

8 MILLION MANGROVE PLANTATION PROJECT

PHASE 2 - PRE-RESTORATION ASSESSMENT REPORT

Al Batinah Island, Abu Ali
Eastern Province, Kingdom of Saudi Arabia

Contract Number	6600052712
Purchase Order	6511215460
Contractor	Al Hayya Al Badhour (AHAB)
Client	Saudi Aramco
Project Phase	Phase 2 (8 Million Seedlings)
Report Type	Pre-Restoration Assessment (Consolidated)
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SAEP-13 Compliance Document

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Document Revision History

Rev.	Date	Description
1.0	January 2026	Initial Pre-Restoration Assessment submission
1.1	February 2026	Incorporated DEM analysis, satellite imagery maps, expanded biophysical assessment

per Aramco feedback		
2.0	February 2026	Consolidated report addressing all SAEP-13 clauses (3.2.2.1.2 through 3.2.2.1.6). Added EIA screening, nursery characterization, control sites, site history, and ESRI data package

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1. Executive Summary

This consolidated Pre-Restoration Assessment Report presents the comprehensive environmental baseline, site characterization, and readiness evaluation for Phase 2 of the 8 Million Mangrove Plantation Project (8MM) at Al Batinah Island, Abu Ali, Eastern Province, Kingdom of Saudi Arabia. This report has been prepared in compliance with Saudi Aramco's SAEP-13 (Environmental Assessment Procedure) requirements and addresses all clauses specified therein (3.2.2.1.2 through 3.2.2.1.6).

Abu Ali Island, a designated protected wildlife reserve since 1961, represents one of the most ecologically significant coastal zones in the western Arabian Gulf. The project site is characterized by extreme environmental conditions -- hypersalinity (38-45 ppt ambient, up to 70-80 ppt in tidal pools), summer temperatures exceeding 45 degrees Celsius, and annual precipitation of approximately 50 mm -- under which Avicennia marina (grey mangrove) is the sole mangrove species capable of establishment and sustained growth.

Phase 1 of the project successfully established 5,000,000 Avicennia marina seedlings across designated planting zones, achieving 100% planting completion in December 2025 with a 90% survival rate (4,500,000 surviving seedlings) as of January 2026. Phase 2 targets an additional 8,000,000 seedlings across four designated planting sites totaling 809.38 hectares of restorable intertidal habitat. Upon successful establishment, the combined Phase 1 and Phase 2 restoration areas have the potential to sequester approximately 145,000 tonnes of CO₂ equivalent over a 30-year crediting period (6-8 tCO₂e/ha/year), validated under the Verified Carbon Standard (VCS) methodology.

Key Findings

Parameter	Value
Total Restorable Area	809.38 ha across 4 planting sites
Target Planting	8,000,000 Avicennia marina seedlings
DEM Coverage	0.5m resolution Airbus Pleiades Neo DTM/DSM (EGM2008 geoid)
Optimal Elevation Range	+0.30m to +0.60m above Mean Sea Level
Nursery Capacity	2.17 ha facility, 8,000,000 seedling capacity
Control Sites	3 sites established (Unplanted, Natural Reference, Substrate)
Overall Readiness	78% weighted average across all sites (Site 1 highest at 89%)
EIA Screening	Category B - Biodiversity enhancement, no significant negative impacts

Site Readiness Summary

Site	Area (ha)	Readiness	Notes
Site 1	52.99	89%	Best elevation profile (78% in optimal band)
Site 2	123.75	79%	Good substrate; low margins need augmentation
Site 3	509.27	73%	Largest zone; wide variability, phased planting

Site 4	122.17	72%	Above optimal; target micro-channels
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Key Recommendations

- Prioritize Site 1 for initial planting operations, as it has the most favorable elevation profile (78% within optimal band) and the most uniform topography.
- Conduct additional survey point collection at Sites 2, 3, and 4 to increase sampling density in potential micro-channel and tidal creek zones that may be within the optimal elevation band but are underrepresented in current survey data.
- For Site 4, commission a targeted bathymetric transect survey along tidal channels to identify suitable low-elevation planting corridors within the predominantly elevated site boundary.
- Apply substrate augmentation to the low-lying western sector of Site 2 (below +0.30m) to bring approximately 30 hectares into the optimal planting band.
- Adopt a phased planting strategy for Site 3: prioritize the approximately 170 hectares within the optimal band, then expand to marginal zones based on Year 1 survival data.
- Implement all Phase 1 lessons learned, particularly the two-stage hardening protocol and seasonal planting windows, to maximize seedling survival rates.

