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Optimizing Aids to Navigation Placement: A GIS and AIS-Based Analysis of Vessel Traffic and High-Risk Areas in West Port

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ABSTRACT

Aids to Navigation (AtoNs) support safe vessel movement through confined port approaches, but their placement must be assessed against changing traffic patterns, bathymetry and charted constraints. This study examines opportunities to improve the distribution of AtoNs in the West Port approaches of Port Klang, Malaysia, using Automatic Identification System (AIS)-associated vessel-density mapping and a geographic information system (GIS) overlay. A geospatial screening framework combines traffic-concentration surfaces, indicative water-depth classes, existing and candidate AtoN symbols, the port boundary and mapped features such as a cable corridor, a spoil ground and an explosive dumping ground. Three map views describe the existing situation and proposed candidate positions. The assessment identifies the channel approach and turning areas as priorities for reviewing lateral and lighted guidance, while charted hazard areas require separate consideration of appropriate warning or danger-marking functions. The maps provide an initial basis for prioritising field assessment but do not establish a measured increase in visibility coverage, a reduction in casualty probability or a globally optimal set of installation coordinates. A site-specific process integrating validated AIS records, bathymetric data, IALA buoyage standards, visual-range analysis and consultation with the competent authority is therefore required before installation. The study offers a practical screening workflow for targeted AtoN planning in congested Malaysian port approaches.

Keywords: aids to navigation; automatic identification system; geographic information system; Port Klang; traffic density

1. Introduction

Safe navigation within busy port approaches depends on reliable position information, awareness of traffic movements and unambiguous external navigational guidance (Xin et al., 2023; Zaman, 2016). Aids to Navigation (AtoNs), including buoys, fixed lights and beacons, assist mariners in recognising safe-water routes, channel boundaries and defined hazards (Alexandrov et al., 2024; Johansen et al., 2016). Their operational value depends not only on whether a mark exists but also on its location relative to ship routes, its purpose, characteristics and effectiveness under foreseeable visibility and traffic conditions (Fang et al., 2015). The International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA, 2023) provides the maritime buoyage framework within which marking types and functions should be understood.

The West Port approaches lie within the Port Klang port system on the west coast of Peninsular Malaysia. The approach setting combines concentrated merchant-vessel movements with channel alignment requirements and charted offshore uses. Vessel traffic can change by time of day, vessel type and operational practice; consequently, AtoN review should use evidence on how ships actually navigate, rather than assume that every fixed point on a chart provides comparable guidance. AIS-derived trajectory and density analysis can help locate major traffic corridors and changes of movement direction (Kim et al., 2022; Lee et al., 2022).

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AIS traffic concentration is nevertheless not synonymous with collision or grounding risk (Xin et al., 2023). Risk also depends on ship encounter geometry, traffic control, navigation complexity, under-keel clearance and the consequences of deviation (Bakdi et al., 2019; Kamis et al., 2026). Relating AIS traffic to geospatial environmental and accident information can improve situational understanding, but each additional analytical step requires explicit assumptions and testable indicators (Li et al., 2019; Xin et al., 2023). AtoN planning must also respect port regulations, restricted infrastructure, hydrographic accuracy and maintenance requirements.

This study addresses three linked objectives: (1) characterising the principal vessel-traffic concentration areas visible in the West Port approach maps; (2) examining how existing AtoN positions relate to traffic, bathymetry and charted constraints; and (3) identifying candidate locations and mark functions for further detailed design and authority review. The contribution is a geographically explicit, GIS-supported siting assessment, not a completed mathematical location optimisation or a measured post-installation navigation-safety trial.

2. Literature Review

2.1 AIS traffic patterns as an input to navigational planning

AIS can provide repeated position and movement observations that make vessel trajectories amenable to spatial aggregation. Sang et al. (2015) demonstrated the relevance of AIS information to navigation-safety screening in the Malacca Strait, while the value of spatial-temporal measures that distinguish vessel occupancy from a simple aggregation of track lines (Huang et al., 2024; Jiang et al., 2025). This distinction is essential: the intensity visible on a map can change according to the reporting interval, cleaning procedure, counting unit and selected colour scale (Tixerant et al., 2018). Without an explicit metric, a density heatmap can reveal a spatial pattern but cannot establish an absolute passage rate (Nétek et al., 2018).

