Post Access Report

Guam Wave Resource Assessment

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EXECUTIVE SUMMARY

A pre-feasibility wave energy resource assessment was conducted for the island of Guam using a structured, standards-based analytical framework consistent with International Electrotechnical Commission (IEC) technical specifications. The primary purpose of this project was to compile, integrate, and analyze publicly available wave, bathymetric, and geospatial data to characterize wave energy potential along Guam's coastline and to identify candidate regions suitable for advancement toward future wave energy project development. The assessment was designed to support early-stage decision-making by reducing uncertainty associated with wave resource availability, spatial variability, and siting considerations in a remote island environment with limited existing observational data.

The specific objectives of the project were to: (1) perform a regional-scale, IEC-compliant screening of wave energy resources around Guam using validated hindcast datasets; (2) integrate wave resource information with environmental, regulatory, and infrastructure constraints to support site selection; (3) identify a limited number of candidate coastal regions that balance wave energy potential with deployment feasibility; and (4) conduct higher-resolution, site-specific wave resource characterization within selected regions to support prefeasibility-level evaluation. Collectively, these objectives were intended to establish a transparent and reproducible foundation for advancing wave energy project deployments on Guam without implying device specific performance or deployment outcomes.

To meet these objectives, the project employed a tiered analytical approach. A desktop study was first conducted to compile Tier 1 and Tier 2 geospatial datasets relevant to wave energy development, including regional wave hindcast products, bathymetry, environmental designations, navigation constraints, and coastal infrastructure. These datasets were integrated into a unified geospatial framework to support consistent spatial analysis. Regional-scale wave resource screening was then performed using the **S**ite **E**nergy **A**ssessment and **MO**nitoring **D**ashboard (SEAMOD) platform, which processed validated WAVEWATCH III hindcast data to derive IEC-recommended wave energy metrics and visualize spatial and temporal patterns in wave conditions around the island. Screening-level results were evaluated alongside infrastructure proximity and spatial constraints to identify candidate regions for further analysis.

Based on this integrated screening process, three candidate regions were selected for advancement: two along the western coastline, where infrastructure density and proximity to population centers are greatest, and one along the northeastern coastline, where wave energy exposure is highest. Higher-resolution numerical wave modeling was subsequently conducted within these regions using the SWAN model at 50-m spatial resolution over an 11-year representative period. The SWAN simulations resolved nearshore wave transformation processes and produced spatially and temporally resolved wave parameters and directional spectra suitable for IEC-aligned prefeasibility assessment. These outputs were used to derive standardized wave energy metrics, including omnidirectional wave power, directional characteristics, joint sea-state distributions, and annual energy production (AEP) estimates for representative study locations.

Results from the high-resolution modeling demonstrate clear and persistent spatial contrasts in wave energy conditions around Guam. The northeastern coastline exhibits the highest wave energy levels, with annual mean omnidirectional wave power reaching approximately 15 kW/m in exposed locations

and relatively persistent dominant wave directions. In contrast, the western and northwestern regions show lower wave energy levels, generally up to approximately 6 kW/m, reflecting leeward sheltering, coastal orientation, and bathymetric effects. Within the northeastern domain, AEP estimates for a representative wave energy converter range from approximately 300 to 1,000 MWh, with the highest values concentrated near the northeastern corner of the island. These results provide a quantitative, standards based comparison of relative wave energy potential among candidate regions and highlight the importance of resolving nearshore spatial variability when evaluating specific deployment locations.

Collectively, the outcomes of this project indicate that wave energy development in Guam is technically plausible at a prefeasibility level, particularly along the northeastern coastline where wave energy resources are strongest and most consistent. The results also demonstrate that regions with more moderate wave energy conditions may remain viable for certain applications when infrastructure access, grid connectivity, or islanded use cases are prioritized. Importantly, this assessment establishes a defensible, IEC-aligned characterization of Guam's wave resource that can be directly used to guide future feasibility-level studies, targeted high-resolution modeling, device-agnostic performance screening, and strategic field data collection. By integrating standardized analysis workflows with interactive decision-support tools, the project provides a scalable blueprint for advancing wave energy assessment and planning in Guam and other remote island settings where reducing early-stage uncertainty is critical to project advancement.

1 Introduction to the Project

The success of marine energy (ME) projects depends on low-cost, agile tools for site characterization and monitoring regardless of the size of the application. The U.S. Department of Energy (DOE) Office of Critical Minerals and Energy Innovation (CMEI) pioneers research and development efforts in ME technologies to improve performance, lower costs, and ultimately support the U.S.'s ability to sustainably meet its growing energy demand. ME technologies are still in early phases and developers are faced with excessive costs and limited resources for conducting the site assessments and monitoring that are necessary for project planning, deployment, and operation. The disparate nature of existing site assessment and monitoring services means that fragmented sources of information must be pieced together to support ME deployments.

Through discussions with Department of War (DoW), , U.S. military installations located on Pacific Islands, such as Guam, rely on diesel fuel as a source of power and are open to expanding their energy portfolio to include renewable resources. Preliminary evaluations have identified wave energy as a strong candidate that has benefits over wind and solar due to the potential of catastrophic failure of wind and solar installations during typhoons. Co-located access to seawater and a clean and inexhaustible energy resource makes wave energy a promising option for desalination, currently powered by diesel, and other energy applications that can enhance the resilience of coastal communities. However, to date, operational green energy-powered desalination systems have not been deployed in the U.S. or its territories. The deployment of a small-scale wave energy converter (WEC) array could support a remote community, such as the remote island of Guam, and its need for a green energy-powered fresh water supply. Bluewater Network, LLC. (BWN), in concert with the DoW, is evaluating the feasibility of a WEC array that supports Guam's freshwater and power needs.

The commercial success of ME projects, such as the Guam project proposed here, depends, in part, on the availability of tools that lower the cost and time required for project site characterization, permitting, construction, and monitoring. Currently, available tools for conducting site assessments require extensive resources for data interpretation that drives costs to well over $1 million. Integral Consulting's recently developed and validated **S**ite **E**nergy **A**ssessment and **MO**nitoring **D**ashboard (SEAMOD) application lowers the cost and time required to evaluate the viability of ME projects (Flanary et al. 2024; Jones et al. 2019; Chang et al. 2018). SEAMOD provides a site assessment that integrates existing wave energy resource data (National Laboratory of the Rockies' (NLR) wave energy dataset[1]) with the ability to couple state-of-the-art wave modeling using a user-friendly tool (SEAMOD) that fulfills the site assessment needs for BWN to evaluate site development plans.

The primary goal of this study was to perform a pre-feasibility wave energy resource study along the Guam coastline. This study compiled and integrated publicly available data crucial for a comprehensive wave energy resource assessment and siting for potential ME project development. The primary objectives were to:

[1] https://registry.opendata.aws/wpto-pds-us-wave/

- Perform a desktop study to characterize wave energy resources at a large scale (on the order of kilometers), focused on evaluating suitable WEC deployment areas near Guam's shoreline.
- Use SEAMOD's interactive database and information on existing WEC technology to support selection and siting.
- Select up to three locations that offer an optimal balance between high energy resource and deploy ability to ensure the feasibility of a WEC project in Guam.

2 Roles and Responsibilities of Project Participants

Bluewater Network, LLC. (BWN) and Integral Consulting Inc. (Integral) performed the tasks outlined in the Work Plan section below.

BWN was established in January 2022 to provide consulting services to the marine renewable energy sector. Since its founding, BWN has been retained on multiple consulting assignments including for the development of international standards, conformity assessment protocols, and guides for the International Electrotechnical Commission (IEC) for strategy development and implementation for the World Ocean Council's SMART Oceans–SMART Industries program, for development of internal and public-facing policies re: marine renewable energy for the Ocean Conservancy), to co-author a report for the Renewable Energy Alaska Project entitled, "Ocean and River Energy Resources in Alaska", to develop safety guidelines for the American Bureau of Shipping on behalf of the Ocean Energy Safety Institute (OESI), to lead an Industry University Collaborative Research Center (IUCRC) funded by the National Science Foundation focused on accelerating marine-related and adjacent domain technology innovations and economic development in support of offshore industries and the blue economy, and to evaluate Integral's SEAMOD software tool.

Integral Consulting Inc. (Integral) is an environmental science and engineering firm that provides technical and strategic support to address environmental, health, and natural resource challenges. The firm was founded in 2002 and has more than 240 staff working from 25 offices in the U.S. and Mexico. Integral's Marine Science and Engineering practice provides expertise across multiple oceanographic disciplines (physical, chemical, biological, and geological) to help clients in both the public and private sectors tackle complex resource management, engineering, permitting, and scientific challenges. Integral's team has extensive experience developing analytical tools for the ME and offshore wind energy industries, as well as developing international offshore energy standards.

2.1 Applicant Responsibilities and Tasks Performed

BWN served as a project manager and marine energy consultant working alongside Integral. As a project manager, BWN maintained constant communications with Integral through a shared communication channel primarily utilizing Microsoft Teams. BWN helped keep the project schedule through bi-weekly progress calls with Integral. BWN lead the following tasks during this project:

- Provided input to Integral as the SEAMOD tool goes through its development iterations. BWN provided input as to 1) data that is important for ME project developers to gather and analyze when evaluating potential sites for project development, 2) international standards compliance with respect to ME resource assessment, and 3) general feedback on SEAMOD usability and effectiveness.

- Developed and maintained a productive relationship with the Naval Facilities Command (NAVFAC) that includes the transfer of information sufficient to evaluate the commercial potential of deploying a wave energy project on Guam using data and insights provided by SEAMOD.

2.2 Network Facility Responsibilities and Tasks Performed

Integral led the technical components of the wave energy resource assessment that BWN will employ for siting potential ME project development in Guam. Integral's staff, who bring a wide range of expertise in ME including tidal, wind, and wave energy, performed the tiered data synthesis and review in accordance with International Electrotechnical Commission (IEC) standards, ensuring the accurate and reliable estimate of wave energy potential. Our technical staff compiled and integrated the publicly available data from NLR's Marine Energy Atlas and MarineCadastre with SEAMOD for a comprehensive wave energy resource assessment and potential project development along the Guam coastline.

The Integral team led the desktop study and wave energy resource assessment, implementing SEAMOD and other wave data sources, including higher resolution nearshore wave modeling tools. Integral also performed the generalized power estimates from publicly available power matrices and created the visualizations to showcase the viability of wave energy along the Guam coastline.

Integral collaborated closely with BWN during the tasks outlined in the test plan to identify viable ME sites, following the IEC standards, and drafting this post access report and questionnaire.

3 Project Objectives

The primary goal of this study was to compile and integrate publicly available data for a comprehensive wave energy resource assessment and identification of potential project development sites along the Guam coastline that could support its freshwater and power needs. As envisioned, a desktop study and site selection process will present and summarize available wave energy as well as relevant geospatial data including, but not limited to, natural resources, oceanographic conditions, existing infrastructure, and anthropogenic considerations throughout the region to identify promising project development sites. Power matrices for generalized WECs will be used to calculate estimated power to support the viability of wave energy in this remote region of Micronesia. This strategic data consolidation will facilitate wave energy resource assessment in Micronesia, and inform future efforts for model refinement, field data collection, and decision-making in the development of sustainable ME projects.

The objectives of this proposed study are to:

- Perform a desktop study to characterize wave energy resources at a large scale (on the order of kilometers), focused on evaluating suitable WEC deployment areas along Guam's shoreline
- Ensure that wave resource assessments are conducted in compliance with published IEC standard TS 62600-101

- Use SEAMOD's interactive database and information on existing WEC technology to support selection and siting along Guam's coastline
- Use the SNL-SWAN modeling capabilities coupled with SEAMOD to provide an IEC-compliant resource assessment for the top deployment sites as informed by the site selection process

NOTE: Using SEAMOD, WEC technology developers should be able to determine the commercial viability of developing an ME project in Guam.

4 Test Facility, Equipment, Software, and Technical Expertise

The Integral team is actively guiding and supporting ME projects and standards development. Through collaborations with the ME industry, U.S. DOE, and Sandia National Laboratories, Integral team members have helped develop and implement tools and techniques designed to evaluate and characterize wave, tidal, and wind energy resources and potential environmental effects of device deployments. The development of these tools and techniques has led to the creation of publicly available tutorials for industry, government, and academic use. Integral has led seminars and workshops with ME technology developers, coastal engineers, academic groups, and resource managers interested in studying the interaction of ME devices with the environment. These seminars have provided audience members with both the theory and the application of these state-of-the-science techniques to support permitting and regulatory efforts. In addition, Integral team members have extensive experience in the deployment, maintenance, and recovery of oceanographic monitoring systems, application of numerical modeling, and integration of site characterization activities for ME projects worldwide.

To assist in the exploration, understanding, and analysis of geospatial data, Integral has experience with both 2- and 3-dimensional geostatistical models and data visualization tools. These tools are used to support site characterization, risk assessment, and engineering evaluations. Integral has extensive experience with geospatial analysis and is developing tools to showcase the spatial and temporal variability of ME data types using open-source and web-based tools. Ongoing projects include supporting the development of Sandia National Laboratories' Spatial Environmental Assessment Tool (SEAT) to evaluate environmental effects associated with ME projects, supporting the PacWave South WEC testing facility with the implementation of a data dashboard to support adaptive management, and the SEAMOD dashboard to support wave energy resource assessments. Each of these projects requires large data sets to be handled efficiently and provide relevant analysis to support ME project goals.

Integral brings a robust approach to marine spatial planning, essential for the successful implementation of ME projects. Utilizing a spatial multi-criteria decision analysis (MCDA) process, BWN and Integral can identify both siting limitations and opportunities. This process involves the creation and identification of key data layers, and expert-driven weighting of these layers to pinpoint areas most suitable for ME technologies. Integral's method for weighting, which could include Saaty's analytical hierarchy process (AHP) or a more advanced choice modeling approach, is designed to be device-agnostic, allowing for future refinement to select optimized locations for specific technologies. This comprehensive approach to a pre-feasibility ME study ensures a balance between identification of viable ME sites, cost-effectiveness, environmental sustainability, and stakeholder benefits.

SEAMOD is a peer-reviewed software (Flanary et al. 2024; Jones et al. 2019) comprised of validated wave resource data from NOAA and NLR hindcast models that supports a Class 2 feasibility wave energy resource assessment. SEAMOD can also provide the boundary conditions for SNL-SWAN (Ruehl et al. 2015) which can incorporate user-defined WEC power matrices to provide a Class 3 site-specific energy resource assessment and project siting tool. Integral's application of SEAMOD for BWN will enable integration of data to accurately characterize available energy resources and the siting conditions (e.g., bathymetry, essential fish habitat, protected areas, coastal electric power infrastructure, vessel routes, ports, seabed conditions, and other hazards) to allow for optimal WEC technology selection and siting.

SNL-SWAN is a modified version of the open-source third generation spectral wave model Simulating Waves Nearshore (SWAN). Sandia National Laboratories has modified the model source code to include the representation of wave energy converters as obstacles, where the energy removed by the device for specific wave conditions is defined by a power matrix or relative capture width. The energy captured by the device is then propagated through the wave field. By coupling with SEAMOD, boundary conditions can be derived for a SWAN model domain and readily developed to conduct a resource assessment that accounts for the range of expected conditions.

5 Test or Analysis Article Description

The success of wave energy projects is heavily dependent on the ability to perform comprehensive site characterizations and assessments efficiently and cost-effectively. This is particularly critical for remote locations such as Guam, where reliable renewable energy solutions, like WECs, could significantly reduce dependency on diesel fuel and increase energy resilience, especially in the face of natural disasters like typhoons. This study is not testing components of a specific wave energy converter. Rather the study is conducting a pre-feasibility study for Guam and providing a blueprint for how such studies can be performed efficiently in the future.

The U.S. DoW has identified wave energy as a promising candidate for expanding Guam's energy portfolio. Due to the island's reliance on diesel for both power generation and desalination, the deployment of a wave energy-powered desalination system could offer a sustainable and inexhaustible alternative to meet these needs. The BWN/Integral team is evaluating the feasibility of deploying a small-scale WEC array along Guam's coastline to support its freshwater and power needs. This project requires accurate and agile tools for site characterization, permitting, and monitoring to minimize costs and optimize performance.

The **S**ite **E**nergy **A**ssessment and **MO**nitoring **D**ashboard (SEAMOD), developed by Integral, serves as a cloud-hosted decision-support tool for advancing ME project evaluation, including the Guam wave energy resource assessment. SEAMOD is deployed within a containerized cloud infrastructure that supports application hosting, secure data integration, and scalable resource allocation. Cloud deployment enables dynamic allocation of computational resources as user demand or data requirements change, while maintaining operational stability and cost-efficiency, thereby enhancing the efficiency of ME management and promoting sustainable energy practices. All display data are stored in secure, cloud-based object storage (Azure Blob Storage), which serves as the centralized repository for pre-processed datasets utilized by SEAMOD. Access to storage resources is governed through controlled authentication and enterprise security protocols. Hosting large wave hindcast data in Azure Blob Storage provides scalable storage capacity, high durability, and redundancy. While management of large datasets can introduce considerations such as data transfer latency, the adopted architecture mitigates these impacts through upstream data pre-processing and optimized data retrieval strategies. This design supports reliable performance while maintaining data integrity and accessibility for authorized users.

The frontend of the SEAMOD application has been developed in RShiny using a modular {golem} framework to promote maintainability and code organization. The dashboard consists of 'Home', 'Map', and 'About' pages. The Home page describes how to use the dashboard. The Map page contains the core analytical functionality, i.e., displaying existing wave datasets spatially and allowing the user to navigate, zoom, and select specific locations for detailed analysis. Interactive visualizations include wave energy information by map point, joint probability distributions, and polar energy plots. These data can also be viewed across multiple temporal scales, including the full hindcast record, monthly, seasonally, and annually.

By utilizing SEAMOD, BWN and the DoW can perform a pre-feasibility wave energy resource study that compiles and integrates publicly available data. This allows for a comprehensive evaluation of the Guam coastline, determining the viability of a WEC array to support local energy needs.

The feasibility analysis conducted in Guam serves as a prime example of how the SEAMOD platform can reduce the cost and time associated with wave energy project development. By simplifying the data interpretation process and integrating key wave resource datasets, SEAMOD enables more informed and cost-effective decision-making for project developers. The results of this analysis are expected to be documented in an upcoming analysis article, which will highlight the methodology and findings of the wave energy resource assessment for Guam, further advancing the understanding and deployment of ME technologies in the region.

This project not only highlights the potential of wave energy converters in remote and disaster-prone regions but also demonstrates how advanced analytical tools can play a pivotal role in making wave energy a commercially viable solution for renewable energy needs.

6 Work Plan

The primary goal of this study was to perform a pre-feasibility wave energy resource study along the Guam coastline that could support its freshwater and power needs. This study compiles and integrates publicly available data crucial for a comprehensive wave energy resource assessment and siting for potential ME project development. The primary objectives are to:

- Perform a desktop study to characterize wave energy resources at a large scale (on the order of kilometers), focused on evaluating suitable WEC deployment areas near Guam's shoreline
- Use SEAMOD's interactive database and information on existing WEC technology to support selection and siting along Guam's coastline

- Use the SNL-SWAN modeling capabilities coupled with SEAMOD to provide an IEC-compliant resource assessment to identify the top deployment sites as informed by the site selection process
- Select up to three (3) locations for further activities (e.g., field data collection, wave energy device testing) based on results of the geospatial data analysis.

The tasks to perform this study relied on data management, processing, and analysis, to support the identification of suitable sites for supplementing the power and fresh water needs of Guam. Those tasks are outlined in detail below.

6.1 Task 1: Desktop Study of Guam's Coastal Systems

Data synthesis and review was conducted for the Guam region. While SEAMOD leverages a comprehensive database of available wave resource data in the region to rapidly characterize wave resources, additional publicly available information on local bathymetry, local wave measurements, and other environmental considerations (e.g., currents, seabed conditions) were downloaded for review and loaded into a geodatabase for location-specific site assessment. Data sources for performing a wave energy project pre-feasibility assessment are publicly available (e.g., Marine Energy Atlas and MarineCadastre). Integral synthesized additional data sources for performing a wave energy project pre-feasibility assessment that is publicly available and will be incorporated into a geodatabase. No site visits are required.

