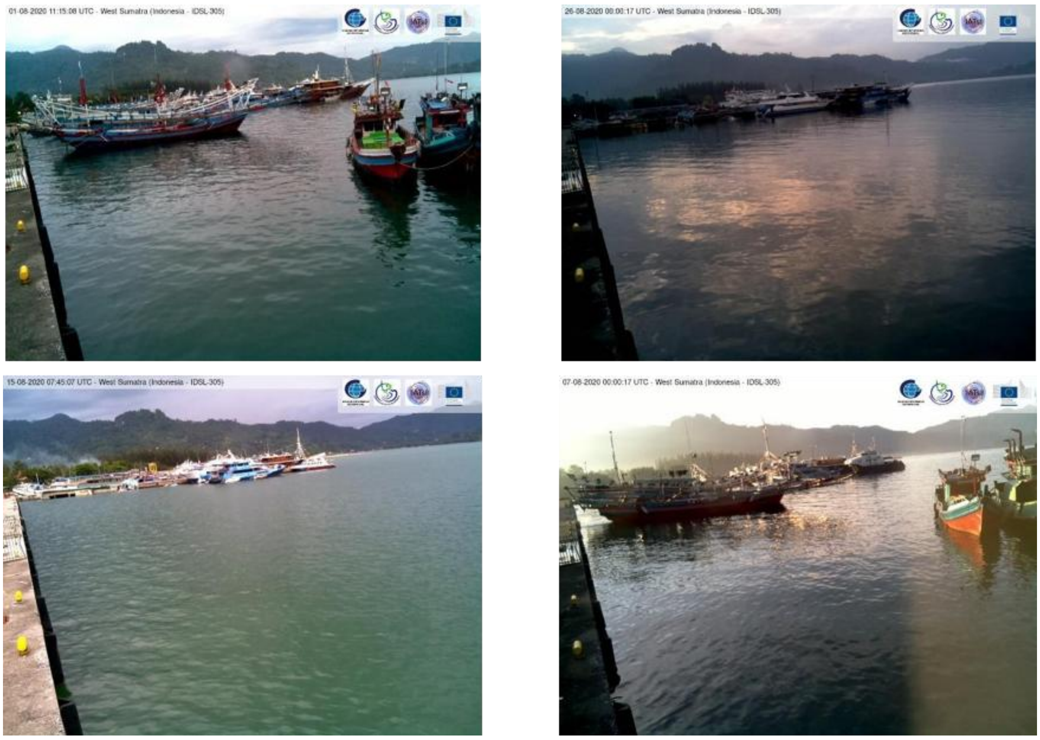

Figure 8 Image captured by the IDSL-305 webcam at Bungus Port

Images categorized as medium quality represented 1.08% of the dataset. These images generally correspond to conditions where sea-level visibility was partially obscured, often due to environmental factors such as rainfall or water droplets covering the camera lens (**Figure 9**). Meanwhile, poor-quality images accounted for 2.28%**,** characterized by insufficient visibility of sea-level conditions, primarily caused by inadequate lighting, especially during nighttime observations.

Given the importance of webcam imagery as a supporting verification tool during sudden sea-level anomalies, improvements in image quality management are necessary to ensure operational reliability. Adequate lighting conditions were found to significantly influence image clarity. Approximately 1134 images, equivalent to 45.36% of all good-quality images, benefited from illumination provided by docked vessels at the Port. This finding highlights the critical role of sufficient artificial lighting around the Port pier, particularly within the camera's field of view, in enhancing nighttime sea-level monitoring capability.

Based on the modeling results and the water level condition graph (Figure 4), sea-level variations exhibit a regular and repetitive pattern, with peak tides around 0.95 m and low tides approximately 0.1 m. This pattern reflects a semi-diurnal tidal regime, characterized by two high tides and two low tides within one day. Overall, the modeled sea level appears relatively stable without extreme spikes, indicating that the water level simulation adequately represents actual tidal conditions.