Trajectory-based route extraction can provide a complementary description of navigation corridors. Lee et al. (2022)developed a statistical-density and clustering framework for identifying traffic routes, and Zhang et al. (2024) examined a DBSCAN-based marine-trajectory clustering method using movement attributes. These studies support route and turning-point screening, yet the appropriate clustering parameters, vessel-category filters and spatial scale require case-specific calibration. Data-rich methods may also under-represent small craft that are not fitted with or do not transmit AIS.

2.2 Integrating geospatial constraints and traffic exposure

GIS can overlay ship tracks with the coastline, charted navigational aids, depth contours, regulated limits and potential obstacles. Li et al. (2019) demonstrated the analytical value of combining vessel movement information with geospatial context when studying maritime accidents. At a port entrance, charted shoals, restricted areas and submarine infrastructure may be relevant even where traffic intensity is lower. Conversely, high traffic in a properly marked channel does not automatically justify adding further floating marks (Yıldız et al., 2022).

Where quantitative risk scoring is intended, indicators require consistent spatial units and interpretable directions. A deeper-water cell should not receive a higher grounding-risk score simply because its raw depth value is larger. The selection of buffers, hazard weights and threshold rules should therefore be tied to a clearly defined question, such as whether a candidate site offers meaningful benefit to approaching vessels without interfering with the safe navigable width.

2.3 AtoN function, visibility and management

The IALA Maritime Buoyage System distinguishes lateral marks, cardinal marks, isolated danger marks, safe-water marks and special marks; they are not interchangeable labels for areas of concern (IALA, 2023). A lateral buoy normally relates to a defined channel side within the regional buoyage convention; an isolated danger mark is appropriate only where a danger with navigable water around it has been established; special marking or another measure may be needed for site-specific restrictions. Risk management and operational management of AtoNs are addressed by IALA R1002 and G1018 (IALA, 2017, 2022).

Visibility analysis should also recognise the difference between charted location, nominal or luminous range and actual conspicuity at sea. The existence of an AtoN symbol near a traffic route does not establish that the mark can be detected in haze, rain, darkness or adverse background lighting. Useful coverage studies account for mark characteristics, observer height, geographic horizon, surrounding lights, meteorological visibility, terrain and line-of-sight constraints.

2.4 Research gap and assessment focus

Published AIS and GIS analyses provide a basis for identifying navigationally relevant corridors, but a practical port-specific siting assessment must connect traffic patterns to the intended purpose of each mark and to constraints imposed by existing infrastructure (Xiao et al., 2014). The present assessment therefore concentrates on describing the available mapped West Port evidence, distinguishing feasible candidate-review zones from assertions of proven optimum positions and specifying the further measurements necessary to support installation decisions (Carneiro et al., 2018).

3. Materials and Methods

3.1 Study area and spatial framework

The study examines the West Port approaches within Port Klang, Malaysia. The presented maps include a portion of the nearshore approach and adjacent offshore waters, with indicated bathymetric bands, port limits, charted cable features, fixed or floating AtoN symbols and named areas such as a spoil ground and an explosive dumping ground. The geographical display is appropriate for relative positioning and candidate screening; it does not independently constitute a certified hydrographic survey or an approved installation chart.