NLR's Marine Energy Atlas and MarineCadastre spatial datasets were evaluated and classified into two tiers for this pre-feasibility assessment based on their relevance to wave energy resource characterization and site screening objectives. While Tier 1 datasets are typically defined to include direct measurements or high-resolution spatial datasets of bathymetry, water levels, currents, and wave characteristics, the availability of such data for Guam is limited. In particular, spatially resolved measurements of nearshore water levels, currents, and in situ wave conditions suitable for wave energy resource assessment were not available for Guam at the resolution, duration, or spatial coverage required to support an IEC-compliant analysis.

As a result, the Tier 1 dataset for this study was defined primarily by validated regional-scale wave hindcast products and supporting bathymetric data, which together provide the minimum information necessary to characterize the wave energy resource at a screening and pre-feasibility level. These datasets were supplemented by numerical wave modeling to improve spatial resolution and better represent nearshore wave transformation processes relevant to wave energy deployment. Direct observational datasets related to water levels and currents were reviewed where available; however, due to their limited spatial applicability and relevance to wave energy metrics, they were not used as primary inputs to the resource assessment.

Tier 1 datasets therefore consisted of bathymetry and modeled wave parameters (e.g., wave height, period, direction, and derived wave power metrics) derived from validated hindcast and numerical modeling products that support a Class 2 and Class 3 wave energy resource assessment.

Tier 2 datasets included regulatory, environmental, and socio-economic spatial layers used to inform siting feasibility, including marine protected areas, infrastructure, navigation constraints, and other coastal use considerations. These datasets provide essential contextual information for site selection but are not directly used to quantify the wave energy resource.

As part of the Task 1 desktop study, publicly available datasets relevant to wave energy development and coastal siting in Guam were compiled, reviewed, and organized to establish a geospatial foundation for subsequent screening and analysis. This effort focused on identifying existing data sources that describe regional wave climate, bathymetry, shoreline geography, environmental and regulatory constraints, and coastal and onshore infrastructure. The purpose of this compilation was to document data availability, spatial coverage, and relevance to prefeasibility-level site selection, rather than to generate new datasets or perform site-specific resource characterization at this stage of the study.

The datasets compiled during the desktop study were classified into Tier 1 and Tier 2 categories based on their role in supporting wave energy assessment versus broader siting considerations. Tier 1 datasets include regional-scale wave and bathymetric data necessary to characterize wave energy conditions at a screening level, while Tier 2 datasets consist of environmental, regulatory, and infrastructure layers used to inform spatial constraints and feasibility considerations. The data layers compiled and reviewed during Task 1 are summarized in Table 1.

Consistent with the scope of this study, no direct engagement with technology developers was conducted, and no outreach or solicitation of development interest was performed. BWN retains discretion regarding any future development activities associated with wave energy deployment in Guam, and the information developed under this desktop study is intended to support internal evaluation and planning rather than external dissemination for project development purposes.

Additional data sources incorporated in the assessment include the Pacific Islands Ocean Observing System (PacIOOS), the National Geodetic Survey (NGS), the National Oceanic and Atmospheric Administration (NOAA), the Guam Coastal and Marine Spatial Planning (CMSP) Data Portal, and the University of Hawaii. Table 1 below displays data layers potentially included in the model for the pre-feasibility tidal energy resource assessment.

Table 1. Publicly available datasets compiled and reviewed during the Task 1 desktop study to support prefeasibility-level wave energy screening and site selection for Guam.

Data Layers	Description	Tier	Source
Bathymetry	Raster layer of Guam bathymetry	1	NOAA
Shallow Water Mooring Buoys	Point layer of the shallow water mooring buoys	2	PacIOOS
Guam Shoreline	Line layer of Guam shoreline	2	NGS, NOAA
Benthic Habitat	Polygon layer of benthic habitat	2	Guam CMSP Data Portal
Restricted Areas - Marine Protected Areas	Polygon layer of restricted areas for marine protected areas	2	PacIOOS
Restricted Areas - Dive Sites	Point layer of dive sites	2	PacIOOS
Restricted Areas - Conservation Areas	Polygon layer of conservation areas	2	PacIOOS

Restricted Areas - Cultural Areas	Point and polygon layers of national registry historic places	2	Guam CMSP Data Portal
Restricted Areas - Anchorage Areas	Polygon layer of anchorage areas	2	PacIOOS
Onshore Connection - Guam Airports	Point layer of Guam public airports	2	Guam CMSP Data Portal
Onshore Connection - Power Plants	Point layer of Guam power plants	2	Guam CMSP Data Portal
Onshore Connection - DoW Properties	Polygon layer of military use areas	2	Guam CMSP Data Portal

6.2 Task 2: Guam Wave Energy Resource Assessment

The goal of this task was to develop a large-scale (on the order of kilometers) assessment of the wave energy resource around the Guam coastline to support overall site selection. Sites with suitable wave energy resources and bathymetric/geomorphic conditions will be identified. The resource characterization was conducted in compliance with the IEC technical specification (TS) for wave resource assessment. Application of this TS improves confidence in the assessment of annual energy production (AEP) for WEC array siting. At this scale, it is anticipated that standard Class 2 feasibility resource assessment level (IEC TS 62600-101) will be sufficient for initial site screening and assessment.

A Class 2 feasibility wave energy resource assessment, as defined in IEC TS 62600-101, provides a standardized framework for screening-level evaluation of wave climate characteristics suitable for early-stage site comparison and prefeasibility decision-making. Class 2 assessments rely on validated regional hindcast datasets to quantify key wave resource metrics, including omnidirectional wave power, significant wave height, energy period, and directional characteristics, without requiring in situ measurements. This assessment level is intended to characterize spatial and temporal variability in the wave resource at regional scales, support comparative estimates of AEP, and identify candidate areas with favorable wave energy conditions and geomorphic suitability for further evaluation.

The foundation of this initial step of the Guam wave energy resource assessment was to further develop and refine the SEAMOD display to analyze and visualize the 18 km Pacific Islands wave grid from the WAVEWATCH III (WWIII) 30-year hindcast. A map of wave and geomorphic metrics were developed using the WWIII hindcast data, further processed into IEC recommended variables within SEAMOD (e.g., omni-directional wave power, wave energy period).

Development of the SEAMOD display functionality required substantial adaptation and extension of the existing dashboard framework to support Guam-specific screening objectives, data volumes, and spatial context. The application was implemented using the RShiny framework with a modular architecture based on the {golem} package, which enabled separation of data ingestion, processing, and visualization components into discrete, maintainable modules. This structure supported iterative development and testing of new functionality while preserving consistency across analytical workflows. Dashboard development focused on ensuring that IEC-aligned wave resource metrics derived from the WWIII hindcast could be interactively explored across space and time without altering or filtering the underlying datasets, thereby maintaining transparency between the processed data products and their visual representation within the application.

A key methodological component of the SEAMOD development effort involved designing interactive visualization workflows that allow users to interrogate screening-level wave resource information in a reproducible and scalable manner. This included implementation of map-based raster rendering for region-wide wave metrics, dynamic temporal aggregation controls, and point-based statistical summaries linked directly to the native WWIII grid structure. Emphasis was placed on ensuring that user selections for wave variables, temporal aggregation, and statistical summaries trigger consistent backend processing logic and standardized outputs suitable for prefeasibility-level comparison. The resulting SEAMOD configuration provides a controlled analytical environment in which large hindcast datasets can be efficiently queried and visualized, supporting informed screening and site selection.

To support visualization and exploratory analysis within SEAMOD, the WWIII Pacific Islands grid was processed to extract bulk wave parameters relevant to regional wave energy screening. Hindcast outputs were spatially subset to the Guam region and organized on the native model grid without interpolation or spatial refinement. Standard bulk parameters provided by WWIII, including significant wave height, peak wave period, and mean wave direction, were retained at their native temporal resolution and used as the basis for subsequent aggregation and display.

To provide additional metrics for visualization, the WWIII bulk wave parameters, to be displayed in SEAMOD, were temporally aggregated to generate annual, seasonal, and monthly summary statistics consistent with screening- and prefeasibility-level assessment objectives. Derived wave energy metrics, including omni-directional wave power, were calculated from the bulk parameters following IEC-consistent formulations and summarized at each grid cell to support regional comparison of wave energy patterns around Guam. These processed datasets were used solely to provide regional-scale context and to inform relative differences in wave energy exposure; higher-resolution characterization and site-specific analyses were performed separately using dedicated numerical modeling approaches described in more detail in the Project Outcomes section.

6.3 Task 3: Site Selection

The goal of this task was to identify the most promising sites along the Guam coastline for wave energy conversion that offer the optimal balance between high energy yield and reliability and to ensure the feasibility and sustainability of a WEC deployment. The sites will be defined by regions on the order of kilometers, utilizing data from Task 2. The user will consider the feasibility of deploying each WEC technology (Task 1) at the selected site considering parameters including proximity to shore-based infrastructure, the impact of seasonal variations, and geomorphologic dynamics. This analysis will help in pinpointing specific locations where WECs could be deployed to maximize energy capture and capacity factor while minimizing the risk of underperformance due to variability in wave conditions. It is anticipated that three sites will be selected for advancement to Task 4. All the site selection data and criteria will be compiled into a geodatabase.

Siting limitations and opportunities can be examined through use of a spatial multi-criteria decision analysis (MCDA) process. This involves the identification or creation of key data layers, and the weighting of these layers to identify the areas most suited for application of WECs. Data layers to be incorporated into the MCDA include binary exclusion zones such as marine protected areas and shipping lanes, raster data related to the wave energy resource, 'cost' factors such as distance to transmission connection points or cable landing areas, and 'benefit' factors such as population density or other demographic attributes. Weighting factors will be a determined with input from BWN and guidance from Integral. The selection of these factors is a key component of the analysis.

Exclusion layers would be used to identify areas worthy of further consideration. Other layers would then be weighted by BWN and Integral, in terms of their importance in promoting or hindering technology deployment and operation. The method for weighting will be agreed upon by BWN and Integral, with a preference for simple methods with a low time and cognitive burden for the experts involved. One potential approach is to use Saaty's analytical hierarchy process (AHP), using a series of pairwise comparisons. This could also be achieved through a simple online survey using ranking or scoring of the parameters described in the spatial data layers available in SEAMOD, or a more advanced choice modeling approach. The weighting process will be device-agnostic but could be refined in a later iteration to result in selection of optimized locations for specific technologies.

6.3.1 Site Selection Metrics

To identify feasible sites for WEC device installations along the Guam coastline, several key metrics have been defined for site selection. The primary data layer is the available wave resource at a site, which directly influences the potential energy output of a WEC. These ranges can be selected based on a typical device's operational window. Additionally, proximity to existing coastal and onshore infrastructure was considered, including power generation facilities, ports, and other relevant shoreline assets identified through publicly available geospatial datasets, to inform relative siting feasibility. Lastly, areas of stakeholder concern, including environmental and socio-economic factors (e.g., where additional fresh water supplies are needed), are considered to ensure sustainable ME development. Metrics and thresholds can be selected during the MCDA analysis based on given features and data sets of relevance. As this process depends on the relevant data sets within a given site, the selection of specific metrics will depend on available data and application regime.

Wave Energy

The first metric, wave energy, is a crucial factor in determining the viability for WEC device installations in Guam. The strength and predictability of the waves in a specific area are key considerations. Energy estimates for a range of significant wave heights will be considered. Sites with consistent wave heights, periods, and a narrow band of mean wave directions are ideal as they can produce a steady supply of renewable energy. Furthermore, the depth and seabed conditions of the site can affect the installation and operation of the WEC devices. Therefore, a comprehensive assessment of the wave characteristics and seabed conditions of the potential sites is essential.

Renewable Energy Infrastructure

The renewable energy infrastructure metric was evaluated at a screening level based on proximity to existing coastal and onshore infrastructure identified through publicly available geospatial datasets. This assessment focused on the spatial presence and relative location of shoreline assets such as ports, power generation facilities, airports, and other relevant coastal infrastructure that may influence siting feasibility and logistical access. No evaluation of grid capacity, power transmission capability, storage, or integration performance was conducted as part of this desktop study. Instead, infrastructure layers were used to provide contextual information for comparing candidate regions and to identify areas where existing infrastructure may reduce deployment complexity or support future project planning considerations.

In the context of the blue economy, where WEC devices are not grid-connected but used to support small-scale energy applications like desalination, the renewable energy infrastructure takes on a different dimension. Here, the focus shifts from grid connectivity to the ability of the site to support standalone, off-grid applications, including desalination. The proximity to these applications, the ease of installation and maintenance of the WEC devices, and the capacity to meet the power demands of these applications become critical factors. This approach aligns with the broader goals of energy independence, resilience, and sustainability in the blue economy.

Stakeholder Concerns

Lastly, stakeholder concerns encompass a range of environmental and socio-economic factors. From an environmental perspective, the potential effects of WEC devices on marine life and ecosystems is a major consideration. Sites that are not in environmentally sensitive areas or in areas of significant marine biodiversity are typically more suitable. From a socio-economic perspective, factors such as the potential for job creation, improvements to the health and welfare of local communities, and the views of local residents and businesses are also important. Engaging with stakeholders early and often throughout the site selection process can help to identify potential issues and mitigate concerns, ensuring the sustainable development of ME.

6.4 Task 4: Site Specific Resource Characterization and Assessment

The goal of this task was to conduct a higher-resolution (on the order of 10s of meters resolution) site characterization and assessment of the site(s) identified in Task 3. The resource assessment(s) will comply with the requirements (to the extent data is available) for a Class 3 design-level assessment. Where specific measurements are unavailable, the assessment will comply with a Class 2 assessment incorporating as many of the Class 3 requirements as possible.

To refine the horizontal resolution of the resource assessment to a scale of 10s of meters along the Guam coastline at the selected sites, SNL-SWAN simulations can be used in areas identified during the site selection process described in Task 3. The inclusion of these higher resolution SWAN numerical model data will provide a higher resolution, site-specific wave resource characterization. SWAN will provide model predictions of the wave resource at many orders of magnitude higher resolution than the SEAMOD hindcast data incorporated into the dashboard. Access to this spatial database will be made available to users using a combination of APIs and pre-processed hindcast statistics, guided by IEC standards. The SNL-SWAN modeling coupled with SEAMOD will provide an IEC-compliant resource assessment and aid in the selection of the top Guam deployment sites as informed by the site selection process.

The resource assessments will use data from SEAMOD and the SNL-SWAN predictions, as well as other publicly available databases to develop a high-resolution assessment. Maps of mean monthly and annual omni-directional wave power at the selected sites along the Guam coastline will be generated and the final results will include directionally resolved estimates of wave power. The SNL-SWAN model will be used to estimate AEP for various layout designs with WEC-specific power matrices. The SEAMOD and SNL-SWAN model will be readily available to BWN for future layout and siting activities.

6.5 Safety

All activities outlined were conducted from a desk. No travel or fieldwork occurred. All work was executed in accordance with Integral's Corporate Health and Safety Policy; a copy of which can be provided upon request. Proper ergonomics during the above proposed activities were encouraged.

6.6 Data Management, Processing, and Analysis

SEAMOD will allow easy, interactive exploration and viewing of the selected spatial data layers important to marine spatial planning for a wave energy project in Guam. It will feature existing omni-directional wave power estimates, bathymetry, natural resources, existing infrastructure, and regional hazards. This strategic data consolidation will facilitate a wave energy resource assessment and inform future data collection and decision-making efforts in developing sustainable ME projects along the Guam coastline.

6.6.1 Data Management

An integral component of the technical work plan focuses on data management. The geospatial data, pulled from various publicly available sources, form the foundation of the wave energy resource assessment. Leveraging the versatility and open-source capabilities of QGIS, our data management approach will employ standard geospatial data formats (e.g., shapefiles, vectors, rasters) applicable to standard GIS-based platforms. A structured file system within QGIS allows for the management of diverse data types, including bathymetric charts, tidal observations and simulations, and coastal morphology datasets. The use of GeoPackage and shapefile formats ensures compatibility with industry-standard geospatial data interchange, while QGIS map project packages will be employed for comprehensive project portability and to support collaborative efforts. This methodology guarantees the efficient handling and integration of geospatial information.

A cloud-based solutions utilizing Microsoft Azure offers the advantage of remote accessibility and efficient data sharing among team members. Through Azume, the final data package and appropriate metadata were made available to the project team and the SEAMOD backend. All base data were derived from publicly available data sets and references to the data source were provided in Section 6.1.

In accordance with TEAMER Post-Access Report requirements, data products generated under this study have been compiled for submission to the Marine and Hydrokinetic Data Repository (MHK DR). The compiled submission package includes the full GIS project directory with all Guam based spatial datasets (e.g., bathymetry, shore based infrastructure, marine protected areas, etc.), the SWAN numerical wave model setups for all domains and years, the SWAN boundary condition files derived from WWIII, the processed SWAN output files utilized for the site specific wave energy resource assessment, and supporting geospatial and summary products developed to support the Guam wave energy prefeasibility assessment. All materials are provided in standard, non-proprietary formats appropriate for long-term archival and reuse, with associated metadata documenting data provenance, processing methods, spatial reference, and temporal coverage. A summary of the data types and formats included in the MHK DR submission package is provided in Table 2.

Table 2. Summary of data products compiled for submission to the MHK Data Repository

Data Category	**Description**	**File Format**	**Notes**
GIS	Geospatial datasets compiled and organized to support screening-level wave energy siting and prefeasibility assessment for the Guam coastline. These data were assembled during Task 1 and include publicly available bathymetry, shoreline geometry, environmental and regulatory designations, navigation and use constraints, and onshore and nearshore infrastructure layers.	Shapefiles, CSVs	Various public data sources
SWAN Boundary Conditions	Offshore wave boundary condition datasets derived from the WAVEWATCH III (WWIII) Pacific Islands hindcast and used to force high-resolution SWAN simulations for selected Guam study regions. Boundary conditions consist of time-varying bulk wave parameters extracted from surrounding WWIII grid points and processed to provide representative offshore forcing.	CSVs	
SWAN Simulations	High-resolution SWAN model simulation datasets prepared for three selected Guam study domains using offshore boundary conditions derived from WWIII. The submission includes full model setup directories and multiyear simulation configurations spanning an 11-year representative period for each domain, configured and ready for execution.	Various ASCII file formats	The raw SWAN outputs were excluded for file size constraints.
SWAN Processed Outputs	Processed outputs derived from multiyear SWAN simulations for three Guam study domains, including annual and monthly averages of omni-directional wave power, directionally resolved wave power, dominant wave direction, maximum directionally resolved wave power, and mean annual energy production (MAEP). Metrics are provided for all modeled station locations across the full 11-year simulation period for each domain.	ASCII	
SNL-SWAN	Single-year SNL-SWAN simulation dataset for the northeastern Guam study domain, including full model output files generated to evaluate	Various ASCII file formats	

	wave energy conditions and representative wave–device interactions under selected forcing conditions. Outputs include spatially distributed wave parameters and supporting model results produced for this domain during the single modeled year.		
Python Scripts	Python scripts developed to process raw SWAN model outputs and derived datasets, and to generate site-specific wave resource assessment graphics and summary tables. Codes support data extraction, aggregation, statistical processing, and formatting of results used in figures and tables presented for the Guam wave energy prefeasibility assessment.	*.py	

6.6.2 Data Processing

The data required for a standardized wave energy resource assessment for Guam was derived from publicly available sources, the primary data processing effort focused on data preparation, standardization, and transformation to ensure consistency with IEC-aligned wave resource assessment methodologies and compatibility with the SEAMOD and SWAN modeling frameworks. Source datasets included regional wave hindcast outputs, bathymetric rasters, and geospatial constraint layers obtained from NREL, NOAA, MarineCadastre, PacIOOS, and other publicly accessible repositories. All datasets were reviewed to confirm spatial coverage, coordinate reference systems, temporal resolution, and metadata completeness prior to integration.