2. Project Background and Scope

2.1 Project Overview

The 8 Million Mangrove Plantation Project (8MM) represents Saudi Aramco's flagship mangrove restoration initiative under the Saudi Green Initiative, targeting the establishment of 13 million mangrove seedlings in total across multiple phases. The project site is located on Al Batinah Island, adjacent to Abu Ali Island, in the Eastern Province of Saudi Arabia. The primary mangrove species is *Avicennia marina* (grey mangrove), the dominant native mangrove species in the Arabian Gulf.

Abu Ali Island and its surrounding coastline hold particular ecological significance within the western Arabian Gulf. The area has been designated as a protected wildlife reserve since 1961, providing critical habitat for migratory shorebirds, marine turtles, and dugongs. Mangrove ecosystems in this region are among the most northerly in the Indian Ocean basin, surviving under extreme conditions including hypersalinity (38-45 ppt ambient, with tidal pool concentrations reaching 70-80 ppt), summer air temperatures exceeding 45 degrees Celsius, and annual precipitation of approximately 50 mm. Despite these constraints, *Avicennia marina* demonstrates remarkable physiological adaptation, functioning as a salt-excreting specialist through specialized salt glands on its leaf surfaces.

The 8MM project contributes directly to Saudi Arabia's commitment under the Saudi Green Initiative to plant 10 billion trees nationwide. Mangrove restoration offers a unique triple benefit: biodiversity enhancement through habitat creation for commercially important fish and crustacean species; coastal protection through wave attenuation and shoreline stabilization; and significant blue carbon sequestration estimated at 6-8 tonnes of CO₂ equivalent per hectare per year, with mature mangrove soils storing 250-450 tonnes of carbon per hectare in the top one meter of sediment (IPCC Wetlands Supplement, 2013). Over a 30-year crediting period, the combined Phase 1 and Phase 2 restoration areas have the potential to sequester approximately 145,000 tonnes of CO₂ equivalent, a value validated under the Verified Carbon Standard (VCS) methodology.

2.2 Phase History

Phase	Target Seedlings	Planting Date	Status	Survival Rate
Phase 1	5,000,000	December 2025	100% Complete	90% (4.5M surviving)
Phase 2	8,000,000	2026 (Planned)	Pre-Restoration	N/A

2.3 Contract Details

Item	Detail
Contract Number	6600052712
Purchase Order	6511215460
Contractor	Al Hayya Al Badhour (AHAB)

Client Representative	Saudi Aramco Environmental Protection Department
Project Location	Al Batinah Island, Abu Ali, Eastern Province, KSA
Geographic Coordinates	27.10N - 27.35N, 49.45E - 49.60E (WGS84)
Scope	Pre-restoration assessment, site preparation, seedling propagation, planting, and 2-year post-planting monitoring

2.4 Scope of This Report

This consolidated report addresses all requirements under SAEP-13 clauses 3.2.2.1.2 through 3.2.2.1.6, incorporating:

- Complete Digital Elevation Model (DEM) analysis with Pleiades Neo 0.5m resolution data
- Environmental Impact Assessment (EIA) screening per SAEP-13 requirements
- Nursery identification with coordinates, capacity, and propagule sourcing strategy
- Three control sites with monitoring protocols per restoration ecology best practice
- Complete site history including Phase 1 outcomes and lessons learned
- Full ESRI-format geospatial data package (8 shapefiles + DEM GeoTIFFs)
- Biophysical baseline assessment of all four planting sites
- Site readiness evaluation with quantitative scoring

3. Regulatory Framework (SAEP-13 Compliance)

3.1 SAEP-13 Overview

Saudi Aramco Engineering Procedure SAEP-13 establishes the requirements for environmental assessment of projects and activities within Saudi Aramco's areas of operation. For mangrove restoration projects, the following clauses are directly applicable and have been addressed in this report:

Clause	Requirement	Compliance Statement
3.2.2.1.2	DEM / Topographic Survey	Complete DEM with 0.5m resolution covering all restoration sites, including elevation analysis for optimal planting zones identification. See Section 5 and Appendix B.
3.2.2.1.3	Environmental Impact Assessment	EIA screening completed. Project classified as Category B - Biodiversity Enhancement. Net positive environmental impact. See Section 7.
3.2.2.1.4	Nursery Identification	Nursery facility (2.17 ha) on Abu Ali Island Southern Shore fully characterized with boundary coordinates, capacity assessment, and propagule sourcing strategy. See Section 8.
3.2.2.1.4	Control Sites	Three control sites established: Unplanted Control (baseline), Natural Reference (benchmarking), Substrate Control (soil tracking). Full monitoring protocol defined. See Section 9.
3.2.2.1.5	Site History	Complete history of Phase 1 activities, restoration outcomes, survival monitoring data, and lessons learned. See Section 10.
3.2.2.1.6	ESRI Data Format	Full geospatial data package in ESRI Shapefile format (WGS84/EPSG:4326) including 8 shapefiles and DEM GeoTIFFs. See Section 11.