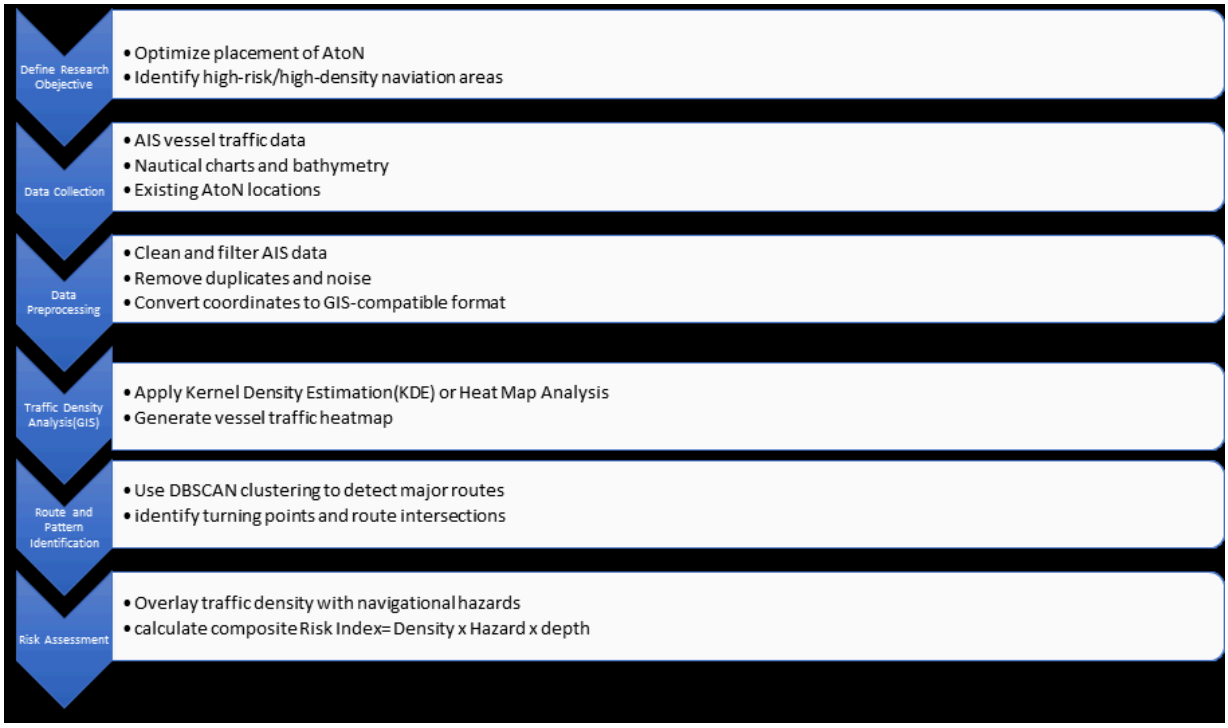


Figure 1. Workflow for traffic, geospatial and navigational-risk screening. The flowchart describes the intended analysis sequence; individual processing parameters require documentation for independent replication.

3.2 Data classes and preprocessing considerations

The spatial assessment brings together three core data classes: AIS-associated vessel movements, bathymetry and charted hazards, and existing/candidate AtoN positions as shown in Table 1. The map products include a traffic-intensity colour surface labelled as MMSI density. In AIS studies, raw fixes are ordinarily filtered for invalid coordinates and duplicate records before being projected into a suitable metric reference system. Since traffic maps can be materially affected by temporal sampling, missing AIS messages, vessel-type coverage and track interpolation, each of these steps should be recorded with the final GIS dataset.

Table 1. Dataset purpose and interpretation

Dataset or layer	Purpose in screening	Interpretation boundary
AIS-linked vessel tracks / density	Locate heavily used approach corridors and manoeuvring zones	Collection interval, MMSI count, traffic-unit definition and cell/kernel settings are not quantified
Bathymetry / charted depths	Differentiate approach waters and shallow-water proximity	Depth classes are indicative; certified survey datum and under-keel-clearance margins are not established
Existing AtoN symbols	Review marks relative to route geometry	Chart status, characteristics, serviceability and range need competent-authority verification
Candidate AtoN symbols	Visualise alternatives for further design appraisal	Exact WGS84 coordinates, channel clearances, costs and approvals are not established
Port limit, cable and hazard labels	Screen potential conflicts with marine infrastructure and restrictions	Boundaries, exclusion distances and hazard marking duties require nautical-chart confirmation

3.3 Vessel concentration and route screening

A practical AIS screening sequence involves selecting an observation window, checking MMSI identity and fix quality, projecting observations into a common coordinate system, and applying a defined spatial density metric. Kernel density estimation (KDE) or a cell-based occupancy rate can then be applied to distinguish frequently occupied corridor segments, while route clustering can help identify repeated approaches and turning sectors (Kim et al., 2022; Lee et al., 2022). The plotted traffic surface is assessed as a relative spatial pattern because numerical density units, display thresholds and processing settings are not reported alongside the maps.

The methodological framework also includes DBSCAN route clustering. The conceptual role of clustering is to distinguish coherent movement corridors from scattered AIS observations; however, no independently interpretable DBSCAN cluster IDs, epsilon distance, minimum-points setting or cluster evaluation statistics are available in the reported results. Accordingly, the figures are analysed as a traffic-density and cartographic overlay rather than as a demonstrated DBSCAN-derived route network.