Wave resource data processing involved extracting, subsetting, and transforming the WWIII hindcast products to derive standardized wave energy parameters suitable for screening- and pre-feasibility level assessment. This included processing spectral and bulk wave parameters to compute derived metrics such as omni-directional wave power, characteristic wave periods, directional indicators, and associated summary statistics across multiple temporal scales. Pre-processing steps were implemented to spatially subset data to the Guam region, harmonize variable naming conventions and units, and aggregate time-series data into consistent monthly, seasonal, annual, and long-term representations. These processed datasets were stored in formats optimized for efficient visualization and retrieval within the SEAMOD dashboard and for use as boundary condition inputs to subsequent SWAN numerical wave modeling.

Geospatial datasets used to inform siting feasibility and spatial screening were processed using standard GIS workflows to ensure consistency across layers. This included reprojection to common coordinate systems, clipping to a common spatial extent, and attribute normalization where required. Quality assurance checks were performed to verify correct spatial alignment among datasets, confirm data integrity following transformation, and ensure that exclusion and constraint layers were correctly represented prior to their use in multicriteria site selection. No filtering or elimination of wave resource data was performed at this stage beyond spatial and temporal subsetting required for computational efficiency and relevance to the study domain.

Uncertainty associated with data processing primarily reflects limitations inherent to the source datasets, including the use of modeled hindcast products rather than in situ measurements and the spatial resolution of regional wave models. These uncertainties were not modified or reduced during processing; instead, they were preserved and carried forward to subsequent analysis stages. Assumptions introduced during data processing, such as temporal aggregation choices or spatial domain definitions, were documented to ensure transparency and to support interpretation of results presented in later sections of the report.

6.6.3 Data Analysis

Data analysis for the Guam wave energy resource assessment was conducted using a structured, tiered workflow designed to support screening through pre-feasibility level evaluation while remaining consistent with applicable IEC guidance. Analytical activities focused on transforming processed wave and geospatial datasets into standardized statistical summaries, spatial products, and visualization-ready formats that enable transparent comparison of wave energy conditions and siting considerations across the Guam coastline. Detailed analytical outputs, figures, and interpretations resulting from these methods are presented in Section 7.1; which documents the analytical approach applied to generate those results.

Wave resource analysis was performed using validated regional hindcast outputs and higher-resolution numerical wave model results. Processed wave datasets were analyzed in gridded formats (e.g., NetCDF and GeoTIFF) to compute standardized bulk and derived wave parameters, including significant wave height, characteristic wave periods, directional indicators, and omnidirectional wave power. Statistical summaries were generated across multiple temporal aggregations, including long-term, annual, seasonal, and monthly groupings, using descriptive statistics such as mean, median, minimum, maximum, standard deviation, and selected percentiles. These statistics were used to characterize persistence, variability, and directional structure of the wave climate at regional and site-specific scales, supporting relative comparison among candidate areas rather than device-specific performance evaluation.

For candidate regions advanced beyond regional screening, outputs from higher-resolution numerical wave modeling were analyzed to refine nearshore wave characterization. Spatially resolved wave parameters and directional spectral information were evaluated to quantify wave transformation processes, spatial gradients in wave energy, and directional spreading within each modeled domain. Analytical products generated at this stage included gridded spatial summaries, time-aggregated statistics, and joint distributions of key sea-state parameters suitable for IEC-aligned reporting. These analyses were intended to support prefeasibility-level assessment and comparison of candidate regions, rather than detailed array design or optimization.

Spatial analysis integrated wave resource metrics with environmental, regulatory, and infrastructure datasets compiled during earlier tasks. Geospatial overlays and multi-criteria evaluation techniques were applied using GIS-based workflows to examine how wave energy potential intersects with bathymetry, exclusion zones, and proximity to shore-based infrastructure. Analytical outputs from this process were used to identify candidate regions and representative study points for further evaluation, providing a consistent and reproducible basis for site screening without imposing prescriptive rankings or final site selection decisions.

Uncertainty in the analysis primarily reflects limitations inherent to the source datasets and modeling approaches, including the use of modeled wave data in lieu of long-term in situ measurements and the spatial resolution of regional hindcast products. Uncertainty was addressed through use of standardized statistical summaries and consistent analytical methods applied uniformly across regions and sites. No formal uncertainty propagation or sensitivity analysis was performed beyond descriptive statistics. Assumptions related to temporal aggregation, spatial domain selection, and screening thresholds were documented and carried forward to support transparent interpretation of results presented in Section 7.1.

In accordance with TEAMER guidance for Post Access Reports, this section provides methodological context for the analyses performed, while detailed results, figures, tables, and outcome-focused discussion derived from these methods are presented in Section 7.1.

7 Project Outcomes

This section presents the outcomes of the Guam Wave Energy Resource Assessment and summarizes the results generated from each task defined in the approved Work Plan. Collectively, these outcomes demonstrate how publicly available wave, environmental, and geospatial data were synthesized and analyzed to support a pre-feasibility evaluation of wave energy development along the Guam coastline. Results are organized to reflect the progression of work from the initial desktop study and technology screening (Task 1), through large-scale IEC-compliant wave resource characterization (Task 2), spatially informed site selection using multi-criteria decision analysis (Task 3), and site-specific, higher-resolution resource assessment using coupled numerical modeling (Task 4). Together, these results provide a transparent and reproducible basis for identifying viable wave energy deployment areas, estimating potential energy production, and informing future field data collection, device selection, and project planning activities in Guam.

7.1 Results

Results are organized by task and reflect the analyses completed to support prefeasibility siting considerations for wave energy development along the Guam coastline. Findings focus on the compilation and evaluation of publicly available datasets, numerical modeling outputs, and spatial screening criteria used to characterize wave energy conditions, infrastructure constraints, and environmental and regulatory considerations.

7.1.1 Task 1: Desktop Study of Guam's Coastal Systems

Task 1 focused on compiling and organizing publicly available geospatial datasets required to support pre-feasibility siting considerations for wave energy development along the Guam coastline. The outcomes of this task established a spatial framework for evaluating where WEC devices could be feasibly installed, permitted, and connected to shore-based infrastructure.

Rather than characterizing the wave resource itself, Task 1 concentrated on identifying environmental, regulatory, and infrastructure constraints and opportunities, including protected areas, restricted zones, coastal facilities, and potential shore-based connection points. These datasets were integrated into a project-specific geodatabase that provided the spatial context necessary to assess siting feasibility and to inform subsequent wave resource screening and site selection activities. Collectively, the outcomes of Task 1 ensured that subsequent analyses were grounded in a clear understanding of permitting constraints, spatial exclusions, and infrastructure considerations relevant to wave energy development in Guam.

Data Inventory and Tier Classification Results

As part of Task 1, a comprehensive inventory of publicly available datasets relevant to wave energy development along the Guam coastline was compiled, reviewed, and organized to support subsequent screening- and pre-feasibility level analyses. The inventory process focused on identifying datasets necessary to characterize the wave energy resource at regional scales, as well as datasets required to understand environmental, regulatory, and infrastructure constraints that influence siting feasibility. All datasets were reviewed for spatial coverage, relevance to the study objectives, and suitability for integration into a unified geospatial framework.

Consistent with the tiered approach described in the Work Plan, datasets were classified into Tier 1 and Tier 2 categories based on their role in supporting wave energy resource assessment versus broader siting and planning considerations. The resulting classification reflects both the availability of data for Guam and the practical requirements of a prefeasibility-level assessment.

Tier 1 datasets consisted of those required to support wave energy resource characterization at screening and prefeasibility scales. For Guam, this primarily included regional-scale wave hindcast products and supporting bathymetric data suitable for deriving standardized wave energy metrics. While Tier 1 datasets typically include spatially resolved measurements of water levels, currents, and nearshore wave conditions, such observational datasets were not available for Guam at a resolution or spatial extent sufficient to directly support wave energy resource quantification. As a result, the Tier 1 inventory relied on validated modeled wave products and bathymetry, which provide the minimum necessary inputs to characterize wave energy conditions and to support subsequent numerical wave modeling conducted later in the study.

Tier 2 datasets consisted of environmental, regulatory, and socio-economic spatial layers used to inform siting feasibility and constraint-based screening. These datasets included marine protected areas, benthic habitat classifications, navigation and anchorage areas, cultural and conservation designations, existing coastal and onshore infrastructure, and DoW land and marine use areas. Tier 2 datasets were not used to quantify the wave energy resource but instead provided essential spatial context for evaluating where wave energy development may be feasible or constrained along the Guam coastline.

All Tier 1 and Tier 2 datasets were incorporated into a project-specific geospatial database to ensure consistent spatial reference and interoperability across subsequent tasks. The finalized data inventory established a transparent and well-documented foundation for the wave energy resource screening performed in Task 2 and the spatial site selection analyses conducted in Task 3.

Geodatabase Development and Spatial Coverage

All Tier 1 and Tier 2 datasets were integrated into a unified geospatial database to support consistent spatial analysis across subsequent tasks. The resulting geodatabase provides continuous spatial coverage around the Guam coastline at resolutions appropriate for regional-scale pre-feasibility assessment.

A QGIS project was created with relative links, loading all the data layers presented above. The initial QGIS geodatabase analysis focused on ensuring all the data layers were compatible (e.g., matching coordinate reference systems, units, data formats). This involved ensuring these inputs were consistent for specific use cases. These data sets were loaded into the QGIS project under a group titled “Input Datasets.” This group contained several subgroups, which include bathymetry, geography, Marine Protected Areas, power facilities, transportation hubs, and military facilities (Figure 1).

The geodatabase refinement process entailed data cleaning, quality control, and reformatting, enabling standardization of the various data sources, to create a unified and consistent geodatabase for Guam. GIS techniques and tools were applied to standardize spatial formats, projections, and attribute structures, enabling seamless data interoperability. Quality control measures were implemented to address inconsistencies or outliers within the data.

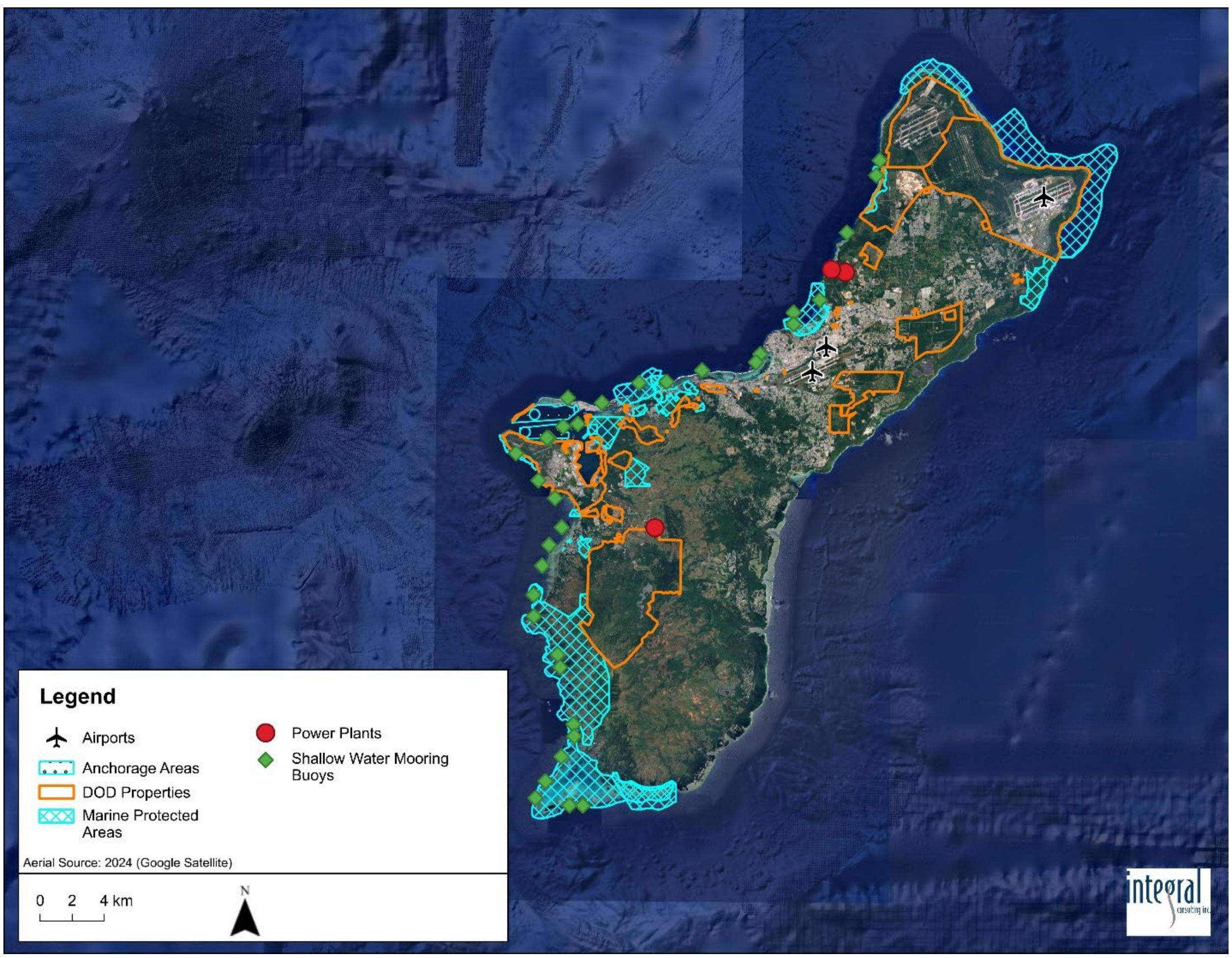

Figure 1. Overview of selected spatial data layers included into the Guam geodatabase.

Task 1 Summary

In summary, Task 1 resulted in a vetted and well-documented dataset, an integrated geospatial framework, and an initial technology context suitable for supporting IEC-aligned wave energy resource assessment.

Results from the Task 1 desktop assessment indicate that Guam's critical coastal infrastructure and population centers are predominantly concentrated along the western (leeward) coastline of the island. This region includes the majority of nearshore and onshore assets relevant to wave energy development, such as shallow-water moorings, commercial ports and anchorage areas, power generation facilities, airports, and grid interconnection points. From a wave energy deployment perspective, this spatial configuration presents a clear advantage for nearshore or intermediate-depth WEC arrays, as proximity to existing infrastructure can significantly reduce subsea cable lengths, installation complexity, and transmission losses associated with delivering power to shore. While the western coastline is also characterized by extensive marine protected areas and other regulatory designations, these features do not universally preclude wave energy development and instead represent spatial constraints that must be considered during site screening and permitting rather than absolute exclusion zones.

The Task 1 geodatabase further identified distinct regional considerations outside the western coastline, including DoW facilities along the northern coast, most notably near Andersen Air Force Base at the northeast corner of the island. Although these areas present additional regulatory and operational constraints, they may offer opportunities for mission-driven or islanded wave energy applications where grid interconnection requirements differ from civilian power systems. By integrating Tier 1 and Tier 2 datasets into a unified geospatial framework, Task 1 established a spatially explicit understanding of where wave energy development is most likely to align with existing infrastructure, permitting feasibility, and transmission requirements. These results suggest that the western coastline represents the most favorable region for initial wave energy development in Guam, particularly for projects intending to transmit power to shore, while other coastal regions may warrant consideration for specialized or future applications as site-specific constraints and energy objectives are further refined.

These outcomes directly informed the large-scale wave resource characterization conducted in Task 2, provided essential inputs to the spatial site selection process in Task 3, and established the foundation for higher-resolution, site-specific modeling performed in Task 4.

7.1.2 Task 2: Guam Wave Energy Resource Assessment

Task 2 focused on the development and application of the SEAMOD platform to support large-scale screening of wave energy conditions around Guam for overall site selection. Rather than performing a detailed or site-specific wave resource assessment, the outcomes of this task centered on configuring, processing, and visualizing the WWIII validated hindcast dataset in a manner that enables consistent, transparent comparison of wave energy conditions along the Guam coastline. These results provided the analytical capability and broad spatial context required to identify candidate regions for further evaluation in Task 3, where higher-resolution assessments and more detailed wave resource characterization were performed.

SEAMOD Development and Display Refinement

As part of this project, the SEAMOD application was refined and configured to support wave energy screening and site selection for the Guam study area. This effort focused on adapting the existing dashboard framework to accommodate the spatial extent, data resolution, and screening objectives relevant to Guam, and on developing an interface that allows users to efficiently explore regional wave resource information derived from the WWIII hindcast dataset. Refinements emphasized clear visualization of screening-level wave metrics, intuitive navigation of spatial and temporal data, and consistent presentation of information needed to support prefeasibility-level comparison of coastal regions prior to higher-resolution analysis.

The Map page of SEAMOD contains the core analytical functionality of the application, featuring an interactive map accompanied by a floating control panel that users leverage to select data to display. As a first step, users select the “Wave Variable”, “Time Period”, and “Wave Statistics” of interest from drop-down menus and then click “Submit” to initiate processing and display the selected data (Figure 2). “Wave Variable” options include Omnidirectional Wave Power, Peak Wave Direction, Directionality coefficient, Swell Width, and Characteristic Wave Period. “Time Period” selections include Monthly, Seasonal, Yearly, and Full. “Wave Statistics” can be displayed as Mean, Median, Standard Deviation, Minimum, Maximum, 10^{th} Percentile, and 90^{th} Percentile. Together, these configurable settings provide multiple perspectives for evaluating potential marine energy sites.

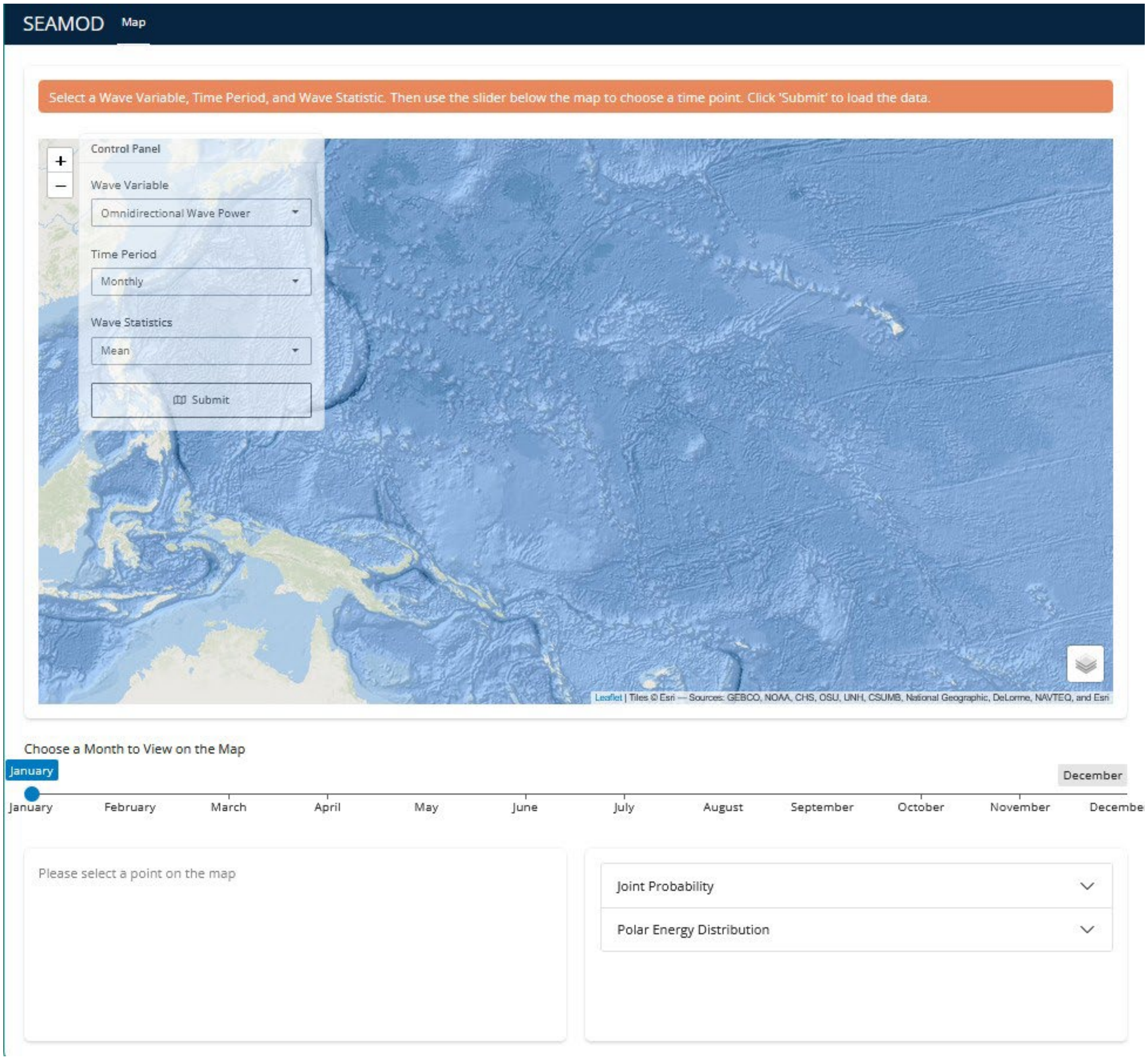

Figure 2. Map Page of the SEAMOD wave resource assessment display prior to data selection.