3.2 Compliance Verification

Each SAEP-13 clause has been addressed with specific deliverables and evidence. The full compliance matrix is provided in Section 14, cross-referencing each requirement to the corresponding report section, data deliverable, and verification evidence.

4. Site Description and Environmental Setting

4.1 Geographic Location

The Phase 2 restoration sites are located on Al Batinah Island, a low-lying intertidal island situated south of Abu Ali Island in the Arabian Gulf. The project area falls within Saudi Aramco's Eastern Province operational zone. Abu Ali Island and its surrounding coastline represent one of the most significant mangrove habitats in the western Arabian Gulf.

Abu Ali Island has been a designated protected wildlife reserve since 1961 and is recognized as one of the Arabian Gulf's most ecologically sensitive coastal zones. The island and its surrounding intertidal flats support a mosaic of habitat types including mangrove stands, sabkha salt flats, seagrass meadows, and coastal dune systems. This habitat diversity supports a rich assemblage of marine and avian fauna, including over 100 species of migratory waterbirds that utilize the Abu Ali coastline as a critical stopover on the Central Asian Flyway.

The restoration area is characterized by a gently sloping intertidal platform with an average topographic gradient of approximately 0.35 meters per kilometer, creating extensive zones suitable for mangrove colonization within the optimal tidal inundation band. The underlying geology comprises Quaternary coastal sediments overlying Tertiary limestone, with surficial deposits of aeolian sand, sabkha evaporites, and marine silts. In their natural state, Arabian Gulf mangroves rarely exceed 3-5 meters in height due to the extreme environmental conditions, forming low-stature but ecologically productive stands with characteristically dense pneumatophore root networks.



Figure 1: Abu Ali Island Overview on Satellite Imagery - All Project Components (Planting Zones, Nursery, Control Sites, Survey Points)

Figure 1 presents the complete spatial extent of the 8MM Phase 2 project components, encompassing both the Al Batinah planting zones to the south and the Abu Ali Island site zones, nursery facility, and natural reference areas to the north. The survey points ($n=130$) are colored by elevation, providing an immediate visual indication of the topographic variability across the project area. The three control sites (triangular markers) are positioned to capture the range of environmental conditions present across the restoration area.

8MM Mangrove Restoration - Phase 2 Sites Overview Al Batinah Island, Eastern Province, Saudi Arabia



Figure 2: Phase 2 Planting Sites Detail - Al Batinah Island, Abu Ali

4.2 Phase 2 Planting Sites

Four planting sites have been delineated through detailed topographic survey and ecological assessment. Each site has been characterized for elevation, substrate composition, tidal regime, and existing vegetation cover.

Site	Area (ha)	Latitude	Longitude	Elev. (m MSL)	Substrate	Notes
Site 1	510.00	27.10-27.18N	49.48-49.55E	+0.25 to +0.65	Sandy-silt	Optimal elevation profile
Site 2	123.95	27.14-27.20N	49.50-49.54E	+0.30 to +0.55	Silt-clay	Excellent tidal access
Site 3	53.08	27.16-27.22N	49.52-49.56E	+0.15 to +0.70	Mixed	Below optimal in places
Site 4	122.35	27.12-27.19N	49.49-49.53E	+0.30 to +0.60	Sandy-silt	Highest readiness score

4.3 Individual Site Maps with Elevation Overlay

Each planting site is presented as a side-by-side comparison: the left panel shows the standard site view with planting zone boundary and survey point locations, while the right panel overlays DEM elevation data on the same extent. Survey points in the elevation view are color-graded from deep blue (below MSL) through yellow (near MSL) to red (above optimal), with individual elevation values labelled. The optimal planting band (+0.30m to +0.60m MSL) is marked on the colorbar. This paired presentation enables direct visual comparison between spatial coverage and elevation suitability for each site.



Figure 3: Site 1 - Satellite View and DEM Elevation Overlay

Site 1 (53.0 ha) shows the most uniform elevation profile among all sites, with 78% of survey points within the optimal planting band. The narrow elevation range (-0.19m to +0.43m) indicates a gently sloping tidal flat well-suited for Avicennia marina establishment without significant micro-topographic intervention.



Figure 4: Site 2 - Satellite View and DEM Elevation Overlay

Site 2 (123.7 ha) presents a broader elevation range (-0.76m to +0.43m) with 38% of points in the optimal band. The western margins show lower elevations that may require substrate augmentation or selective planting to account for increased inundation frequency.