3.4 Screening potential navigational hazards

Vessel-traffic concentrations are viewed together with bathymetric classes, channel geometry and charted restrictions. The initial framework proposes combining density and hazard information in a composite risk score. A physically interpretable score would first normalise its components—such as traffic exposure D_i, hazard proximity H_i and shallow-water exposure S_i—before applying a stated weighting or decision rule. An illustrative prospective form is $R_i = w_D D_i + w_H H_i + w_S S_i$, with each component scaled from 0 to 1 and non-negative weights summing to 1. This expression indicates the design requirement for a subsequent quantitative model; it is not a score calculated for the current map cells.

Risk here means a priority for further examination rather than a calculated probability of accident. The assessment does not assign collision likelihood, grounding probability or severity distributions to individual map locations. Such quantities would require encounter studies, hydrographic under-keel-clearance analysis and supporting historical records.

3.5 AtoN-coverage and siting appraisal

Candidate locations are screened against (a) the navigational purpose of the mark, (b) traffic density and direction changes, (c) hazard proximity, (d) existing aids and visual clutter, (e) charted submarine cable and port boundary constraints, and (f) navigation width and safe anchoring or mooring areas. A complete visibility study would additionally document geographical and luminous range, installed intensity and elevation, sector

characteristics, background lighting, meteorological visual range and observer eye height. As these variables are not quantified in the present spatial outputs, references to possible coverage gaps should be read as planning hypotheses, not measured failures of individual AtoNs.

3.6 Standards and decision sequence

The IALA buoyage framework and relevant risk-management guidance serve as the reference for deciding which, if any, AtoN type should be considered (IALA, 2017, 2022, 2023). Candidate sites should progress from GIS screening to updated nautical-chart verification, consultation with port users and pilots, hydrodynamic and visual assessments, cost/maintenance appraisal and approval by the competent Malaysian authority. No candidate location presented here is designated as authorised for installation.

4. Results

4.1 Existing AtoN and traffic-density map

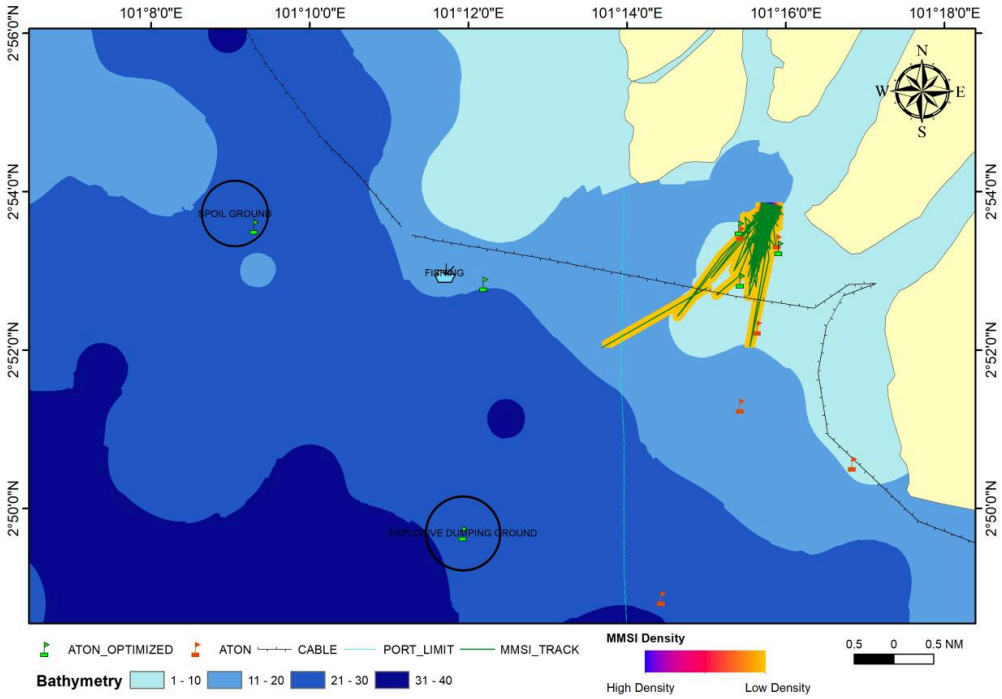


Figure 2. Mapped bathymetric bands, vessel-density pattern, existing AtoN symbols and charted constraints within the West Port approach study area.