Once selections have been made and the "Submit" button has been clicked, the application processes the request and renders the corresponding output as a raster layer on the map (Figure 3).

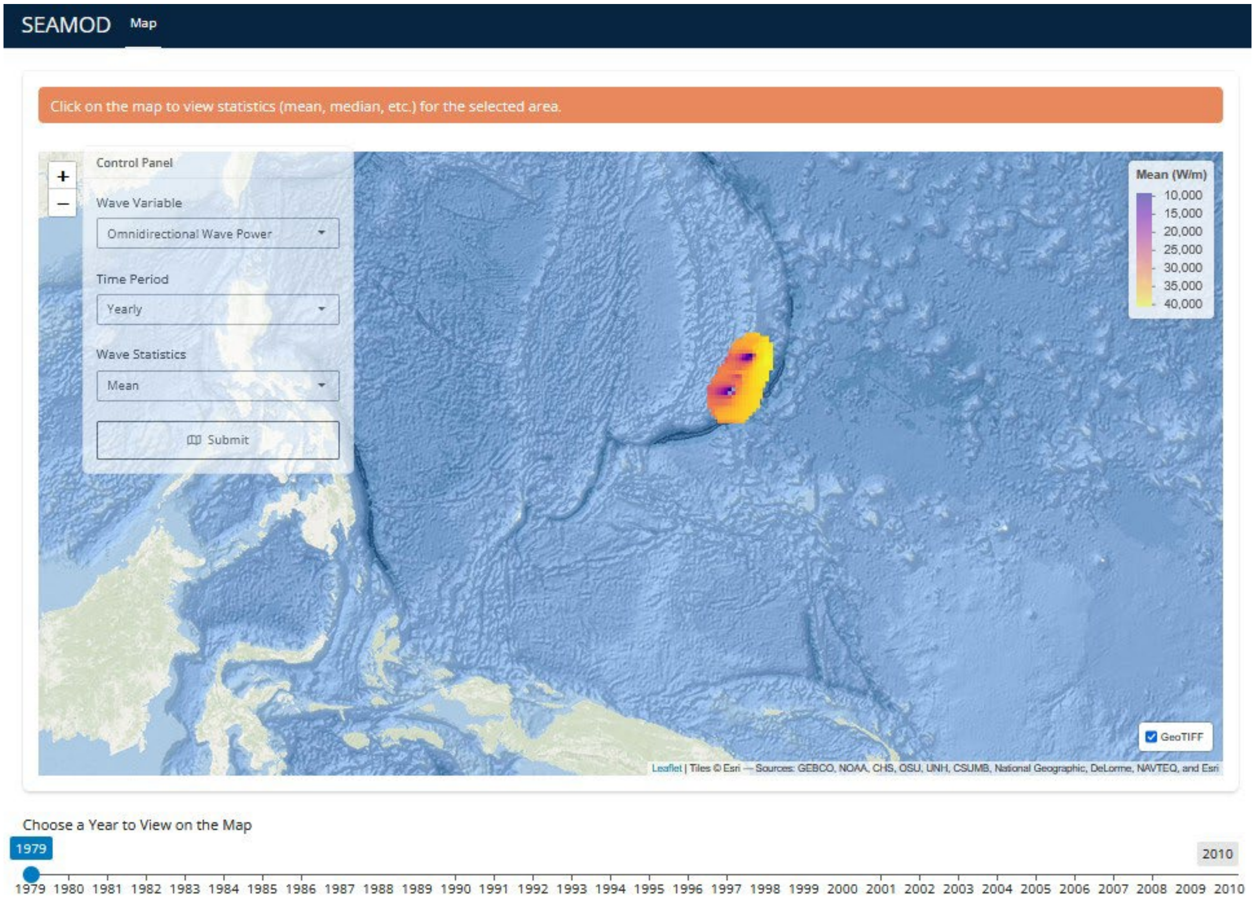

Figure 3. Raster layer rendered on the map based on user-selected wave variable, time period, and wave statistics. The example shown displays the mean omni-directional wave power for 1979.

After the initial raster is generated on the map with user-selected values for the "Wave Variable", "Time Period," and "Wave Statistics", the user may wish to adjust the display for specific time periods within the project area. This is possible using the time slider located below the map. The time slider will display time period options to display based on the initial user-selection for the "Time Period" (Figure 4). Specifically, when "Monthly" is selected, the slider displays the 12 calendar months, with data aggregated by month across all years. Selecting "Yearly" presents the full range of available years (1979–2010) with data summarized for each individual year. A "Seasonal" selection displays the four meteorological seasons, with data aggregated by season across the complete record. In all cases, the aggregation method corresponds to the option selected in "Wave Statistics."

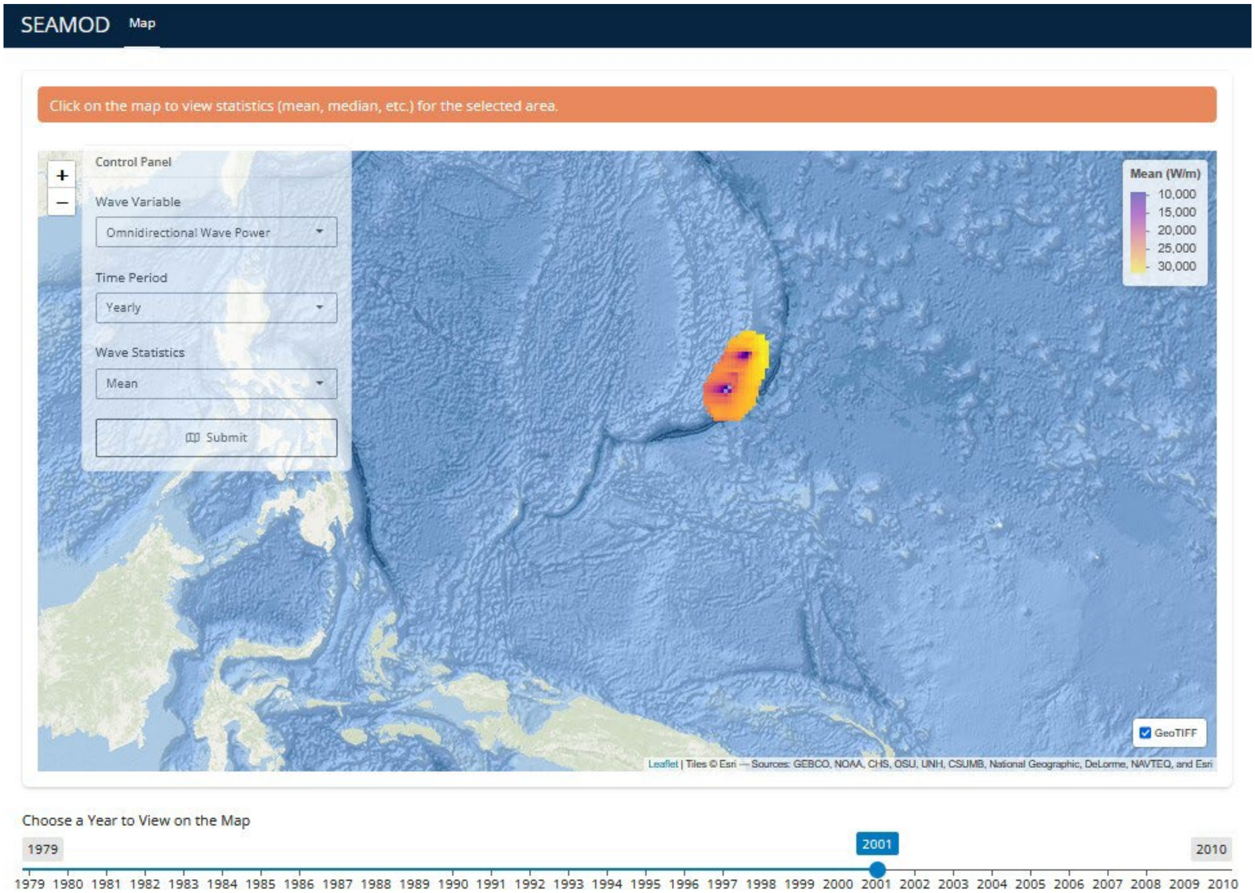

Figure 4. Time slider updated dynamically based on the selected time period in the floating panel, with data aggregated at the chosen temporal scale and displayed as a raster layer on the map. The example shown displays the mean omni-directional wave power for 2001.

Once the user wants to dive further into exploring a specific location within the region of interest, they can click a specific location on the map. This results in a marker placed at the selected point and displays the corresponding statistical summary for the grid cell corresponding to that location in a table below the map (Figure 5). The statistics include the mean, median, standard deviation, minimum, maximum, 10th percentile, and 90th percentile values for the chosen wave parameter in the "Wave Variable" selection in the floating panel.

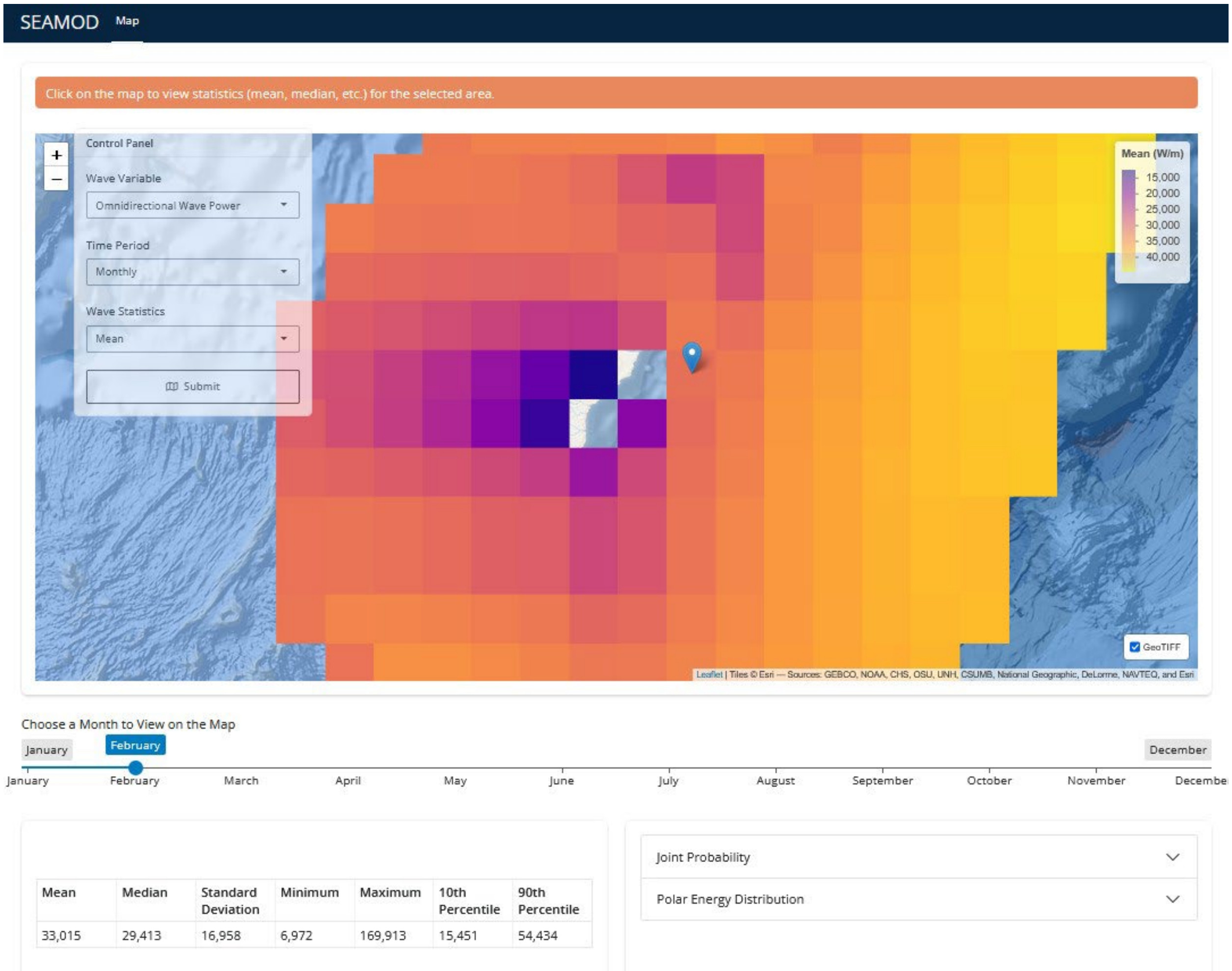

Figure 5. Selected map location showing the corresponding marker and statistical summary. The example shown displays mean omni-directional wave power for February.

SEAMOD Configuration and Screening-Level Outputs

As part of Task 2, the SEAMOD platform was configured to support screening-level evaluation of wave energy conditions along the Guam coastline using validated regional hindcast datasets. Configuration focused on enabling consistent visualization and extraction of standardized wave resource metrics at spatial scales appropriate for regional comparison, rather than detailed site-specific assessment. SEAMOD was used to process and display derived wave parameters such as omni-directional wave power, wave period, and related statistical summaries across user-selectable temporal aggregations, including monthly, seasonal, annual, and long-term representations. This configuration provided a transparent and repeatable framework for examining broad spatial patterns in wave energy exposure around Guam.

The screening-level outputs generated through SEAMOD were used to support relative comparison of coastal regions and to inform subsequent site selection activities, rather than to quantify device-specific performance or final energy production. Spatial raster products and point-based statistical summaries enabled identification of systematic differences in wave energy conditions between windward and leeward coastlines, as well as temporal variability relevant to prefeasibility considerations. These outputs were evaluated in conjunction with bathymetric and infrastructure context developed under Task 1 to identify regions warranting further investigation. By providing a consistent, IEC-aligned screening-level view of wave conditions, SEAMOD served as the primary analytical tool for narrowing the focus from island-wide assessment to candidate areas suitable for higher-resolution numerical wave modeling conducted later in the study.

Spatial and Temporal Patterns in Wave Conditions

Screening-level evaluation of omnidirectional wave power derived from the WWIII hindcast dataset reveals clear spatial variability in wave energy conditions around Guam, despite the relatively coarse horizontal resolution of approximately 18 km. At this scale, higher wave energy is consistently observed along the eastern, windward side of the island, while lower wave energy conditions dominate along the western, leeward coastline. This contrast is evident in both wave power and associated bulk wave parameters and reflects the influence of prevailing wind and swell directions interacting with the island’s orientation. Reduced wave energy on the western side is consistent with wind and swell shadowing effects induced by Guam’s landmass, which attenuate incoming wave energy before it reaches the leeward nearshore environment.

To further characterize temporal variability in wave conditions around Guam, time-series analyses were performed using bulk wave parameters extracted from representative WWIII grid cells located on the northeastern and western sides of the island (Figure 6 and Figure 7, respectively). These figures summarize interannual variability across the 31-year hindcast record using three complementary metrics. The top subplot presents a composite annual score based on the frequency and duration of higher-energy wave events, while the second subplot shows the number of such events occurring each year. The third subplot displays the annual mean significant wave height. Together, these metrics illustrate differences in both wave energy intensity and event structure between the windward and leeward sides of the island. The northeastern grid cell exhibits generally higher annual scores and greater numbers of energetic wave events, along with higher mean significant wave heights, whereas the western grid cell shows fewer high-energy events and lower mean wave heights, consistent with spatial patterns observed in the screening-level wave energy maps. Interannual variability is evident in both locations, highlighting periods of enhanced and reduced wave activity within the hindcast record that were evaluated when identifying representative time windows for subsequent high-resolution wave modeling.

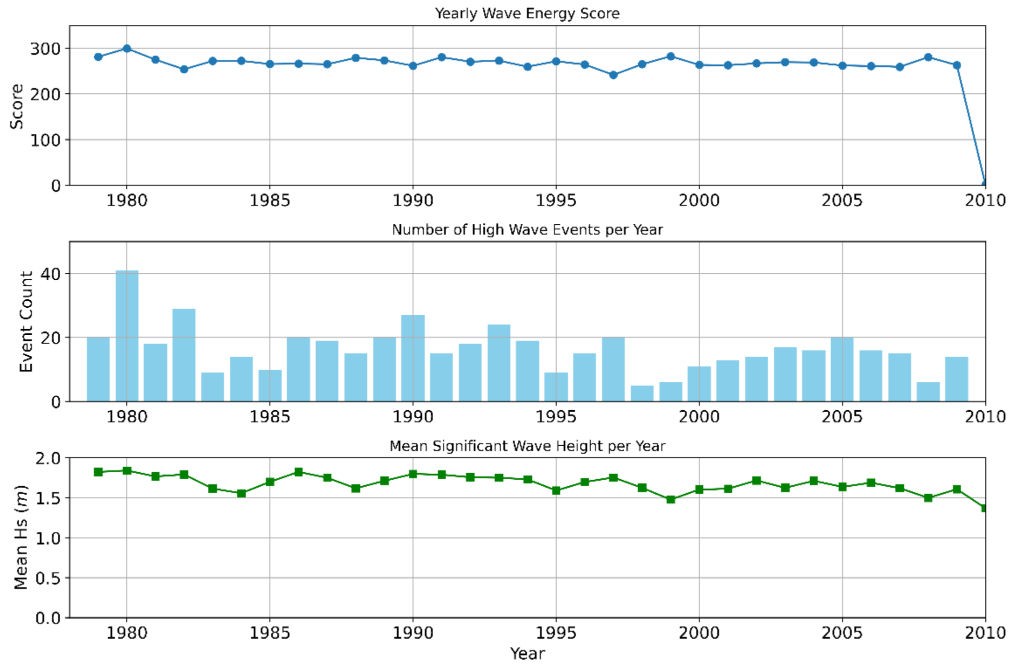

Figure 6. Time-series summary of bulk wave conditions derived from the northeastern WWIII grid cell offshore of Guam. Panels show the annual wave energy score based on the frequency and duration of high-wave events (top), the number of high-wave events per year (middle), and the annual mean significant wave height over the 31-year hindcast record (bottom).