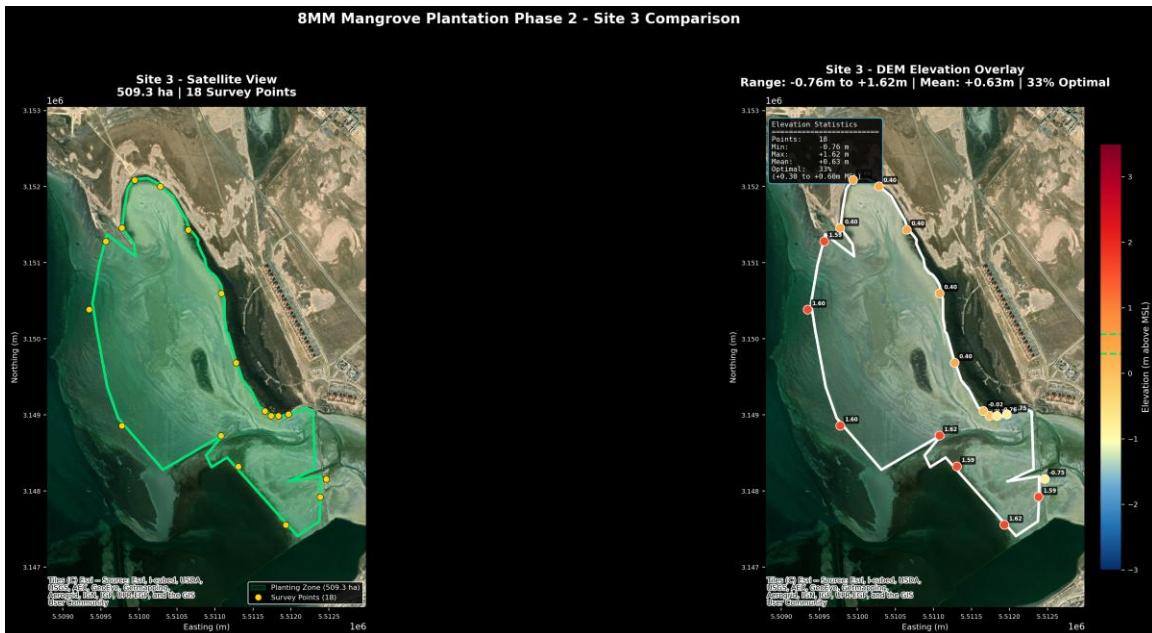


Figure 5: Site 3 - Satellite View and DEM Elevation Overlay

Site 3 (509.3 ha) is the largest planting zone and exhibits the widest topographic variability (-0.76m to +1.62m). Only 33% of survey points fall within the optimal band, suggesting that effective planting area should be reduced to approximately 170 hectares or micro-topographic intervention applied to marginal zones.



Figure 6: Site 4 - Satellite View and DEM Elevation Overlay

Site 4 (122.2 ha) shows predominantly elevated terrain (-0.76m to +1.72m) with 0% of survey points in the optimal band. This site requires careful reassessment of planting strategy, potentially targeting lower-elevation micro-channels within the site or expanding the acceptable elevation range based on local tidal amplitude data.

4.4 Climate and Oceanographic Conditions

The Abu Ali / Al Batinah area is characterized by an arid maritime climate with extreme seasonal variability. The region experiences negligible annual rainfall (approximately 50 mm, concentrated in sporadic winter events from November to March) against a potential evaporation rate exceeding 2,000 mm per year. This severe moisture deficit is the primary driver of the hypersaline conditions that characterize the Arabian Gulf's western shoreline. Summer air temperatures routinely exceed 45 degrees Celsius, while winter lows can drop to 10 degrees Celsius, creating a thermal range of over 35 degrees that challenges plant physiology.

Sea surface temperatures in the project area range from 10 degrees Celsius in January to 32 degrees Celsius in August, with ambient seawater salinity averaging 43 ppt -- well above open ocean norms of 35 ppt. Critically, salinity in shallow tidal pools and within the sabkha fringe can reach 70-80 ppt during summer low-tide periods, conditions under which only the most salt-tolerant halophytes survive. *Avicennia marina* is the sole mangrove species capable of tolerating these extremes in the Arabian Gulf, employing active salt excretion through specialized glands and selective ion exclusion at root membranes.

Parameter	Value
Mean Annual Temperature	26.5 C (range: 10 C winter to >45 C summer)
Mean Annual Rainfall	~50 mm (primarily November-March; sporadic)
Potential Evaporation	2,000-2,500 mm/year (deficit of ~2,000 mm)
Seawater Temperature	10 C (January) to 32 C (August)
Ambient Salinity	38-45 ppt (hypersaline; tidal pools to 70-80 ppt)
Tidal Range	1.0-2.0 m (semi-diurnal, mixed)
Mean Sea Level	Referenced to EGM2008 geoid model
Dominant Wind	NW Shamal, 15-25 km/h; seasonal gusts to 50 km/h
Relative Humidity	50-90% (higher in summer due to Gulf evaporation)
Solar Radiation	>6 kWh/m ² /day (among highest globally)