Figure 2 shows a concentrated set of vessel tracks near the channel approach and inner port access, superimposed on graded bathymetric classes. Mapped AtoN symbols are present along parts of the approach; charted cable segments, port-limit markings and named offshore areas provide additional context. Depth-band labels distinguish shallow and deeper classes, while the traffic display uses a relative colour ramp rather than a numeric count of passages. Consequently, it establishes the broad spatial relationship between vessel routes and existing marks but does not measure whether any individual AtoN falls outside its specified coverage envelope.

The representation also makes colour-legend quality important. The map uses a multicolour MMSI-density ramp with qualitative labels; without numerical breaks and a confirmed density encoding, the colours should not be translated into exact encounter exposure or used alone to rank installation sites. The named spoil-ground and explosive-dumping-ground areas are treated as mapped features requiring chart verification, not automatically as unmarked navigational dangers.

4.2 Candidate AtoN-placement view

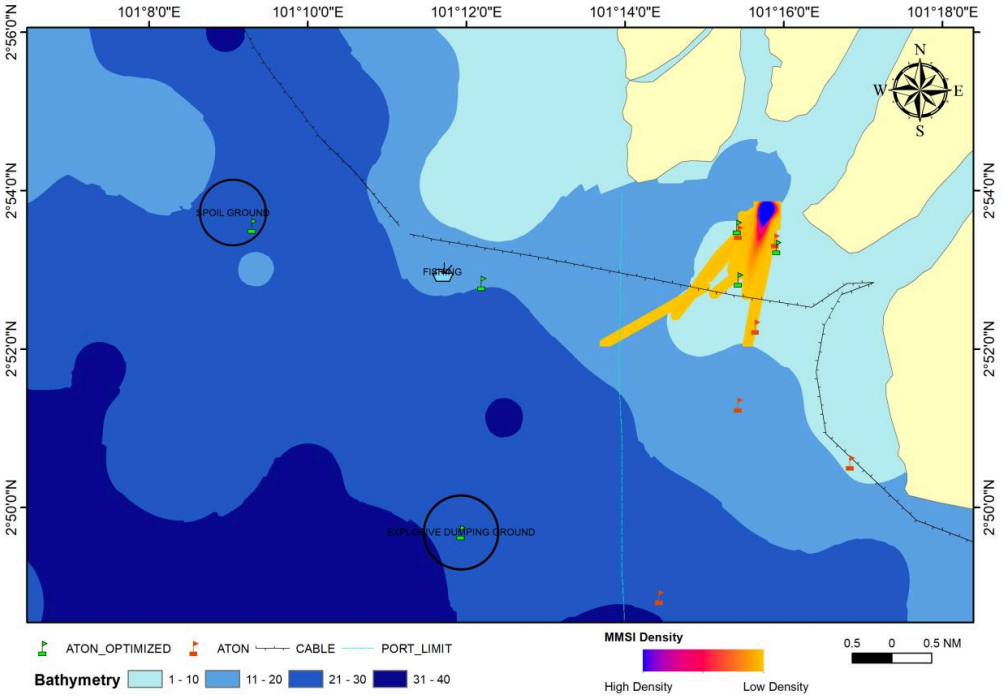


Figure 3. GIS screening view showing candidate AtoN symbols relative to existing marks, AIS-linked vessel concentrations, bathymetry and charted hazard areas.

Figure 3 places candidate AtoN symbols alongside existing marks and the traffic-density depiction. Several candidates appear around the approach alignment and its changes of direction, where directional guidance may assist route recognition. Other marks are displayed near more offshore mapped features. These patterns warrant differentiated review rather than a uniform conclusion that every location requires the same class of aid. The map also depicts a cable corridor, illustrating why practical installation assessment must include anchoring and mooring restrictions and seabed constraints.