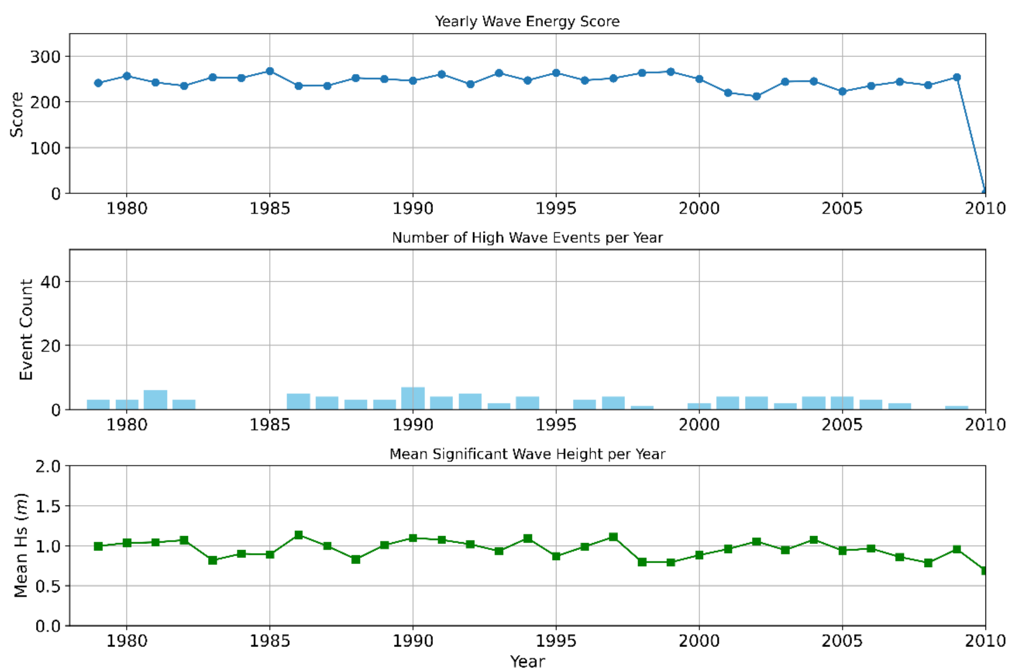

Figure 7. Time-series summary of bulk wave conditions derived from the western WWIII grid cell offshore of Guam. Panels show the annual wave energy score based on the frequency and duration of high-wave events (top), the number of high-wave events per year (middle), and the annual mean significant wave height over the 31-year hindcast record (bottom).

In addition to spatial visualization of wave energy patterns, bulk wave parameters were extracted from all WWIII grid cells surrounding Guam to support subsequent high-resolution wave modeling efforts. This data extraction step was completed prior to refinement of candidate regions for higher-resolution analysis and included downloading wave parameters from multiple offshore grid points encompassing the full perimeter of the island. The extracted parameters provide a comprehensive representation of offshore wave conditions and were used to inform boundary condition selection for the SWAN simulations applied in Task 4. Although only a subset of these grid cells was ultimately required for site-specific modeling, compiling the full set of surrounding WWIII data ensured flexibility in domain definition and boundary condition specification during the transition from regional screening to higher-resolution assessment.

Role of Task 2 Results in Overall Site Selection

The primary role of Task 2 was to establish a screening-level wave energy context that could be integrated with geospatial constraints and infrastructure considerations during site selection. The SEAMOD-based screening outputs provided a consistent, island-wide view of relative wave energy exposure and temporal variability around Guam, enabling broad differentiation among coastal regions without relying on site-specific assumptions. These screening-level results were used to identify areas where wave energy conditions were persistently higher or lower and to characterize contrasts between windward and leeward coastlines that are relevant to prefeasibility planning. Importantly, Task 2 results were not used in isolation to select sites, but instead served as one component of a broader, multi-criteria evaluation process.

During site selection, screening-level wave resource information from Task 2 was considered alongside bathymetric characteristics, proximity to existing infrastructure, and spatial constraints compiled under Task 1. The Task 2 outputs helped narrow the spatial focus from island-wide assessment to a limited number of candidate regions where wave energy conditions were sufficient to warrant further investigation and where development feasibility could reasonably be evaluated. These candidate regions defined the spatial domains for subsequent, higher-resolution numerical wave modeling, ensuring that more computationally intensive analyses were targeted to locations with both meaningful wave energy potential and practical siting relevance. In this way, Task 2 results provided a defensible and efficient bridge between regional screening and the more detailed site-specific assessments conducted in later tasks.

Task 2 Summary

Task 2 established a screening-level, IEC-compliant characterization of the wave energy resource around Guam using validated regional hindcast data processed and visualized through the SEAMOD platform. Results demonstrated clear and persistent spatial contrasts in wave energy exposure around the island, with higher wave power and more energetic sea states along the eastern (windward) coastline and comparatively lower, more sheltered conditions along the western (leeward) coastline. Temporal analyses further showed interannual variability in wave energy intensity and event frequency that is consistent across the hindcast record and relevant for prefeasibility planning. While the coarse spatial resolution of the regional dataset limits site-specific interpretation, the Task 2 outcomes provide a defensible, island-wide context for differentiating relative wave energy potential among coastal regions. These screening-level results were not used to select sites directly but instead served as a critical input to Task 3, where wave energy patterns were evaluated alongside bathymetry, infrastructure proximity, and spatial constraints to identify candidate regions for focused site selection and higher-resolution analysis.

7.1.3 Task 3: Site Selection

Task 3 focuses on integrating wave resource screening outputs with environmental, regulatory, and infrastructure datasets to identify candidate wave energy deployment areas along the Guam coastline. Building on the screening-level wave information developed in Task 2 and the geospatial framework established in Task 1, this task evaluated siting opportunities and constraints at regional scales. The outcomes of Task 3 include the identification of areas suitable for further evaluation, refinement of siting considerations, and selection of candidate regions for higher-resolution, site-specific assessment performed in Task 4.

Integration of Screening-Level Wave Data and Geospatial Constraints

Task 2 focused on integrating the geospatial siting framework developed under Task 1 with large-scale wave energy resource information derived from the SEAMOD platform to identify candidate regions for more detailed evaluation. The Task 1 geodatabase was first used to screen coastal areas based on proximity to population centers, existing electrical and port infrastructure, military facilities, and potential shore-based connection points. These siting considerations were then evaluated alongside spatial patterns in wave power observed using SEAMOD, which provides screening-level visualization of omnidirectional wave power derived from the WWIII hindcast dataset (Figure 8). Results from SEAMOD indicate a clear contrast in wave energy exposure around Guam, with generally higher wave power along the eastern (windward) coastline and comparatively lower wave energy along the western (leeward) side. While the windward coast offers increased energy availability, the leeward coast benefits from substantially greater infrastructure density, highlighting an inherent tradeoff between wave resource strength and feasibility of power transmission to shore.

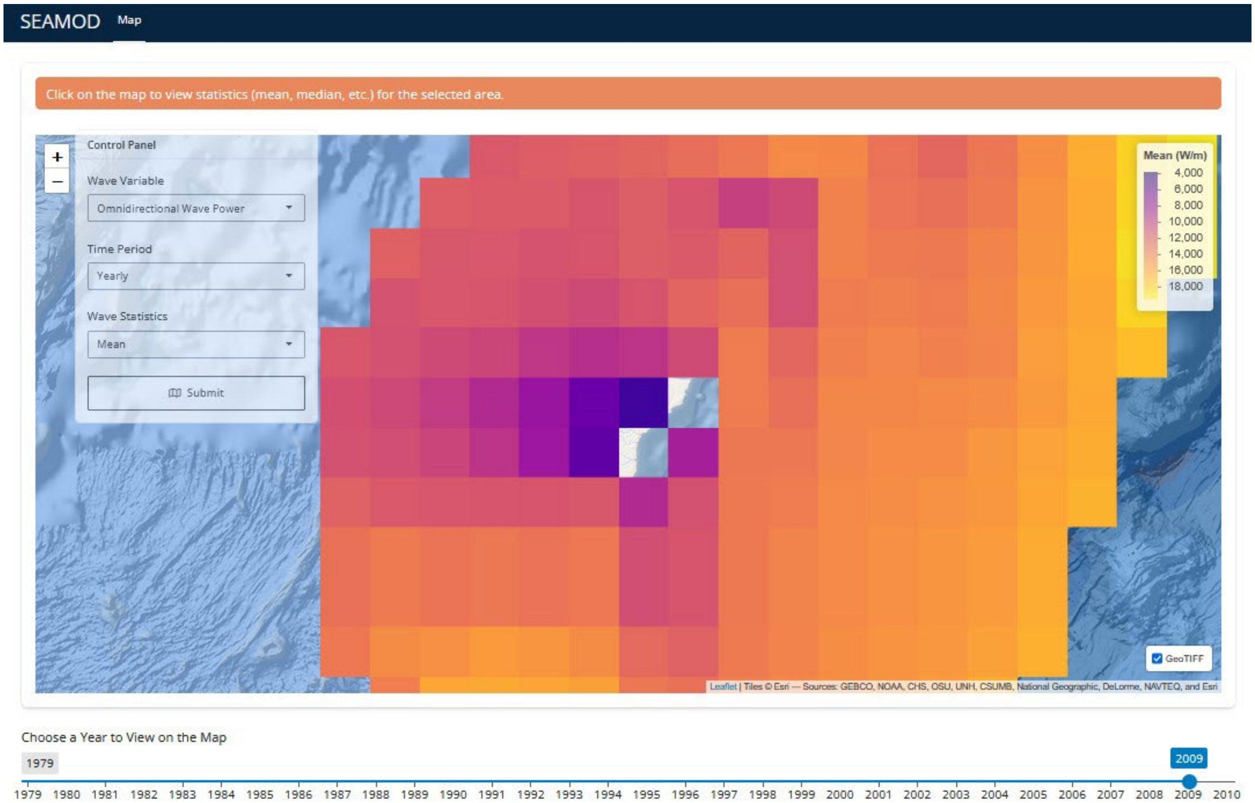

Figure 8. Mean omni-directional wave power for 2009 around Guam, showing higher wave energy along the windward (eastern) coastline and reduced wave energy along the leeward (western) coastline due to wave shadowing.

By combining the infrastructure- and constraint-based screening from Task 1 with the large-scale wave energy patterns observed in SEAMOD, three regional areas were selected for advancement to Tasks 3 and 4 (Figure 9). Two of these areas are located along the western coastline to leverage proximity to Guam's primary population centers and grid infrastructure, while one area was selected along the northeastern coastline to capture higher wave energy exposure offshore of Andersen Air Force Base. The southern western region, located immediately north of Apra Harbor, encompasses approximately 20 km of coastline adjacent to Guam's most densely populated corridor and represents a favorable balance between accessibility and development potential. A second western region at the northwest corner of the island spans roughly 10 km of coastline and offers reduced competing uses while maintaining reasonable access to shore. The third region, located offshore of Andersen Air Force Base at the northeastern corner of Guam, covers approximately 8 km of coastline and was selected to evaluate wave energy feasibility in a higher-energy environment with distinct operational and permitting considerations. These three regions define the spatial domains for subsequent higher-resolution SWAN modeling, which will be used to refine wave conditions and evaluate the prefeasibility of WEC deployments at scales appropriate for site-specific assessment.

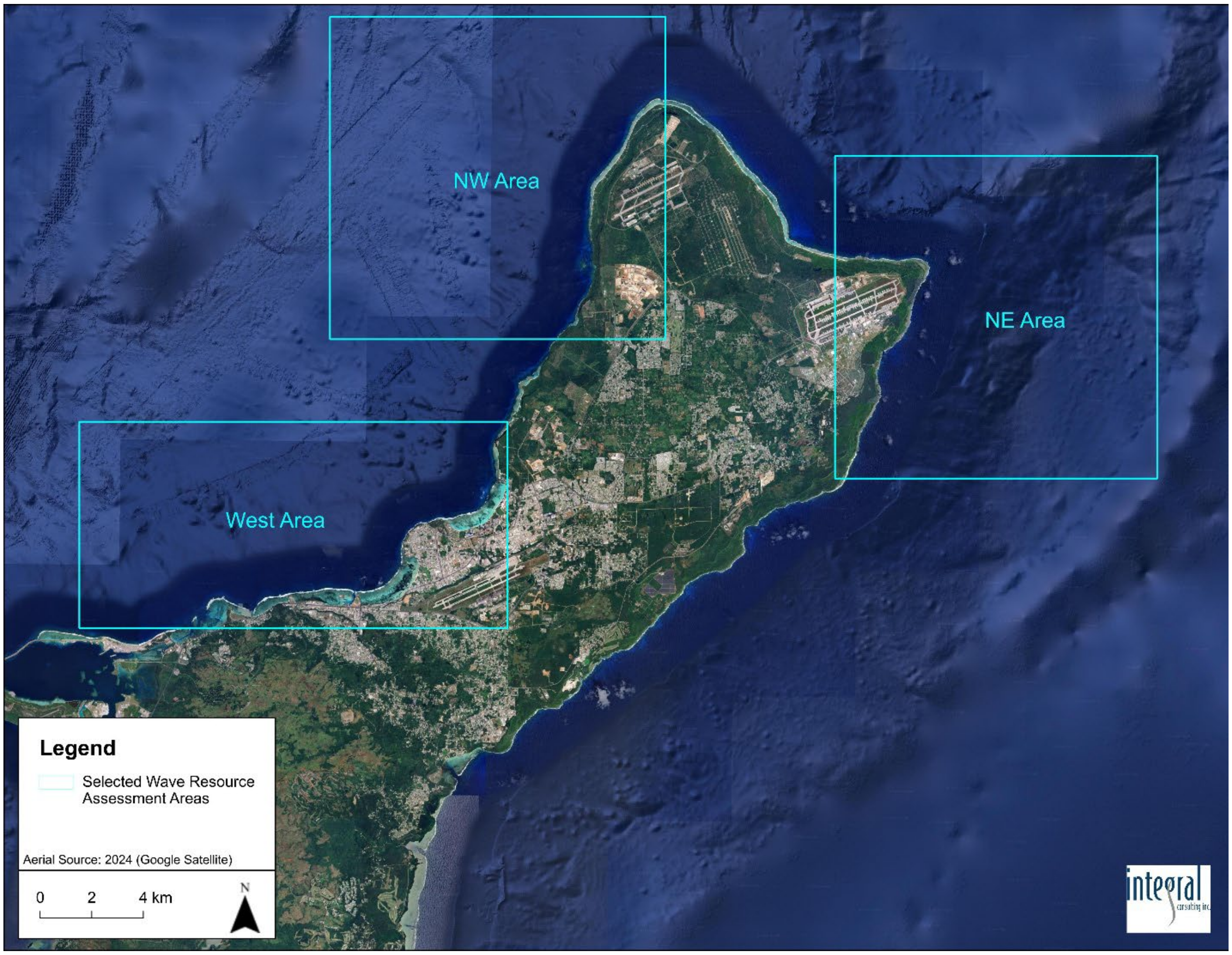

Figure 9. Outline of selected Guam coastal site areas for high resolution wave energy resource assessment.

Bathymetric conditions within the three selected regions further inform their suitability for wave energy development by defining the range of operational water depths available for potential WEC deployments (Figure 10). The two western regions exhibit relatively broad shallow shelves adjacent to the shoreline, followed by a gradual transition into deeper water with increasing distance offshore. This bathymetric profile provides flexibility for device siting across a range of depths, supporting both nearshore and intermediate-depth WEC concepts while allowing developers to balance energy capture, mooring design, and cable routing considerations. In contrast, the northeastern region offshore of Andersen Air Force Base also includes an extensive shallow nearshore area; however, water depths increase more rapidly moving offshore compared to the western sites. This steeper bathymetric gradient may constrain the available deployment footprint but also enables access to deeper water and higher wave energy over shorter distances from shore. Collectively, these bathymetric characteristics are critical for evaluating WEC operational envelopes, foundation and mooring requirements, and transmission feasibility.

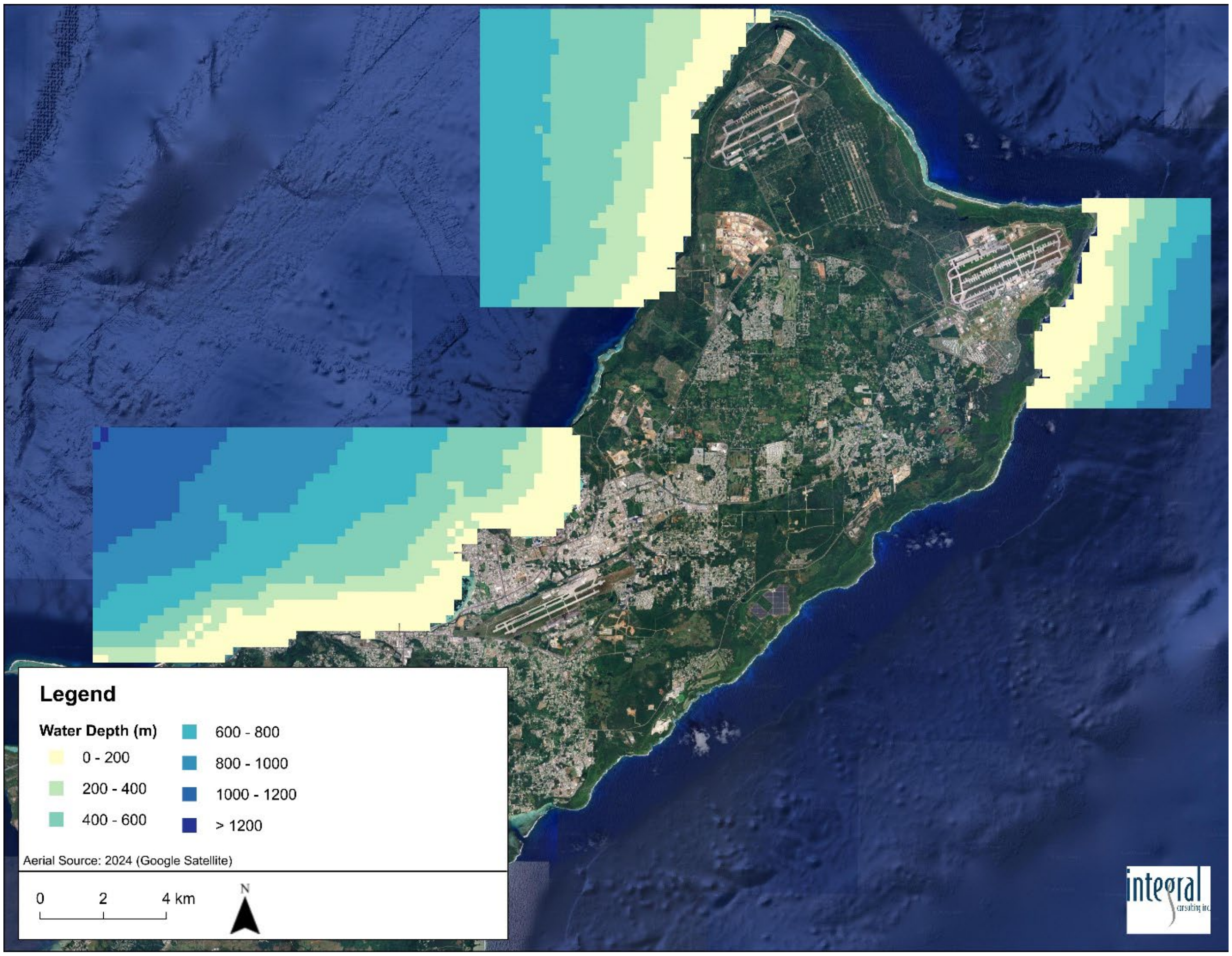

Figure 10. Bathymetry within Guam sites for high resolution SWAN wave modeling.

Suitability Factors and Weighting Considerations

The selection of candidate regions for advancement was guided by a balanced evaluation of wave energy potential, infrastructure accessibility, and spatial constraints relevant to feasible wave energy development. Screening-level wave energy patterns derived from the SEAMOD visualization of the WWIII hindcast dataset were used to identify coastal areas exhibiting relatively higher and more persistent wave exposure at regional scales. These energy patterns were considered alongside bathymetric conditions and coastal orientation to ensure that selected regions could plausibly support WEC operation within typical device depth and performance envelopes. Importantly, wave energy availability was evaluated as one component of overall suitability, rather than as a sole determinant, to avoid prioritizing regions with high energy potential but limited development feasibility.