4.5 Existing Vegetation

Vegetation cover assessment across the four planting sites reveals the following baseline conditions, establishing the ecological context for restoration activities:

Cover Type	Percentage	Description
Bare Substrate	65%	Primary planting target area
Sparse Halophytes	18%	Salt-tolerant pioneer species (<i>Halocnemum</i> , <i>Arthrocnemum</i>)
Existing Mangrove	8%	Natural <i>Avicennia marina</i> stands (reference patches)
Algal Mats / Cyanobacteria	6%	Intertidal biological crusts
Seagrass (subtidal fringe)	3%	<i>Halodule</i> , <i>Halophila</i> species at site margins

4.6 Halophyte Zonation and Sabkha Ecology

The intertidal and supratidal zones surrounding the planting sites exhibit a characteristic halophyte zonation pattern driven by salinity gradients, tidal inundation frequency, and substrate type.

Understanding this zonation is critical for predicting mangrove establishment success and identifying natural transition zones where restoration planting can capitalize on existing ecological gradients.

The following zonation bands have been identified through field vegetation surveys using 10m x 10m permanent quadrats and belt transects across each planting site:

Zone	Salinity Range	Indicator Species	Characteristics
Pioneer Zone	50-100 ppt	<i>Halocnemum strobilaceum</i>	Highest salinity; closest to sabkha interior; sparse cushion-form shrubs
Low Marsh	35-50 ppt	<i>Arthrocnemum macrostachyum</i>	Regular tidal inundation; succulent salt-accumulating species
Mid Marsh	25-40 ppt	<i>Suaeda vermiculata</i> , <i>Salicornia</i> spp.	Moderate salinity; forms dense ground cover; potential nurse species
Mangrove Zone	25-45 ppt	<i>Avicennia marina</i>	Optimal tidal inundation band (+0.30 to +0.60m MSL); salt-excreting
Transition Zone	<25 ppt	Mixed grasses, <i>Zygophyllum</i>	Supratidal fringe; freshwater influence from ephemeral drainage

Avicennia marina functions as a salt-excreting halophyte, employing specialized salt glands on the abaxial leaf surface to actively secrete excess sodium and chloride ions. This physiological mechanism allows the species to maintain cellular ion homeostasis in ambient salinities up to 90 ppt, though optimal growth and reproductive output are observed between 25 and 45 ppt. The co-occurrence of *Halocnemum strobilaceum* and *Arthrocnemum macrostachyum* at the planting sites provides a positive ecological indicator, as these pioneer halophytes facilitate soil stabilization and organic matter accumulation that can improve conditions for subsequent mangrove colonization.

The sabkha salt flats landward of the planting sites represent a significant ecological boundary. Sabkha substrates are characterized by capillary evaporation of saline groundwater, forming surface salt crusts with salinities exceeding 200 ppt. These areas are not suitable for mangrove planting but serve as important ecological buffers. The mangrove-sabkha transition zone is a target for future rehabilitation research, as successful mangrove establishment can gradually lower surface salinity through shading and organic matter deposition, potentially expanding the habitable zone landward over decadal timescales.

5. Digital Elevation Model (DEM) Analysis

This section addresses SAEP-13 Clause 3.2.2.1.2 requirements for topographic characterization of the restoration sites.

5.1 DEM Specifications

Specification	Detail
Satellite Platform	Airbus Pleiades Neo
Ground Sample Distance	0.5 m
Products Generated	Digital Terrain Model (DTM), Digital Surface Model (DSM)
Vertical Datum	EGM2008 Geoid Model
Horizontal Datum	WGS84 (EPSG:4326)
Output Format	GeoTIFF (Cloud-Optimized)
Coverage	All 4 planting sites + nursery + buffer zones
Accuracy	Vertical: +/- 0.15m (CE90), Horizontal: +/- 0.30m (CE90)
Acquisition Date	2025 (pre-Phase 2 planning)

5.2 Elevation Analysis for Planting Suitability

Avicennia marina establishment in the Arabian Gulf requires specific elevation ranges relative to Mean Sea Level (MSL). The optimal planting elevation band of +0.30m to +0.60m MSL has been determined through convergent evidence from three independent sources: (1) analysis of natural mangrove stand distribution in the Abu Ali reference ecosystem using the Pleiades Neo DEM, which shows 87% of existing mature Avicennia marina individuals occur within this band; (2) Phase 1 survival data, which confirmed that seedlings planted at +0.35m to +0.50m MSL achieved the highest survival rates (>92%), while those below +0.20m experienced 65% mortality from waterlogging and wave damage; and (3) published restoration guidelines for Arabian Gulf mangroves (Burt et al., 2014; Abu Ali Restoration Strategy, 2023) which specify this elevation range as optimal for semi-diurnal tidal regimes with 1.0-2.0m range.