4.3 Detailed map and candidate-siting rationale

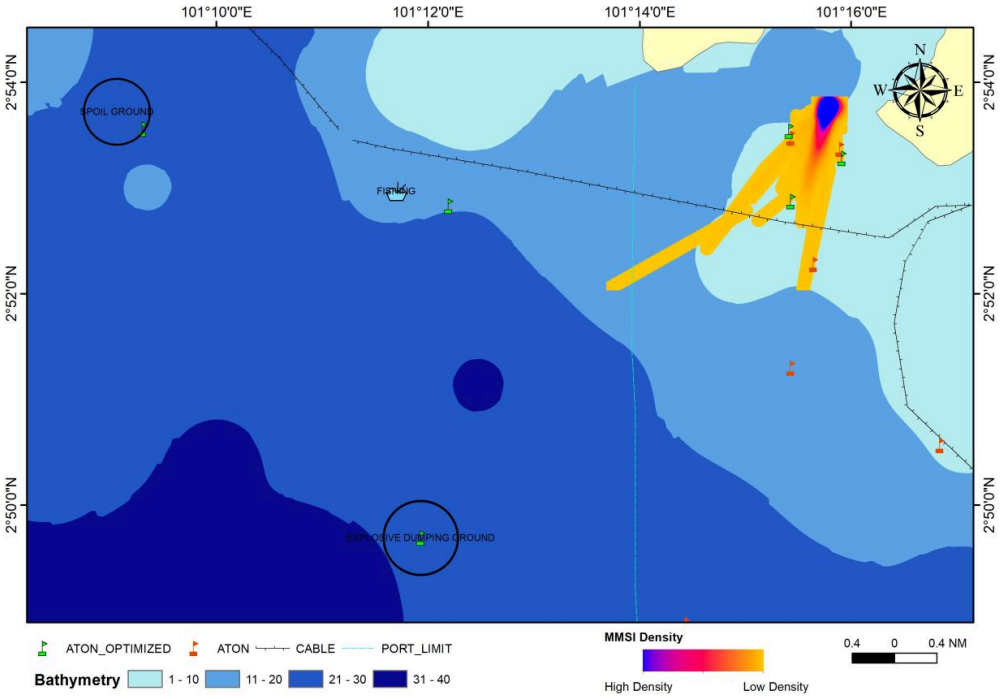


Figure 4. Detailed view of the charted approach, candidate AtoN positions and traffic overlay for site-by-site navigation appraisal.

Figure 4 provides a second detailed view of the mapped candidate network and its relation to the main traffic alignment. The figures enable preliminary grouping of siting functions, but they do not identify exact geographic coordinates, light characteristics or proven visibility-gain measurements. In particular, a channel-bend candidate should be evaluated for its lateral-marking purpose; an offshore hazard candidate should be assessed for its precise danger-marking function; and approach lighting should be assessed against existing lights and background illumination as shown in Table 2. Table 3 summarise the observable result, conclusion and further evidence needed.

Table 2. Screening zone AtoN purpose and confirmation

Screening zone or concern	Possible AtoN purpose	Necessary confirmation before a location is adopted
Approach-channel boundaries / turning points	Lateral route guidance and, if required, conspicuous night marking	Fairway direction, IALA Region A side conventions, channel clearance, traffic direction and current charted marks
Areas adjoining mapped shallow-water limits	Conspicuity of depth-related constraints	Survey datum, under-keel clearance, actual obstruction and whether AtoN marking is justified
Spoil-ground feature	Potential special marking or navigation warning, if designated	Legal status, extent and need for permanent marking; avoid presuming an isolated-danger mark
Explosive-dumping-ground label	Potential restriction/special-purpose marking subject to designation	Published limits, authority instructions, hazard status and permitted uses
High-use port entrance / approach	Review of lighted aid detectability and route alignment	Visibility, luminous/geographical range, navigation clutter, maintenance and pilot consultation
Cable corridor / port boundary	Conflict-avoidance constraint rather than automatic AtoN site	Cable protections, mooring footprint, exclusion limits and competent-authority approval

4.4 What the mapped results establish

Table 3. Result, conclusion and evidence needed

Observable result	Conclusion supported	Further evidence needed
AIS-linked density surface is co-plotted with bathymetry	Main navigational movement corridors can be identified visually	Counts or vessel-hours, sampling window, sensitivity to smoothing
Existing AtoN and candidate symbols occupy different plotted positions	Alternative locations are available for planning comparison	Coordinate register, functional inventory and official chart status
Hazard, cable and boundary layers overlap the study region	AtoN decisions must address non-traffic constraints	Certified chart positions, exclusions and seabed feasibility
Maps include no quantified pre/post service area or incident measures	A planning proposal—not a measured accident-risk reduction—is supported	Visibility model, before/after coverage, traffic conflicts, pilot trials

5. Discussion

5.1 Navigational significance of traffic concentration

The mapped traffic pattern reinforces the operational importance of channel entrance and alignment transitions. These are locations where vessel manoeuvres may require early visual confirmation, reliable chart information and coordination with traffic services. Evidence from AIS/GIS literature indicates the value of examining the relation between traffic behaviour and geospatial constraints (Li et al., 2019; Xin et al., 2023). Nevertheless, an AIS heatmap should not be interpreted as a direct estimator of collision probability. More transits can increase exposure, but safe separation and established traffic-management procedures may materially alter actual risk.