Infrastructure proximity and spatial constraints were incorporated as complementary suitability factors to reflect practical considerations associated with deployment, power transmission, and long-term operation. Regions with reasonable access to population centers, existing electrical infrastructure, ports, and potential cable landing areas were favored to reduce installation complexity and lifecycle costs. At the same time, environmental protections, navigation and anchorage areas, and military use zones were treated as limiting or exclusionary factors depending on their regulatory context. Applying these considerations in combination resulted in the selection of two western coastline regions that emphasize infrastructure access and community proximity, and one northeastern region that captures higher wave energy exposure within a distinct operational setting. Together, these factors provided a transparent and reproducible basis for identifying three candidate areas suitable for further refinement through multicriteria evaluation and higher-resolution wave modeling.

Task 3 Summary

In summary, Task 3 applied an integrated spatial decision-making framework to narrow the regional focus for wave energy development in Guam from island-wide screening to three candidate areas suitable for further refinement. By jointly considering wave energy exposure, bathymetric characteristics, infrastructure accessibility, and spatial constraints, the site selection process balanced energy potential with practical feasibility and operational considerations. The resulting candidate regions represent areas where wave energy development is technically plausible at a screening level and where subsequent analysis can meaningfully reduce uncertainty. These regions do not represent final deployment sites; rather, they define focused spatial domains for higher-resolution evaluation. Building on this screening-level selection, Task 4 advances the analysis by resolving nearshore wave conditions at finer spatial scales using coupled numerical modeling, enabling site-specific assessment of wave energy characteristics and supporting prefeasibility evaluation of WEC deployments.

7.1.4 Task 4: Site Specific Resource Characterization

Task 4 focused on refining the wave energy resource characterization within the three candidate regions identified through the site selection process by applying higher-resolution, site-specific numerical wave modeling. Building on the regional screening and spatial constraints evaluated in earlier tasks, this phase of analysis utilized the SWAN model to resolve nearshore wave conditions at spatial scales appropriate for prefeasibility assessment. Outputs from the SEAMOD platform were used to inform model domain selection, boundary conditions, and interpretation of results, providing continuity between regional screening and site-specific evaluation without directly coupling the two modeling systems. This workflow enabled a more detailed assessment of wave transformation processes, spatial variability in wave energy, and site-dependent conditions relevant to potential WEC deployment within each candidate area.

High-Resolution Wave Modeling Framework

High-resolution numerical wave modeling was conducted using the SWAN model to refine characterization of nearshore wave conditions within the three candidate regions identified during site selection. SWAN is a third-generation spectral wave model widely applied for nearshore and coastal wave transformation studies, including applications in marine energy resource assessment, due to its ability to resolve processes such as refraction, shoaling, depth-induced breaking, and directional wave spreading. These processes are not captured at the regional screening scale but are critical for evaluating site-specific wave conditions relevant to potential WEC deployment. For this study, SWAN provided the capability to resolve spatial variability in wave energy across each candidate region while maintaining consistency with established wave resource assessment methodologies.

Model grids were developed for each candidate region using a horizontal resolution of 50 m, selected to balance spatial detail with computational efficiency and output requirements (Figure 9). This resolution is sufficient to capture gradients in bathymetry and nearshore wave transformation while allowing for the generation of two-dimensional wave spectra, which are required to compute wave resource metrics in accordance with IEC guidelines. Bathymetric data compiled during Task 1 were used to define each grid, ensuring consistency between the site selection framework and the higher-resolution modeling domains. The spatial extent of each grid was designed to encompass the full candidate region identified in Task 3 while extending offshore to adequately represent incoming wave conditions prior to nearshore modification.

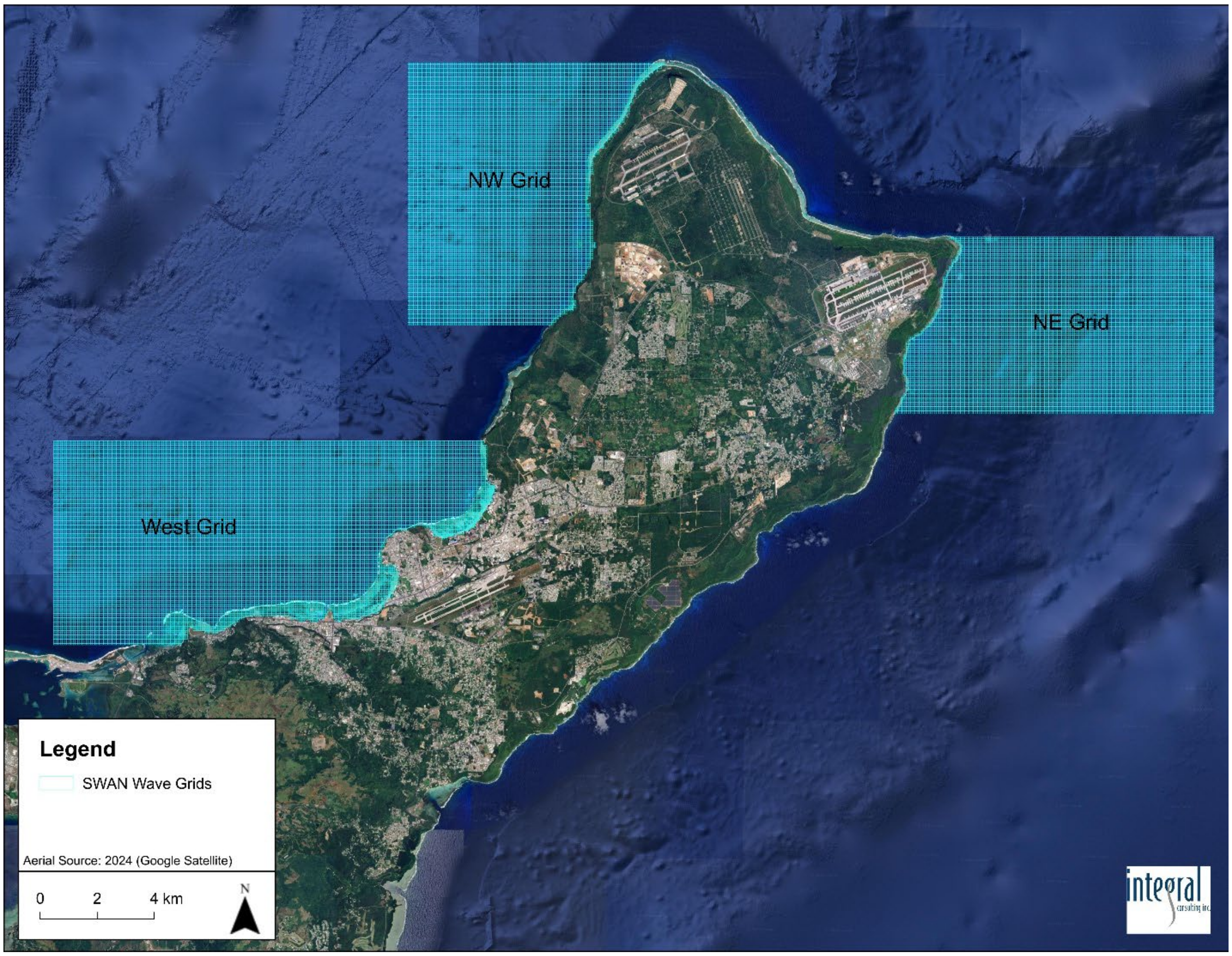

Figure 11. Overview of the SWAN high resolution model domains for the selected site areas.

Boundary conditions for each SWAN model domain were defined using bulk wave parameters derived from the WWIII hindcast dataset. Based on prior analysis of the long-term hindcast record, an 11-year period from 1980 through 1990 was selected for high-resolution modeling. The selected period captures a range of wave conditions representative of the broader hindcast record, as indicated by time-series analyses of bulk wave parameters at representative windward and leeward locations around Guam. These analyses show that the early portion of the hindcast record includes variability in wave event frequency, duration, and mean significant wave height comparable to longer-term patterns observed across the full record. For each domain, time-varying boundary conditions were specified at 3-hour intervals using offshore bulk wave parameters representative of regional wave climate conditions adjacent to the model boundaries. These boundary conditions were extracted from multiple WWIII grid cells surrounding Guam to ensure appropriate representation of offshore forcing for each domain and to support consistency across the modeling period.

SWAN simulations were executed for each of the three domains over the full 11-year period, producing outputs at 3-hour intervals. Model outputs included bulk wave parameters as well as full two-dimensional wave spectra throughout each domain. These outputs formed the basis for calculation of wave energy resource metrics, including those required to characterize wave power, directional distribution, and temporal variability consistent with IEC guidelines. The resulting datasets provide spatially and temporally resolved wave information suitable for prefeasibility-level wave energy resource assessment and support subsequent evaluation of site-specific conditions relevant to WEC deployment within each candidate region.

Site-Specific Wave Resource Characteristics

Site-specific wave resource characteristics were derived from the high-resolution SWAN simulations to provide spatially resolved representations of wave conditions within each candidate region. Consistent with established wave resource assessment guidance, outputs were processed using a uniform methodology across all three domains to ensure comparability among sites. Bulk wave parameters and directional wave information were computed from the 11-year simulation period using temporally averaged statistics appropriate for prefeasibility-level assessment. The resulting spatial datasets characterize key aspects of the wave climate relevant to wave energy development, including omnidirectional wave power, wave energy period, and directional distribution of wave energy.

Annually averaged omni-directional wave power derived from the SWAN simulations exhibits clear spatial variability among the three candidate regions (Figure 12). Omni-directional wave power was calculated from the two-dimensional directional wave spectra produced by the SWAN simulations following the methodology defined in IEC TS 62600-101. Specifically, wave power was computed as the time-averaged energy flux per unit crest width by integrating spectral energy density across all frequencies and directions, accounting for frequency-dependent group velocity to produce long-term mean estimates of omni-directional wave power at each study location. The highest wave power is observed along the northeastern coastline, where values reach approximately 15 kW/m, reflecting increased exposure to prevailing wind and swell conditions. Elevated wave energy is also evident along the northern edge of the northwestern domain, where wave energy wraps around the northern tip of Guam before propagating southward along the coast. In contrast, the western domain exhibits comparatively lower wave power levels, with values generally reaching up to approximately 6 kW/m, consistent with reduced exposure in the leeward wave environment. These spatial patterns are presented in the following figure, which summarizes the annually averaged omnidirectional wave power across all three domains based on the 11-year SWAN simulations.

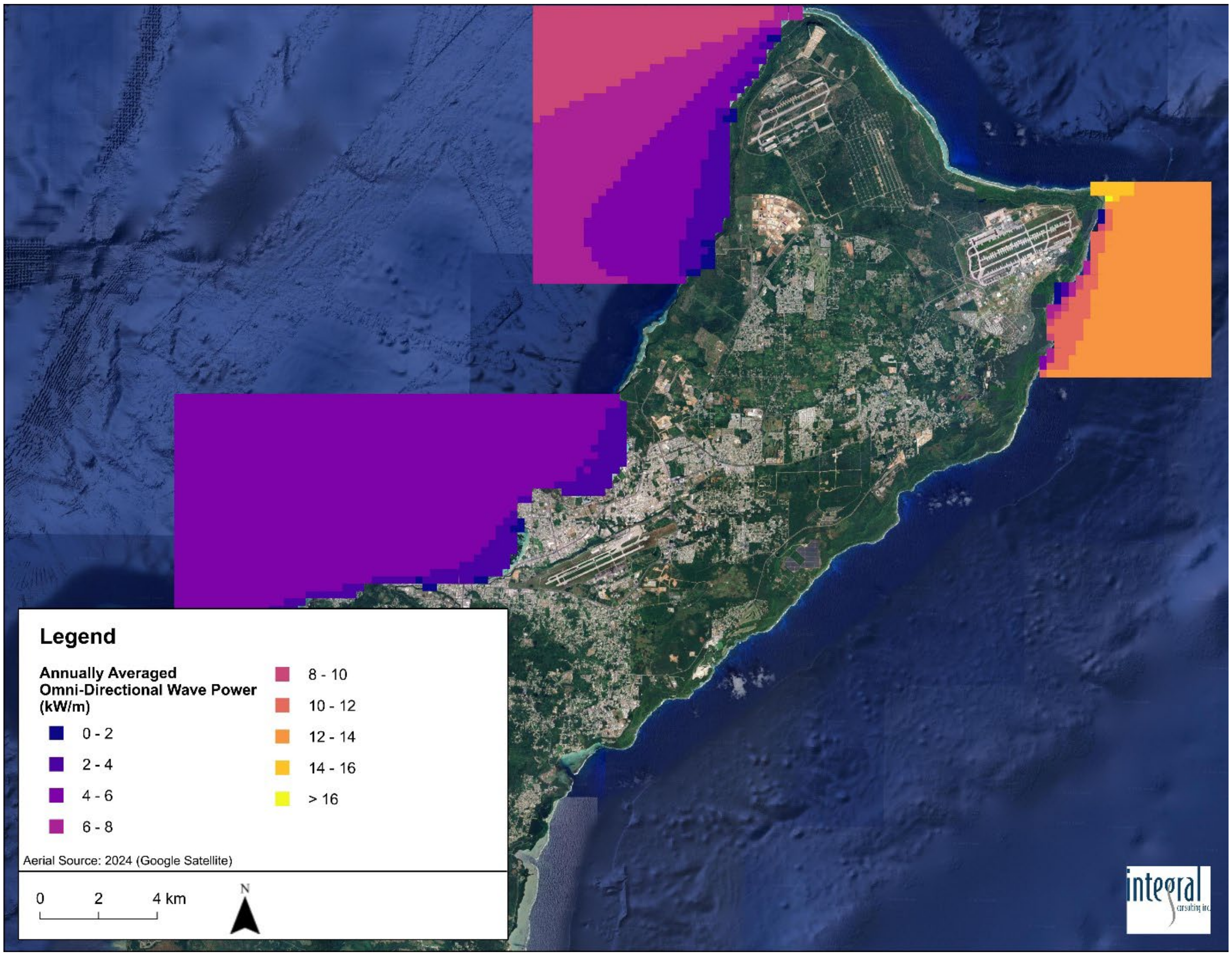

Figure 12. Annually averaged omni-directional wave power for the three SWAN domains around Guam

Comparison of site-specific wave resource characteristics across the three modeled domains indicates that the northeastern region consistently exhibits higher wave energy levels and more favorable wave conditions relative to the western domains. Spatial patterns derived from the SWAN simulations show increased omni-directional wave power along the northeastern coastline, while the western domains display reduced wave energy consistent with leeward exposure. These results provide a quantitative basis for prioritizing more detailed examination of the northeastern domain using additional IEC-based analyses presented in subsequent figures. The site-specific datasets developed for all three regions establish a consistent foundation for comparative evaluation, while the northeastern domain demonstrates wave resource characteristics that warrant further technical investigation within the scope of this assessment.

Directional and Temporal Refinement at Selected Sites

Directionally resolved wave power and the corresponding direction of maximum wave energy flux were derived from the two-dimensional directional wave spectra produced by the high-resolution SWAN simulations following the methodology defined in IEC TS 62600-101. For each modeled sea state, omni-directional wave power was resolved into directional components, and the maximum energy flux and its associated propagation direction were identified prior to aggregation into long-term mean values. The resulting spatial patterns indicate consistently elevated directionally resolved wave power across the exposed northeastern coastline, with dominant wave energy propagation oriented toward the southwest, reflecting persistent open-ocean wind and swell forcing, while localized variations in magnitude and direction highlight the influence of bathymetric controls and nearshore wave transformation processes within the domain (Figure 13).

Results for the northwestern Guam domain indicate generally lower maximum directionally resolved wave power relative to the northeastern domain, consistent with partial sheltering and reduced exposure to prevailing Pacific swell. Dominant wave energy propagation exhibits greater directional variability across the domain, with localized shifts in both magnitude and direction reflecting the influence of coastal orientation, bathymetric gradients, and wave transformation processes along the northwestern coastline (Figure 14).

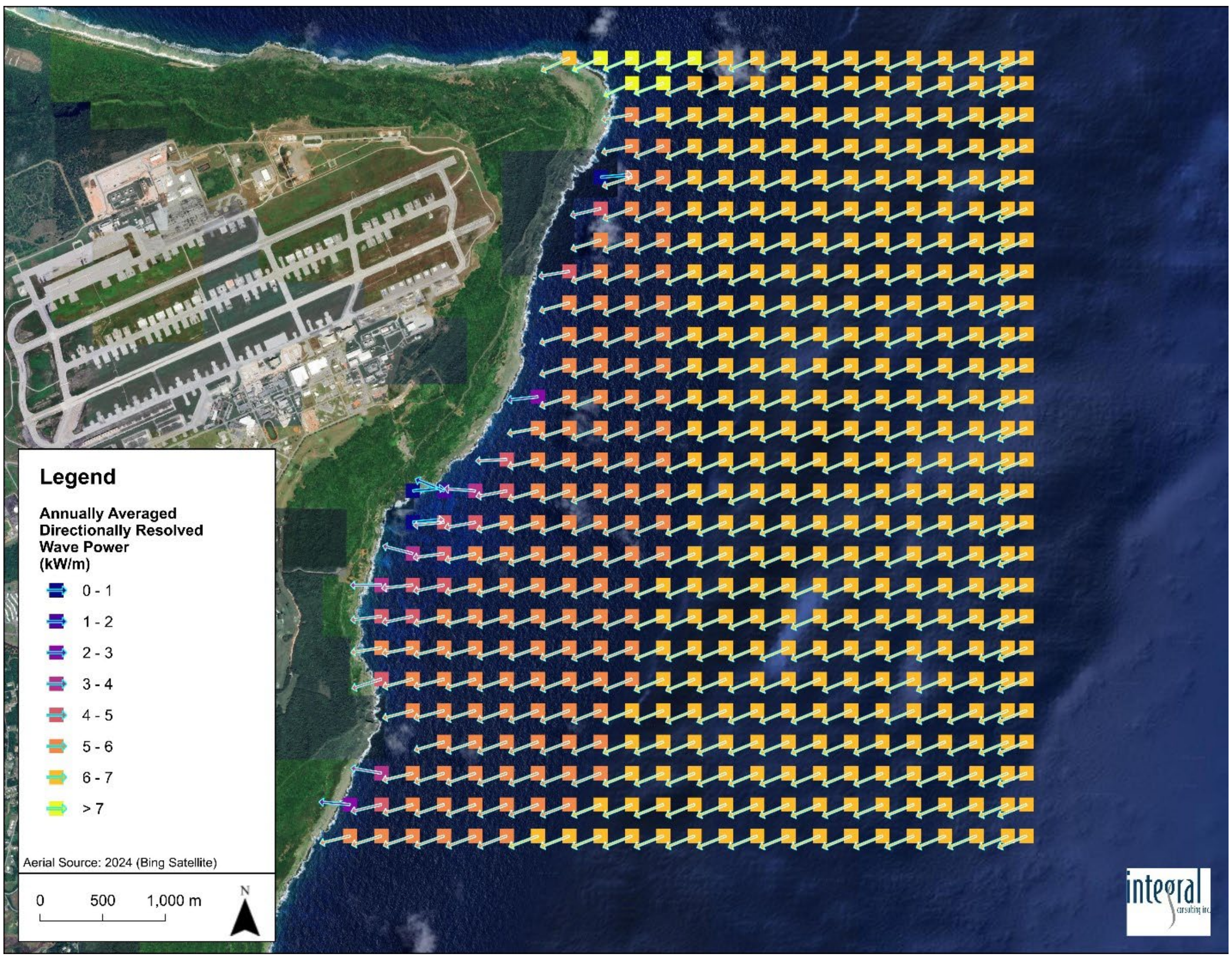

Figure 13. Spatial distribution of annually averaged maximum directionally resolved wave power and the direction of maximum wave power for the northeast SWAN domain.