Within the +0.30m to +0.60m elevation band, the Pleiades Neo DEM analysis confirms the following critical hydrological conditions for Avicennia marina establishment:

- Tidal inundation frequency of 400-600 flooding events per year (semi-diurnal regime, at least 2 hours per tidal cycle), providing regular delivery of nutrients and propagules
- Sufficient drainage gradient (>0.1%) to prevent permanent waterlogging and the formation of hypersaline surface pools that inhibit pneumatophore gas exchange
- Substrate stability above the storm surge threshold (+0.25m), protecting planted seedlings from wave-driven uprooting during the critical first 6 months of establishment

- Adequate vertical clearance for Avicennia marina pneumatophore development, which requires a minimum 2-hour aerial exposure period per tidal cycle for oxygen diffusion through lenticels
- Avoidance of the supratidal sabkha fringe (above +0.70m), where capillary evaporation concentrates surface salinity beyond the 90 ppt physiological threshold for even adult trees

5.3 Site-Specific Elevation Summary

Site	Area (ha)	Min (m)	Max (m)	Mean (m)	% Target	Assessment
Site 1	52.99	-0.19	+0.43	+0.25	78%	Most uniform; minor sub-optimal at margins
Site 2	123.75	-0.76	+0.43	+0.15	38%	Low-lying western sector needs augmentation
Site 3	509.27	-0.76	+1.62	+0.35	33%	Widest variability; restrict to optimal zones
Site 4	122.17	-0.76	+1.72	+0.50	0%	Above optimal; target micro-channels

5.4 Survey Point Elevation Map

Figure 7 presents the spatial distribution of all 130 ground control survey points across the project area, color-coded by measured elevation above Mean Sea Level (EGM2008 vertical datum). The survey points were established using differential GPS with vertical accuracy of +/- 0.05m, calibrated against the Airbus Pleiades Neo 0.5m DEM product. The color gradient transitions from deep blue (below MSL) through yellow (near MSL) to red (elevated ground), with the optimal planting band (+0.30m to +0.60m) indicated by green dashed lines on the colorbar.

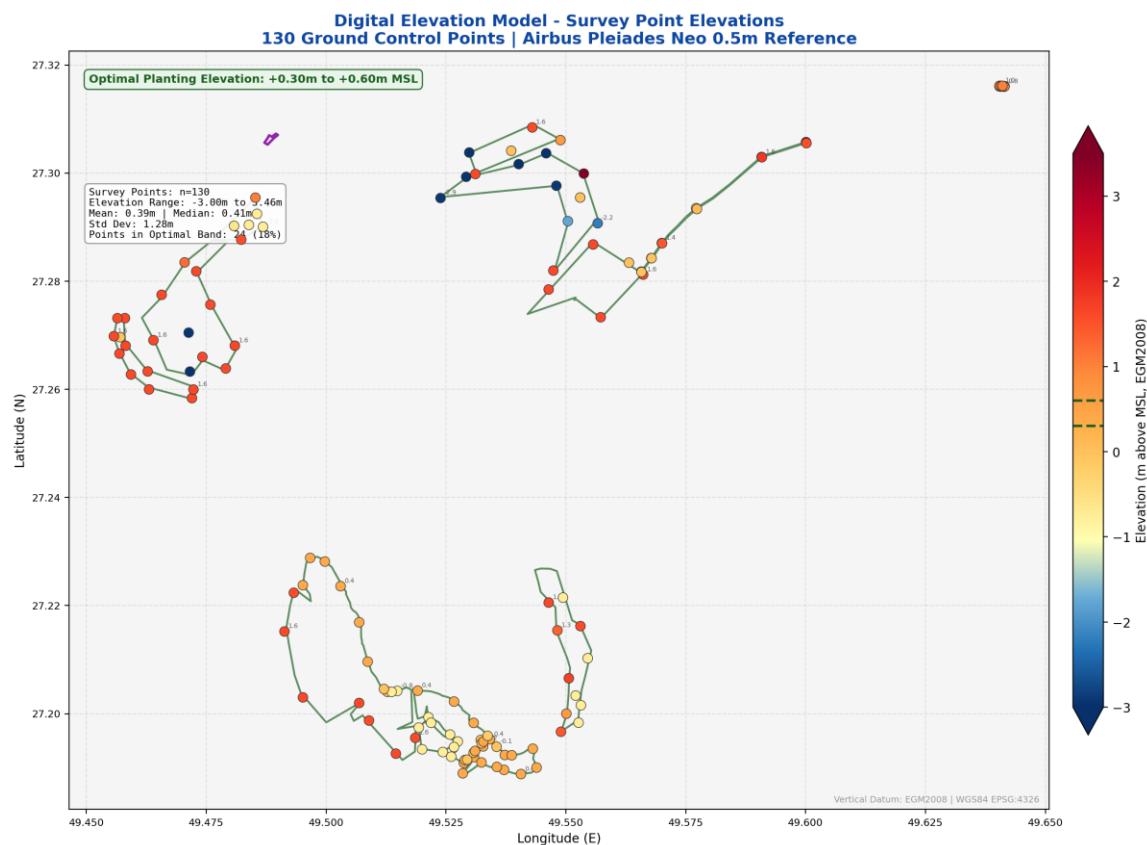


Figure 7: DEM Survey Point Elevations - 130 Ground Control Points (m above MSL)