5.2 Choosing the right marking function

AtoN selection should begin with the specific message that a mariner needs to receive. A lateral mark can support channel-edge recognition when the permitted route and approach direction are well established. By contrast, marking a dumping ground or another charted restriction may require a special mark, warning

information or a different regulatory measure, depending on the current designation; an isolated-danger mark should not be installed merely because a map contains a circled label. The categories, colours and topmarks must comply with the applicable IALA Region A conventions and approved local practice (IALA, 2023).

An additional mark is not necessarily beneficial if it increases light clutter, conflicts with existing buoy sequences, obstructs safe transit or complicates maintenance. Improved publication of updated chart information, an adjustment to mark characteristics, a revised route layout or mariner guidance might address some concerns with less physical infrastructure. For that reason, the proposed AtoN screening results are best treated as a prioritised review programme.

5.3 Operational and regulatory considerations

Any practical proposal requires an approved location plan showing coordinates, chart datum, mark type, characteristic and assessed clearance from charted facilities. Submarine cable alignments and any port or anchorage restrictions shown in the maps require additional protection analysis. The installation footprint, mooring swing circle and maintenance approach route should not reduce navigable width or create a new collision or grounding hazard. A transparent authority review involving the port operator, pilots, hydrographic services and AtoN maintenance personnel would also test whether the marks address genuine information needs.

The cost of procurement and ongoing inspection, servicing and replacement should be considered alongside navigational benefit. AtoNs may fail or shift position, and service availability should be incorporated into operational risk management in accordance with IALA guidance (IALA, 2017, 2022). Field checks by day and night are required to confirm practical visibility before any declaration of service enhancement.

5.4 Limitations and future validation

The spatial evidence is limited by incomplete reporting of the underlying AIS observation period, message population, vessel selection and density-estimation settings. Exact AtoN site coordinates, official chart status, hydrographic survey datum, luminous range, and numerical GIS viewshed or visibility outputs are also not reported. Consequently, the analysis cannot identify a provably optimal network, a precise coverage percentage or the magnitude of any collision or grounding risk reduction. The plotted candidate points are preliminary planning locations.

A stronger validation programme would record a representative seasonal AIS sample and the proportion of non-AIS traffic; test density surfaces under alternate cell sizes and smoothing rules; evaluate proposed sites against certified chart and metocean information; compute before-and-after visible route coverage and geometric sight lines; and test bridge-team or pilot recognition in simulator and field assessments. Quantitative risk measures might include ship encounters, closest-point-of-approach distributions, near-miss indicators, deviation near shoals and task-specific mark detectability. Prospective improvements should be accepted only when matched to measurable, reproducible indicators.

6. Conclusions

An integrated GIS and AIS-based assessment of the West Port approaches identifies a set of navigational locations suitable for more detailed AtoN planning. The maps relate vessel concentration to bathymetric bands, existing charted aids, offshore features and candidate placements. Channel approaches and turns merit particular examination for lateral and lighted guidance; marked offshore uses require separate determination of the appropriate navigational message and buoyage category. The maps also emphasise the need to avoid conflicts with the cable corridor, port boundary and safe navigable channel.

The findings provide a preliminary location-screening framework rather than validated installation coordinates or measured improvements in casualty outcomes. To translate the candidate placements into an operational plan, a subsequent study must quantify AIS processing and optical coverage, verify charted constraints, evaluate design and maintenance requirements, and obtain competent-authority approval. This approach can support transparent, risk-informed prioritisation of AtoN enhancements within busy Malaysian port approaches.

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Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this manuscript, the authors used generative AI-assisted technologies to support language editing, grammatical refinement, and improvements in readability. The authors subsequently reviewed and verified the content and take full responsibility for the accuracy, originality, and integrity of the published work.

Conflict of Interest

The authors declare that they have no known financial or non-financial competing interests that could have influenced the research presented in this manuscript.

Author Contributions

Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request, subject to applicable ethical and confidentiality requirements.

Ethics Statement

The authors affirm that this research was conducted in accordance with applicable institutional and ethical standards. Where required, informed consent was obtained from participants, and appropriate measures were implemented to protect confidentiality, privacy, and data integrity.

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