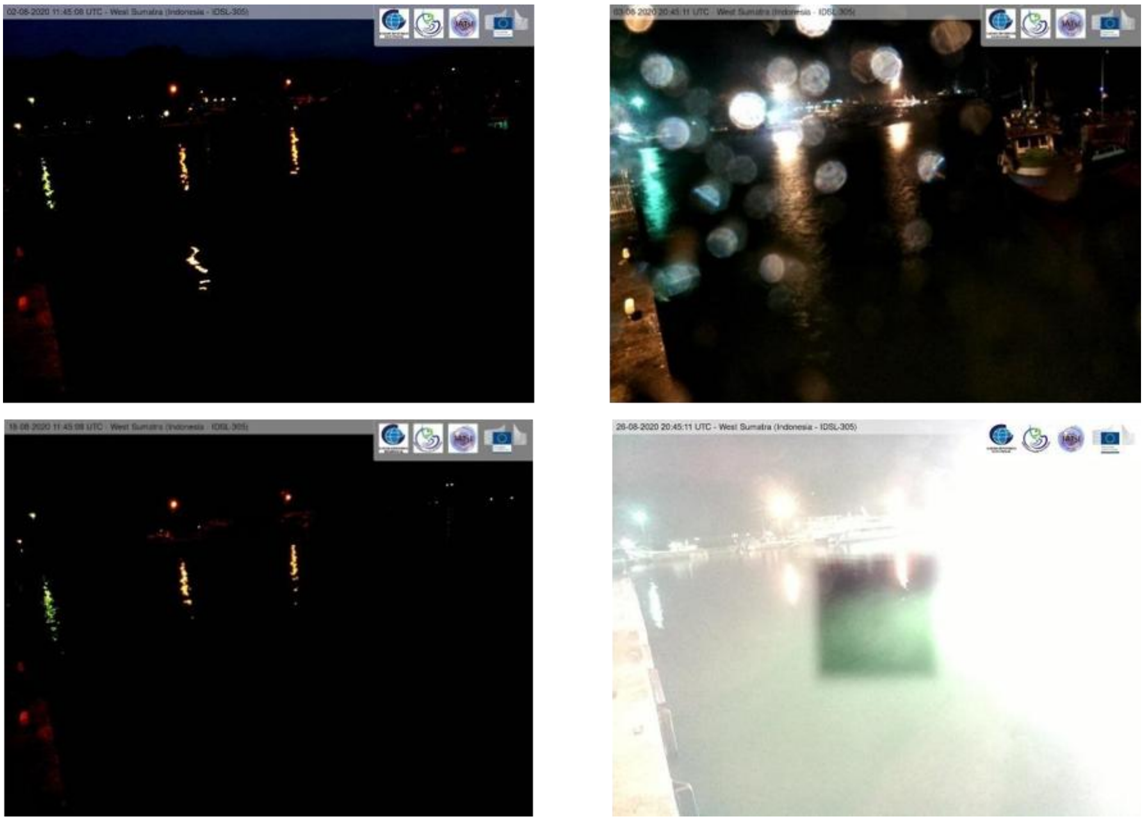

Figure 9 Unclear image captured by the IDSL-305 webcam

F. IDSL for Tsunami early warning system in West Sumatera

The IDSL sea-level elevation data demonstrate excellent agreement with tidal predictions obtained from the BIG tide gauge system, indicating high measurement reliability. During the monitoring period, data gaps at the Bungus stations were predominantly observed within intervals of three to five minutes, mainly caused by communication signal disturbances. Longer data gaps, ranging from several hours to days, were primarily associated with technical issues such as delays in internet service renewal. Observed latency values of 3–10 seconds satisfy operational requirements for near-field tsunami detection, where warning decisions must be issued within minutes following tsunami generation. Compared with conventional tide gauges that may experience reporting delays of up to 10 minutes, the IDSL system provides substantially improved detection responsiveness.

The IDSL alert mechanism demonstrates adequate capability for the early detection of anomalous wave conditions; however, alerts are occasionally triggered by localized disturbances, particularly vessel-induced waves near the instrument location. These false alerts emphasize the need for adaptive filtering approaches or integration with multi-sensor verification within broader Tsunami Early Warning System (TEWS) frameworks (Adityawan et al, 2023). Overall, webcam imagery exhibits excellent performance, with average image quality exceeding 90%. Adequate lighting conditions around the jetty were identified as a critical factor in maintaining high-quality visual observations, particularly during nighttime monitoring. The results indicate that the IDSL system is operationally reliable and technically suitable as a complementary component of tsunami early warning systems in tsunami-prone regions of Indonesia.

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Based on latest tsunami numerical simulation, Bungus bay, West Sumatera will experience tsunami inundation up to 5 m and tsunami arrival time in less than 45 minutes (Kongko et al, 2010). This means, the golden time for warning system allowing the people to evacuate, in even shorter period of time or within a range of 15-30 minutes. The performance of IDSL in detecting the anomalies (tsunami signals), almost instantly after the earthquake event due to the rapid changes of earth elevation and rundown of tsunami waves will help the existing InaTEWS network to immediately provide tsunami early warning at the community level. The early warning system at the community level were always a challenging tasks due short period of time to react to the emergency situation (UNDRR & UNESCO/IOC, 2019). Practically, in field operations, deploying IDSL stations addresses this bottleneck by translating abstract seismic alerts into confirmed hydrodynamic threats within seconds. This rapid physical validation provides local disaster management agencies (BPBD) with the decisive empirical evidence required to confidently trigger coastal evacuation sirens without hesitation. The necessity of this approach is strongly echoed in global coastal monitoring literature, which heavily advocates for the densification of observational networks using low-cost, highfrequency sensors. Studies emphasize that standard spatial gaps in traditional, sparse tide gauge networks often delay the confirmation of near-field tsunamis (Lauterjung et al., 2010). Therefore, additional sensors, such as IDSL will always be needed to fill the technological gaps within the InaTEWS system.

IV CONCLUSION

From tidal analysis, data gaps, alerts, latency, and webcams, IDSL is suitable to enhance the existing tsunami early warning system (InaTEWS). Rapid detection and visual validation will help authorities to provide early warning at the community level (e.g. to switch on the emergency alarms). The following are suggestions and recommendations that the author can provide regarding the performance of IDSL so that it can work even better in the future.

a. Cooperate with cellular telecommunications operators in Indonesia to avoid delays in payment of internet quota on equipment and signal repair in the local area to reduce data *gaps*.
b. For *websites*, *raw data* latency can also be accessed for further analysis.
c. The location of the instrument installation should be kept away from passing ships (or a particular policy can be made where there is a certain perimeter that is free from disturbance by ships).
d. The lighting of the dock, especially in the area captured by the *webcam, is* essential to provide good lighting to cope with dark conditions at night. A similar suggestion is to provide a *flashlight* on a device to light the captured image.
e. External factors can interfere with the quality of the captured image, such as insects adhering to the lens, water dew on the lens, etc. The webcam's position can be adjusted so that things like this can be avoided.
f. The Tsunami Early Warning System (TEWS) should be redeployed in tsunami-prone areas to provide early warnings to surrounding communities as part of mitigation efforts, in accordance with the responsibilities of Indonesia’s national disaster management authorities

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