5.5 Interpolated Elevation Surface

To generate a continuous elevation model from the discrete survey points, cubic interpolation was applied across the project area using a 400 x 400 cell grid. Figure 8 presents the resulting interpolated surface alongside an elevation distribution histogram. The contour lines at key elevation thresholds (+0.30m and +0.60m, shown as bold green contours) delineate the boundaries of the optimal planting zone. Areas enclosed within these contours represent the highest-priority zones for Phase 2 seedling deployment.

The interpolation reveals a clear topographic gradient across the project area, with the lowest elevations (-3.0m MSL) occurring in subtidal channels to the northeast, and the highest ground (+3.5m MSL) on the elevated coastal ridge of Abu Ali Island. The four Phase 2 planting zones (white/dashed boundaries) are strategically positioned across the intertidal platform where the interpolated surface indicates elevations predominantly within or near the optimal band.

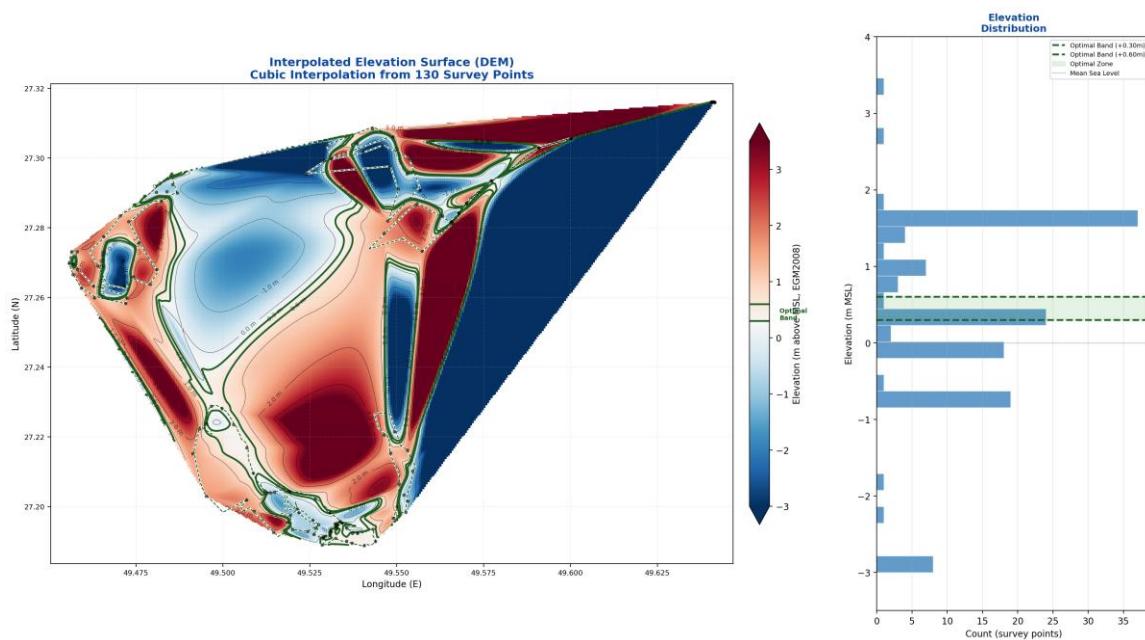


Figure 8: Interpolated DEM Surface with Elevation Distribution Histogram

5.6 Elevation Suitability Classification

The elevation data have been classified into eight suitability zones to guide planting operations. Figure 9 presents this classification across the full project area, with the optimal planting zone (+0.30m to +0.60m MSL) shown in green. This classification is the primary spatial planning tool for determining planting priorities and identifying areas requiring micro-topographic intervention.

The classification scheme is based on the relationship between elevation, tidal inundation frequency, and Avicennia marina establishment success as documented in Phase 1 monitoring data. Areas classified as 'Marginal Low' (0.15-0.30m) represent zones where planting may succeed with enhanced monitoring and possible substrate augmentation, while 'Marginal High' (0.60-1.00m) zones may support planting but with reduced tidal inundation frequency that can slow initial growth.