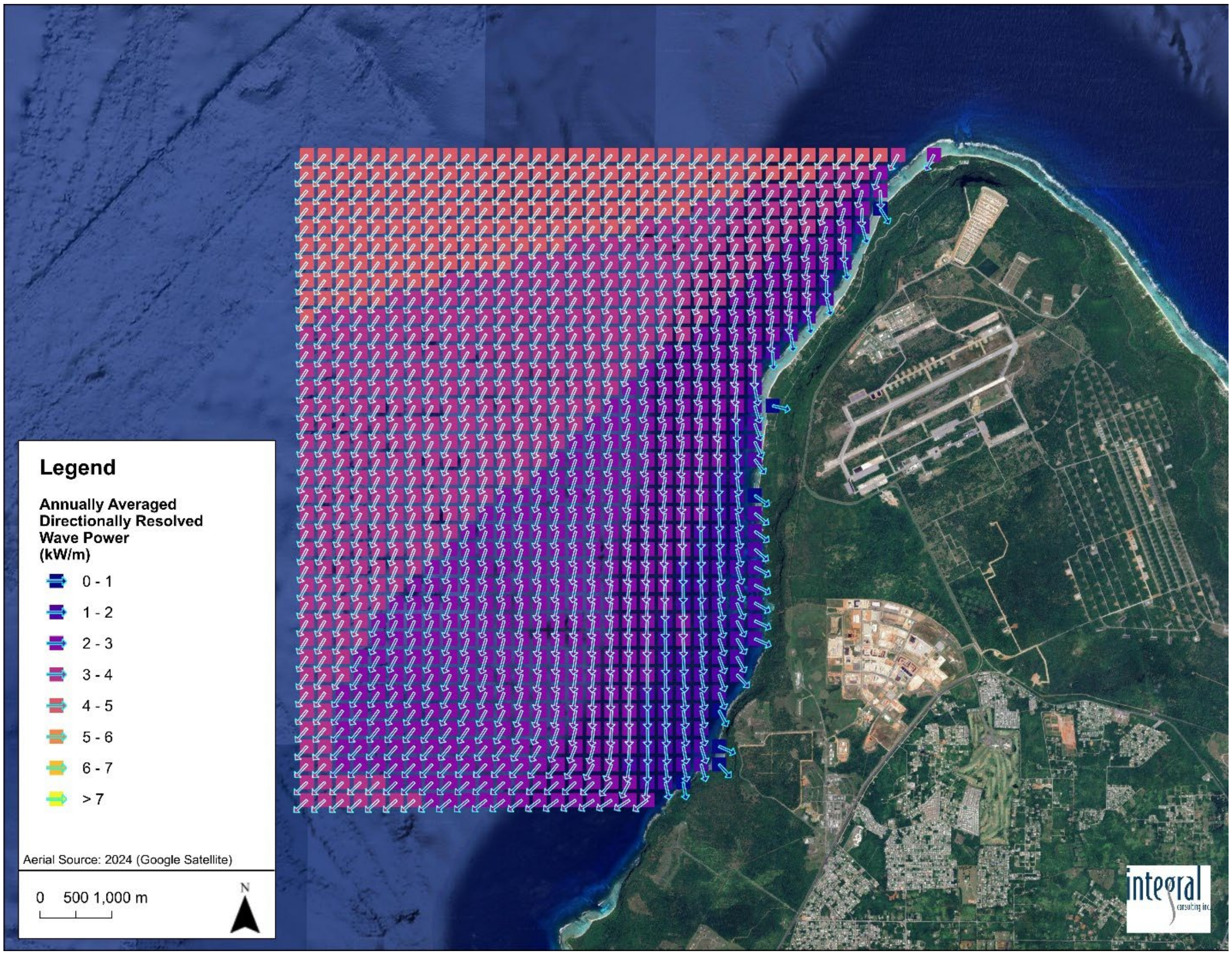

Figure 14. Spatial distribution of annually averaged maximum directionally resolved wave power and the direction of maximum wave power for the northwest SWAN domain.

Preliminary Energy Metrics

Preliminary energy metrics were developed from the 11-year, high-resolution SWAN simulation outputs using a consistent, standards-based processing workflow to characterize the modeled wave climate and support site-level comparison within the NE domain. Following IEC guidance for wave energy resource assessment and reporting, analysis products were generated from time-varying sea-state information (including directional spectral information at the study locations) to produce standardized wave resource parameters and statistics suitable for feasibility-class reporting and subsequent device-level screening.

The first figure in this subsection provides a zoomed view of the NE SWAN domain showing the spatial distribution of annually averaged omnidirectional wave power, with three study points identified for more detailed evaluation (Figure 15). These study points were selected as discrete locations coincident with SWAN grid points to represent spatial variability in the modeled wave resource within the NE domain and to support detailed reporting of wave climate characteristics at fixed locations. The study points serve as reference locations where time histories and derived statistics can be summarized in standardized plots and tables to enable transparent comparison of sea-state conditions within the candidate area.

The three study points selected within the northeastern Guam domain are located within the Pati Point Preserve MPA. Inclusion within this MPA does not inherently preclude consideration of wave energy development; rather, these locations were retained to evaluate wave resource characteristics in a high-energy, windward setting where regulatory considerations would require further site-specific assessment. The study points were selected based on their elevated modeled wave energy exposure along the windward coastline, proximity to Andersen Air Force Base, and representation of a range of nearshore bathymetric and spatial conditions relevant to potential WEC deployment. Water depths at the selected locations range from 15 to 40 m, with distances to shore of 200 to 400 m, and modeled mean significant wave heights of 2 to 3 m, collectively capturing plausible deployment conditions for comparative, prefeasibility-level evaluation rather than identification of preferred or permitted development sites.

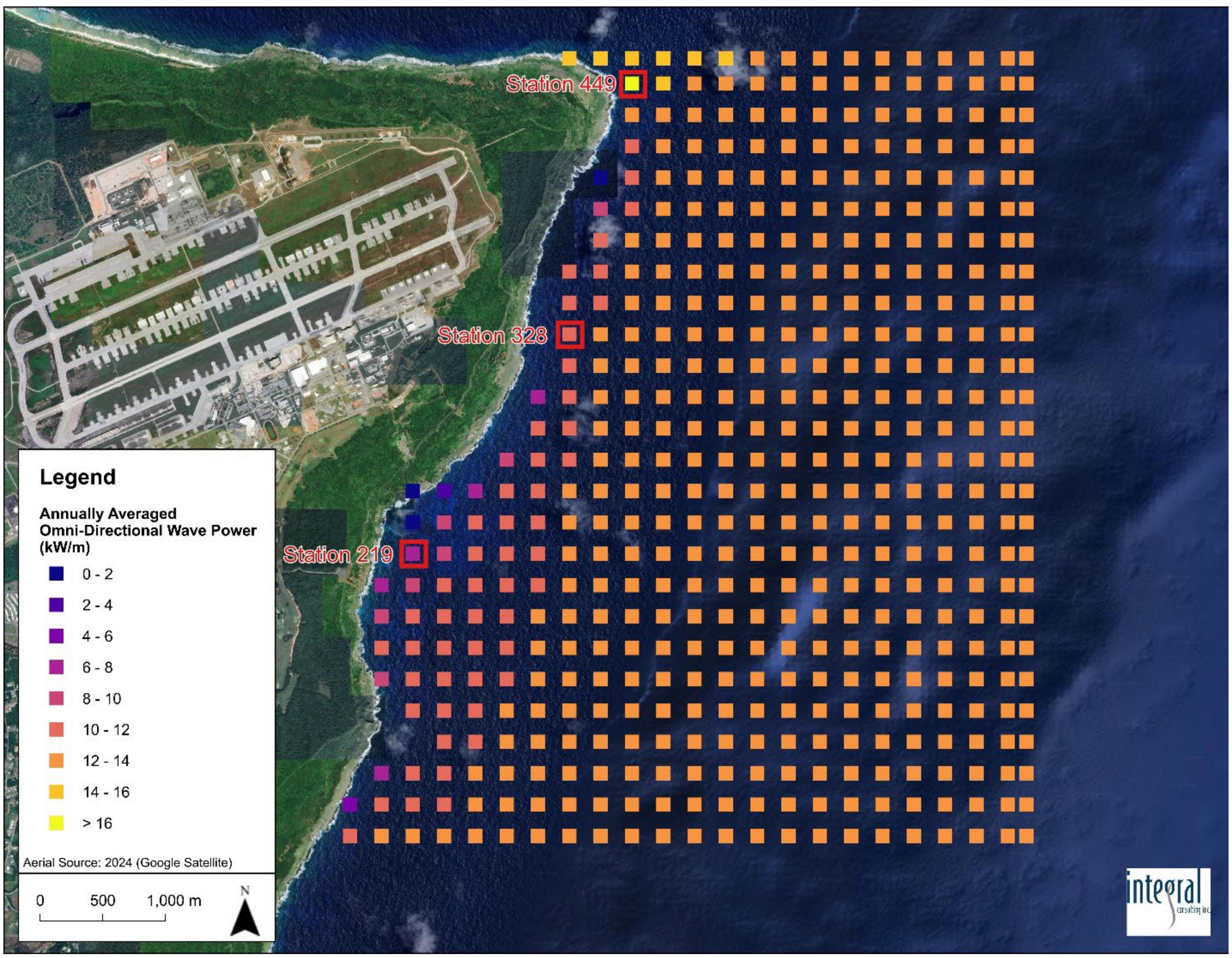

Figure 15. Annually averaged omni-directional wave power for the northeast SWAN domain with example study points highlighted for further investigation.

Following identification of the study points, monthly distributions of wave power are presented to describe intra-annual variability at the selected location(s) based on the long-term SWAN simulation record (Figure 16, Figure 17, and Figure 18). These plots summarize wave power by month using aggregated statistics derived from the multi-year time series, enabling comparison of the seasonal structure of the modeled resource and identification of months with relatively higher or lower wave power. Figure 16 illustrates the wave power by month for a northern study point of the model domain, showing the highest annually averaged omni-directional wave power. The winter and early spring months, November through April, produce higher wave power as compared to the annual average, and the remainder of the months are below the annual average. Figure 17 and Figure 18, representative of the other two study points along the NE Guam coastline, show similar trends in monthly wave power throughout the year.

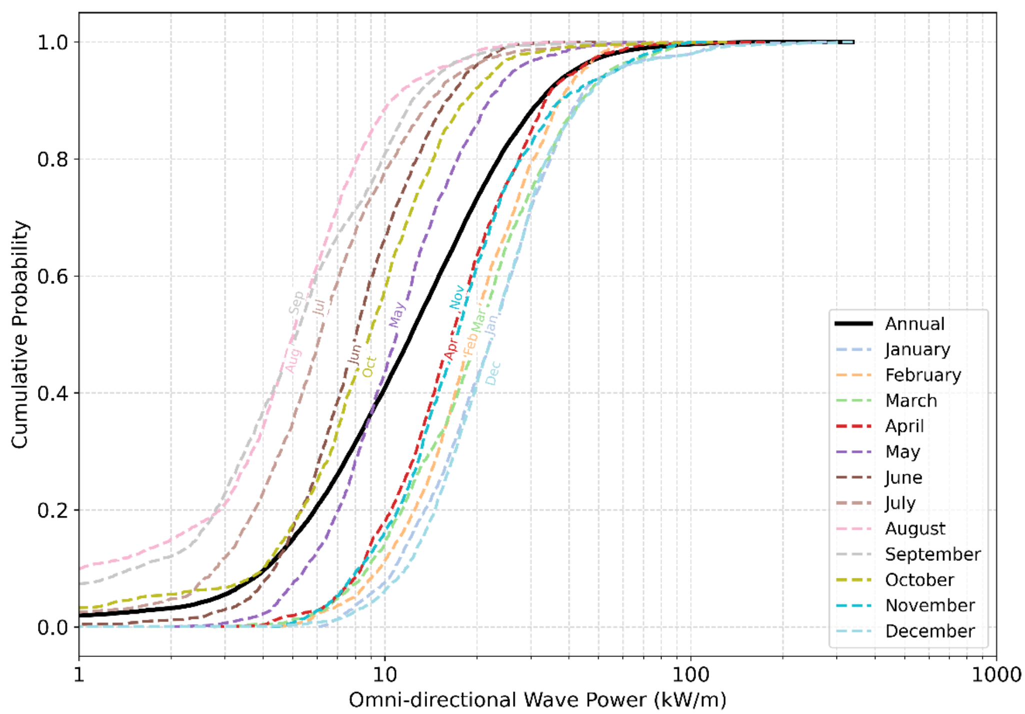

Figure 16. Cumulative probability distribution of omni-directional wave power by month for study point 449 in the northeastern SWAN domain.

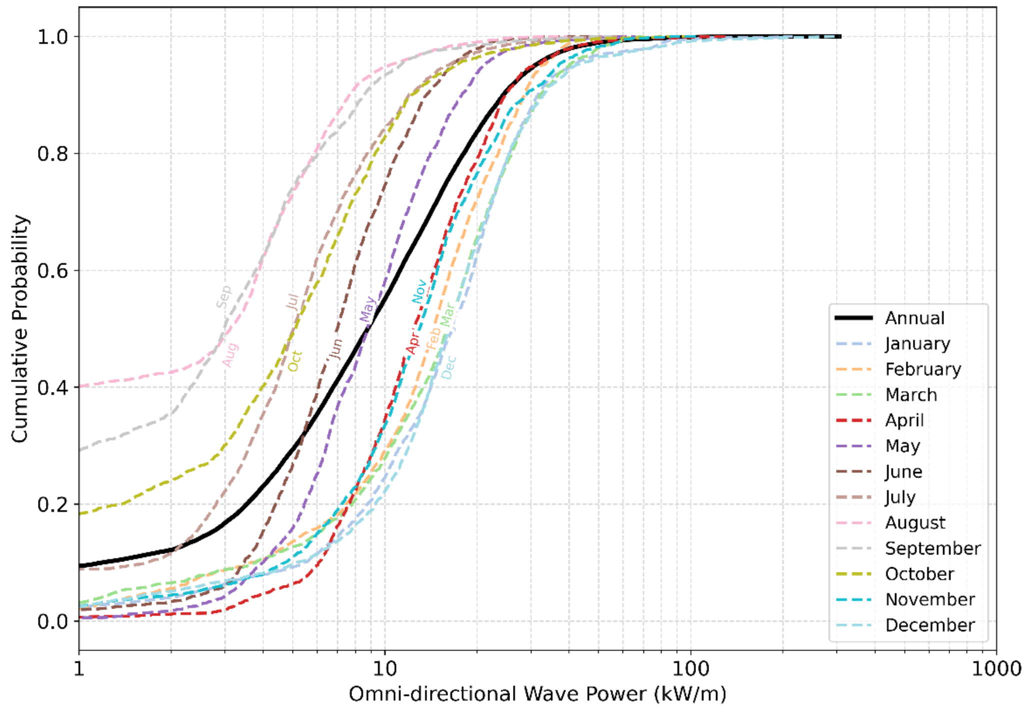

Figure 17. Cumulative probability distribution of omni-directional wave power by month for study point 328 in the northeastern SWAN domain.

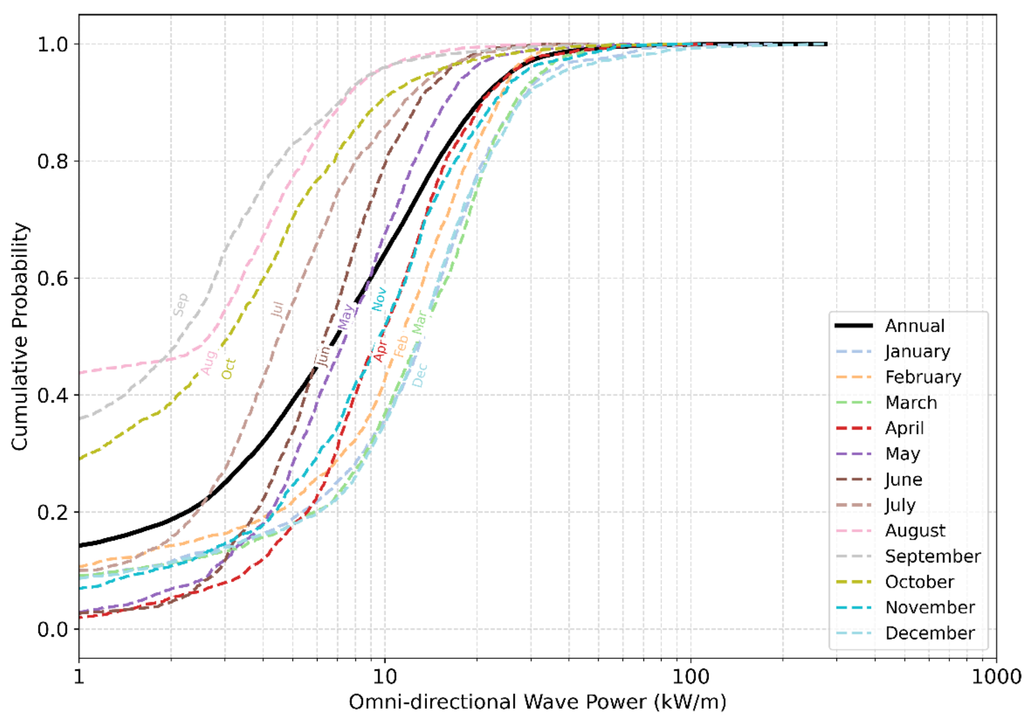

Figure 18. Cumulative probability distribution of omni-directional wave power by month for study point 219 in the northeastern SWAN domain.

For two of the study points, scatter tables are provided to summarize the long-term joint distribution of sea states parameterized by significant wave height and energy period (Table 3 and Table 4). Significant wave height and wave energy period were calculated from the two-dimensional directional wave spectra produced by the SWAN simulations following IEC TS 62600-101 standards. Significant wave height was derived from the zeroth spectral moment of the frequency spectrum, while the energy period was computed as the variance-weighted mean period based on the ratio of negative-first and zeroth spectral moments. These parameters were calculated for each modeled sea state and aggregated over the full simulation period to construct joint probability distributions of significant wave height and energy period at the selected study points. These tables depict the frequency structure of the modeled wave climate in a form commonly used for wave energy resource characterization, supporting consistent description of the range of sea states represented in the SWAN simulations at each location. For both stations, 449 and 219, the predominant wave heights and energy periods are in the 1 – 2 m and 7 – 9 s range, respectively.

Table 3. Significant wave height and wave energy period scatter table for study point 449 in the northeastern SWAN domain.

Significant Wave Height (m)	Energy Period (s)													
	3.0–4.0	4.0–5.0	5.0–6.0	6.0–7.0	7.0–8.0	8.0–9.0	9.0–10.0	10.0–11.0	11.0–12.0	12.0–13.0	13.0–14.0	14.0–15.0	15.0–16.0	%
0.0–0.5	0.01	0.06	0.15	0.26	0.28	0.62	0.54	0.20	0.04	0.00	0.00	0.00	0.00	2.13
0.5–1.0	0.00	0.01	0.06	0.68	3.09	4.51	1.54	0.71	0.19	0.03	0.02	0.01	0.00	10.86
1.0–1.5	0.00	0.04	0.35	1.48	8.80	12.99	4.28	1.74	0.80	0.21	0.05	0.02	0.01	30.78
1.5–2.0	0.00	0.01	0.24	1.40	7.52	10.90	4.50	1.96	0.77	0.44	0.21	0.04	0.01	27.99
2.0–2.5	0.00	0.00	0.05	0.72	3.23	7.07	3.71	1.88	0.55	0.16	0.23	0.10	0.03	17.73
2.5–3.0	0.00	0.00	0.00	0.08	0.93	2.32	2.21	1.25	0.22	0.07	0.03	0.04	0.01	7.16
3.0–3.5	0.00	0.00	0.00	0.00	0.11	0.57	0.73	0.43	0.13	0.09	0.07	0.01	0.00	2.15
3.5–4.0	0.00	0.00	0.00	0.00	0.01	0.10	0.19	0.18	0.13	0.02	0.03	0.02	0.01	0.69
4.0–4.5	0.00	0.00	0.00	0.00	0.00	0.03	0.06	0.11	0.07	0.02	0.00	0.00	0.00	0.28
4.5–5.0	0.00	0.00	0.00	0.00	0.00	0.01	0.03	0.07	0.04	0.00	0.00	0.00	0.00	0.15
5.0–5.5	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.02	0.00	0.00	0.00	0.00	0.00	0.04
5.5–6.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
6.0–6.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.02
%	0.01	0.12	0.85	4.62	23.97	39.11	17.80	8.56	2.96	1.05	0.64	0.23	0.08	100

Table 4. Significant wave height and wave energy period scatter table for study point 219 in the northeastern SWAN domain.

Significant Wave Height (m)	Energy Period (s)													
	3.0–4.0	4.0–5.0	5.0–6.0	6.0–7.0	7.0–8.0	8.0–9.0	9.0–10.0	10.0–11.0	11.0–12.0	12.0–13.0	13.0–14.0	14.0–15.0	15.0–16.0	%
0.0–0.5	0.01	0.03	0.10	0.21	0.76	1.74	2.62	3.77	3.00	1.98	0.64	0.16	0.04	15.07
0.5–1.0	0.00	0.02	0.02	1.14	6.97	8.09	2.56	1.11	0.55	0.26	0.24	0.10	0.03	21.09
1.0–1.5	0.00	0.04	0.49	2.15	11.57	9.96	2.75	0.93	0.26	0.20	0.17	0.11	0.05	28.69
1.5–2.0	0.00	0.00	0.18	1.76	7.87	8.65	3.09	1.06	0.13	0.09	0.06	0.03	0.00	22.92
2.0–2.5	0.00	0.00	0.01	0.24	2.56	4.05	1.98	0.43	0.13	0.07	0.04	0.02	0.01	9.52
2.5–3.0	0.00	0.00	0.00	0.03	0.22	0.79	0.47	0.27	0.06	0.00	0.00	0.00	0.00	1.84
3.0–3.5	0.00	0.00	0.00	0.00	0.03	0.15	0.20	0.13	0.03	0.00	0.00	0.00	0.00	0.53
3.5–4.0	0.00	0.00	0.00	0.00	0.01	0.06	0.03	0.05	0.04	0.00	0.00	0.00	0.00	0.19
4.0–4.5	0.00	0.00	0.00	0.00	0.00	0.02	0.02	0.03	0.01	0.00	0.00	0.00	0.00	0.09
4.5–5.0	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.04
5.0–5.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.02
%	0.01	0.09	0.80	5.54	29.99	33.50	13.74	7.81	4.22	2.61	1.15	0.41	0.13	100

Annual Energy Production

Annual Energy Production (AEP) provides an integrated measure of the long-term energy yield potential at a site by combining wave resource characteristics with representative device performance. In accordance with IEC TS 62600-100, AEP is used as a standardized metric to translate site-specific wave climate conditions into expected annual energy output under idealized availability assumptions, enabling consistent comparison among candidate sites and supporting prefeasibility-level assessment of wave energy potential. Higher AEP values are generally associated with locations exhibiting both elevated wave power and a narrow directional distribution, while reduced AEP is observed in more sheltered areas where wave energy is attenuated by coastal orientation and bathymetric effects.

AEP was calculated following the standard methodology defined in IEC TS 62600-100 using the high-resolution SWAN wave simulations. Directional wave spectra were used to characterize the long-term joint distribution of significant wave height and energy period at each modeled location, and representative capture length and power performance relationships were applied to each sea state to estimate energy production. The contribution of individual sea states to AEP was weighted by their frequency of occurrence over the multiyear simulation period, and total annual energy production was obtained by summing energy contributions across all sea states assuming continuous availability, consistent with IEC guidance.

Results presented in Figure 19 demonstrate that the NE domain exhibits the highest estimated AEP among the three candidate regions evaluated, reflecting both elevated wave power levels and favorable directional persistence along this portion of Guam's coastline. Mean AEP values across the NE domain range from approximately 300 to 1,000 MWh for the representative wave energy converter considered, with the largest values concentrated near the northeastern corner of the island where exposure to prevailing Pacific swell is greatest. This spatial pattern is consistent with the distribution of omni-directional wave power derived from the SWAN simulations and highlights the combined influence of coastal orientation, reduced sheltering, and bathymetric controls on wave energy availability. Gradients in AEP across the domain further illustrate the effects of nearshore wave transformation processes, including refraction and depth-induced attenuation, which result in localized reductions in energy yield closer to shore despite broadly energetic offshore conditions. While these AEP estimates are based on idealized availability assumptions and a generalized device representation, they provide a standardized, IEC-consistent basis for comparing relative energy potential within the NE domain and between candidate regions.

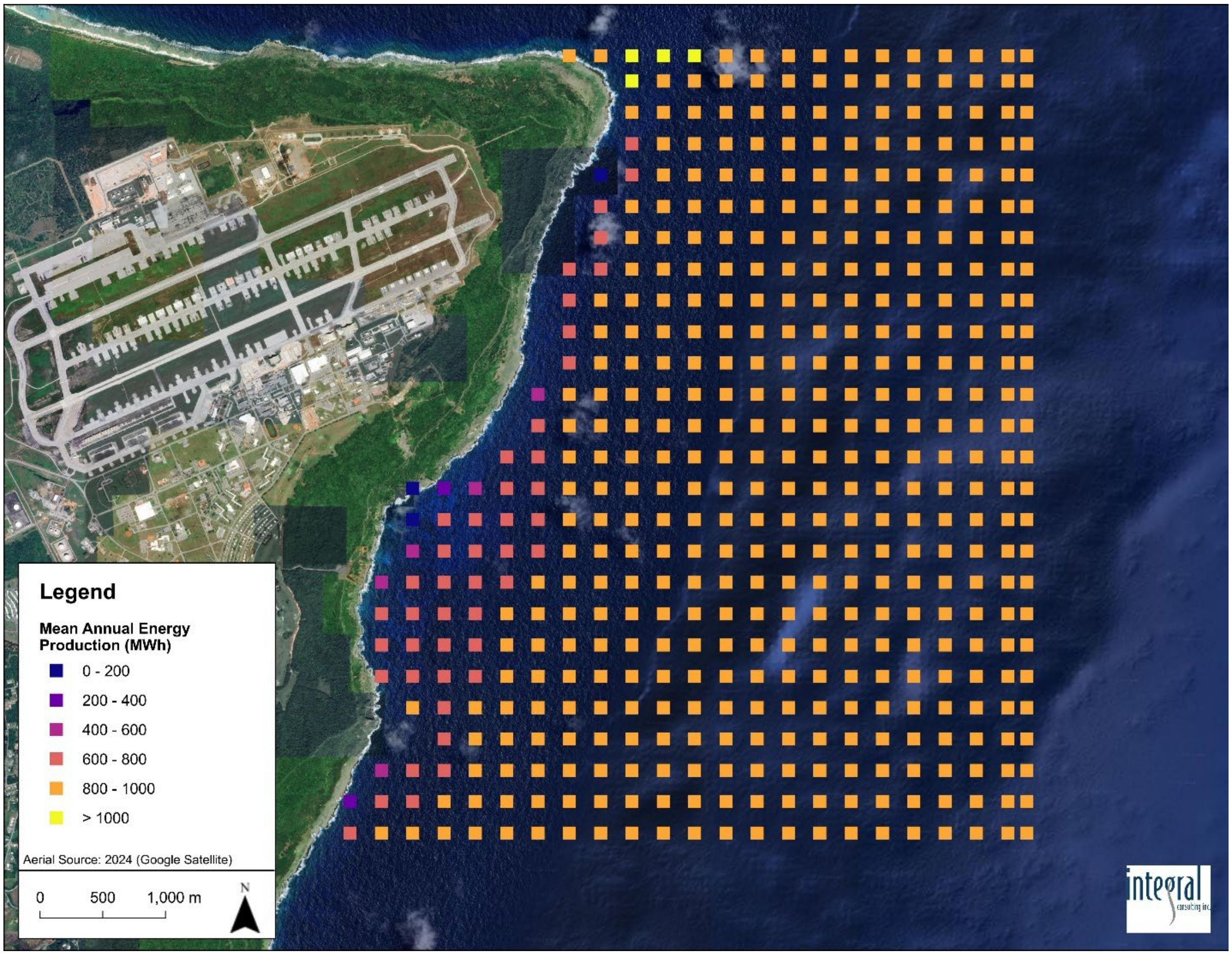

Figure 19. Mean annual energy productions for the northeast SWAN domain for an example wave energy converter.

Task 4 Summary

Task 4 advanced the regional screening and site selection outcomes by conducting higher-resolution, site-specific wave resource characterization within the three candidate areas identified in Task 3 using multiyear SWAN numerical wave modeling. Simulations were performed at 50 m horizontal resolution over an 11-year representative period, producing spatially and temporally resolved bulk wave parameters and directional spectra suitable for IEC-aligned prefeasibility assessment. These outputs were processed to derive standardized wave energy metrics, including omni-directional wave power, directionally resolved wave power, wave energy period, and associated statistical summaries, providing a consistent and reproducible basis for evaluating spatial variability in wave conditions across the selected areas.

Comparison of the Task 4 results across the northeastern, northwestern, and western domains indicates clear differences in wave energy magnitude, directional persistence, and spatial structure that are relevant at a prefeasibility level. The northeastern domain exhibits higher wave energy levels and a more persistent dominant wave direction, while the northwestern and western domains display lower energy conditions and greater directional variability associated with partial sheltering, coastal orientation, and bathymetric controls. Within the northeastern domain, analysis of three representative study points highlights localized variability in wave power and directional characteristics driven by nearshore transformation processes, while remaining broadly consistent with the regional wave climate identified during earlier screening. Collectively, these results demonstrate how both inter-area contrasts and intra-area variability influence site-specific wave energy conditions, establishing a technically defensible foundation for comparative prefeasibility-level assessment without implying device-specific performance, array design, or deployment outcomes.

7.2 Lesson Learned and Test Plan Deviation

A key lesson learned from this study is the demonstrated value of SEAMOD as a front-end decision-support environment for wave energy resource screening and site selection when applied within a structured, standards-based assessment framework. The integration of regional wave hindcast data, geospatial constraints, and IEC-derived wave resource metrics within a single interactive platform enabled efficient exploration of spatial patterns and facilitated informed narrowing of candidate areas prior to more computationally intensive modeling. This capability proved particularly effective during early stages of the assessment, where rapid visualization and comparison of wave energy, bathymetry, and infrastructure considerations supported transparent and reproducible decision-making.

At the same time, the study highlighted the practical limitations of attempting to incorporate all components of a feasibility or design-level wave energy assessment directly into a single dashboard environment. High-resolution numerical wave modeling, long-term time-series analysis, and device-specific performance evaluation require specialized tools, computational resources, and workflows that are not readily encapsulated within a general-purpose visualization platform without substantial back-end development and maintenance. Rather than replacing established modeling and analysis tools, SEAMOD was most effective when used as an integrative layer that contextualized and organized outputs generated through targeted, study-specific analyses.

Looking forward, a key opportunity identified through this effort is the potential for SEAMOD to evolve as a platform for integrating and exploring study-specific datasets once they have been developed using external modeling and analysis workflows. Enabling users to ingest high-resolution wave modeling outputs, refined bathymetric surfaces, and other geospatial layers into SEAMOD would allow wave energy developers and planners to interactively examine wave power distributions, depth constraints, and exclusion zones within a unified interface. Such functionality could significantly reduce barriers to site identification and comparison, particularly in regions like Guam where renewable energy goals, infrastructure constraints, and spatial considerations must be evaluated concurrently. This study illustrates how SEAMOD can serve as a foundation for bridging complex technical analyses and practical decision-making in support of advancing marine energy development.

During site selection, formal MCDA methods were not explicitly applied to identify candidate regions or study sites for further investigation. Instead, candidate regions and subsequent study sites were identified through a structured, expert-driven evaluation of multiple criteria, including wave energy exposure, bathymetric suitability, proximity to existing infrastructure, and spatial constraints. This approach reflects a pragmatic application of screening- and prefeasibility-level decision-making consistent with IEC guidance, which does not require formal MCDA frameworks at early stages of wave energy resource assessment. The use of multiple technical and practical criteria, applied transparently and iteratively, provided a defensible and efficient basis for narrowing candidate areas and selecting sites for higher-resolution modeling, while avoiding unnecessary analytical complexity at this stage of project development.

As part of the original test plan, SNL-SWAN was identified as a tool to simulate the effects of generic WEC arrays to support the Guam wave energy resource assessment. During Task 4, SNL-SWAN was tested using an array of representative, generic WEC devices configured within the northeastern modeling domain (Figure 11). This exercise demonstrated the capability of SNL-SWAN to estimate wave power capture by individual devices under specified wave conditions. However, the current implementation of SNL-SWAN is designed to operate on a single time-step basis, producing snapshot estimates of device-level power extraction rather than time-continuous simulations across extended periods.

Through this evaluation, it was determined that single-snapshot estimates of wave power were less informative for the prefeasibility-level objectives of this study than time-integrated metrics derived from long-term wave simulations. In contrast, the multi-year SWAN simulations provided temporally resolved bulk wave parameters and two-dimensional wave spectra suitable for calculating wave energy resource metrics consistent with applicable IEC guidance. As a result, the assessment prioritized analysis of the long-term SWAN outputs to characterize wave conditions and resource variability across the selected sites. This deviation from the original plan reflects an improved alignment between available modeling capabilities and the objectives of a screening-to-prefeasibility wave energy resource assessment, while still meeting the technical requirements defined for the project.

8 Conclusions and Recommendations

This study successfully completed a comprehensive pre-feasibility wave energy resource assessment for the Guam coastline using a structured, IEC-aligned, and tiered analytical framework. Through integration of publicly available datasets, regional wave hindcast products, geospatial screening, and high-resolution numerical wave modeling, the assessment met its primary objective of identifying and characterizing candidate areas with sufficient wave energy potential to warrant further consideration for wave energy development. The workflow applied across Tasks 1 through 4 provides a transparent and reproducible basis for evaluating wave energy feasibility in Guam and for guiding future refinement efforts.

Regional screening analyses demonstrated clear spatial contrasts in wave energy conditions around Guam, with consistently higher wave power along the eastern and northeastern (windward) coastline and reduced energy levels along the western (leeward) coast. These patterns reflect the combined influence of prevailing Pacific wind and swell forcing, island sheltering effects, and coastal orientation. Screening-level results, evaluated alongside bathymetric characteristics and proximity to infrastructure, supported the selection of three candidate areas, northeastern, northwestern, and western, for higher-resolution site-specific assessment.

High-resolution SWAN simulations conducted under Task 4 refined characterization of nearshore wave conditions within each candidate area and revealed meaningful differences in wave energy magnitude, directional persistence, and spatial variability at scales relevant to pre-feasibility assessment. The northeastern domain exhibited the highest annual mean omni-directional wave power, with values reaching approximately 15 kW/m in exposed locations, and a relatively persistent dominant wave direction. In contrast, the northwestern and western domains displayed lower wave energy levels, generally up to approximately 6 kW/m, and greater directional variability associated with partial sheltering and nearshore transformation processes. These differences indicate that wave energy conditions are not uniform around Guam and that site-specific assessment is essential for evaluating deployment feasibility.

Detailed analysis of three representative study points within the northeastern domain further demonstrated that localized variability in wave power, directional characteristics, and temporal structure exists even within a single candidate area. While all three study points were broadly representative of the regional wave climate, differences driven by bathymetry and coastal geometry influence site-level energy availability and directional consistency. Scatter tables, directional metrics, and AEP estimates derived at these study points provide a quantitative foundation for comparing site-specific conditions and illustrate the importance of resolving nearshore wave processes when assessing wave energy feasibility.

Collectively, the results of this study indicate that wave energy development in Guam is technically plausible at a pre-feasibility level, particularly along the northeastern coastline where wave energy levels are highest and directional characteristics are more persistent. The northwestern and western areas exhibit more moderate wave energy conditions that may still support certain wave energy applications, especially where infrastructure proximity or specific use cases (e.g., islanded or mission-driven systems) are prioritized. Importantly, this assessment does not imply device-specific performance or deployment outcomes; rather, it establishes a robust, standards-based characterization of the wave resource that can inform subsequent stages of feasibility analysis.

Recommendations

Building on the outcomes of this pre-feasibility assessment, several logical next steps are recommended to further reduce uncertainty and advance wave energy development potential in Guam. These recommendations reflect both the results of this study and the lessons learned during its execution.

First, targeted refinement of site-specific wave characterization is recommended within the northeastern domain, where results indicate the strongest and most consistent wave energy resource. Additional high-resolution modeling focused on narrower spatial extents, extended simulation periods, or alternative representative years could improve confidence in long-term variability and extreme condition characterization. Such refinement would support transition from prefeasibility toward feasibility-level assessment without requiring immediate field deployment.

Second, integration of device-agnostic performance screening should be expanded using a broader range of representative wave energy converter concepts. While this study relied on generalized power and capture assumptions consistent with IEC guidance, future work could evaluate sensitivity of AEP and performance metrics to different device classes, operational envelopes, and directional sensitivities. This would enable more informed comparison of how site-specific wave conditions align with emerging WEC technologies.

Third, targeted observational data collection is recommended to complement the modeled results, particularly in the northeastern domain. Even limited-duration measurements of nearshore wave conditions, directional spectra, or currents would provide valuable validation data to further reduce uncertainty associated with numerical modeling and hindcast reliance. Such measurements could be designed strategically to maximize information gain while minimizing cost and logistical burden.

Finally, future assessments should continue to leverage integrative tools such as SEAMOD to support iterative site evaluation, stakeholder engagement, and decision-making. Lessons learned during this study demonstrate that combining standardized, IEC-aligned analysis workflows with interactive visualization platforms significantly enhances transparency and efficiency at early stages of wave energy project planning. Expanding the ability to ingest site-specific modeling outputs and observational datasets into such tools would further strengthen their utility for developers, regulators, and stakeholders considering wave energy development in Guam.

Together, these recommendations outline a clear and technically grounded pathway for advancing wave energy assessment and development in Guam beyond the pre-feasibility stage, while remaining consistent with international standards and the practical realities of early-stage marine energy projects.

9 References

Chang, G., C.A. Jones, J.D. Roberts, and V.S. Neary. 2018. A comprehensive evaluation of factors affecting the levelized cost of wave energy conversion projects. *Renewable Energy* 127:344–354.

Flanary, C., Jones, C., Ellenson, A., and T. Nelson. Dashboard for Marine Energy Site Assessment and Monitoring. Paper presented at the Offshore Technology Conference, Houston, Texas, USA, May 2024. doi: https://doi.org/10.4043/35141-MS

IEC. 2012. Marine energy – Wave, tidal and other water current converters – Part 100: Electricity producing wave energy converters. IEC TS 62600-100. International Electrotechnical Commission. Danish Standards Foundation.

IEC. 2015. Marine energy – Wave, tidal and other water current converters – Part 101: Wave energy resource assessment and characterization. IEC TS 62600-101. International Electrotechnical Commission. Danish Standards Foundation.

Jones, C.A., G. Chang, K. Raghukumar, S. McWilliams, A. Dallman, and J.D. Roberts. 2019. Spatial Environmental Assessment Tool (SEAT): A modeling tool to evaluate potential environmental risks associated with wave energy converter deployments. *Energies 11*(8):2036.

Ruehl, K.M., Roberts, J.D., Porter, A., Chang, G., Chartrand, C.C. and Smith, H. 2015. *Development Verification and Application of the SNL-SWAN Open Source Wave Farm Code* (No. SAND2015-10622C). Sandia National Lab.(SNL-NM), Albuquerque, NM (United States).

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