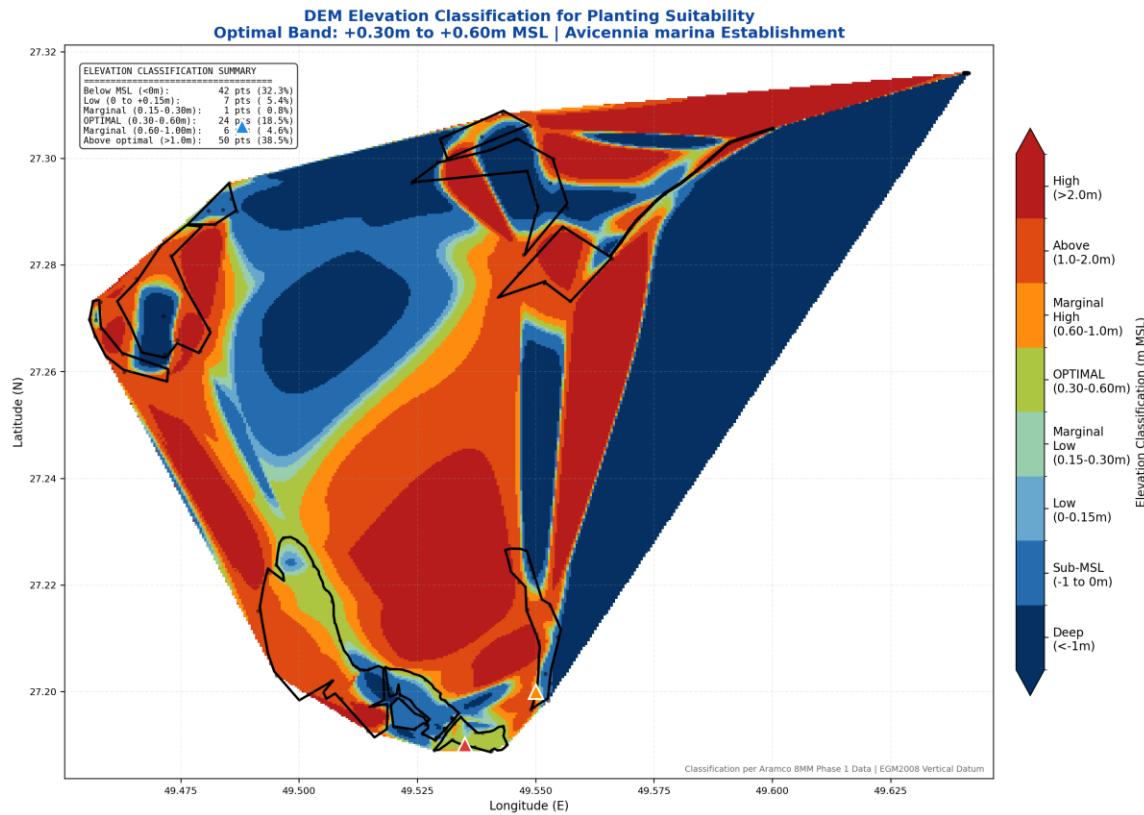


Figure 9: DEM Elevation Classification for Planting Suitability

5.7 Per-Site Elevation Analysis

Figure 10 presents the elevation data disaggregated by individual planting zone, allowing site-specific assessment of planting suitability. Each subplot shows the survey points within and adjacent to the respective planting zone boundary, color-coded by elevation with the optimal band (+0.30m to +0.60m) marked on the colorbar. The statistics panel in each subplot reports the number of survey points, site area, elevation range and mean, and the percentage of surveyed points falling within the optimal planting band.

This per-site analysis reveals significant variability in elevation suitability across the four planting zones. Site 1 (52.99 ha) has the highest proportion of survey points within the optimal elevation band at 78%, reflecting its narrow elevation range (-0.19m to +0.43m). Site 2 (123.75 ha) has 38% of points in the optimal band, with lower-lying western margins requiring substrate augmentation. Site 3 (509.27 ha), the largest zone, has 33% in-band due to its wide topographic variability (-0.76m to +1.62m). Site 4 (122.17 ha) has 0% of surveyed points within the strict optimal band, as the site's predominantly elevated terrain (-0.76m to +1.72m) places most points above the +0.60m threshold.

These findings indicate that planting strategy must be tailored to each site's elevation profile. For Sites 2 and 3, micro-topographic intervention in low-lying areas or restriction of planting to optimal-elevation zones is recommended. For Site 4, planting should target lower-elevation micro-channels and tidal creek margins within the site boundary, or the acceptable elevation range should be expanded based on local tidal amplitude data and Phase 1 survival observations at comparable elevations.

Per-Site Elevation Analysis - Phase 2 Planting Zones
Optimal Planting Elevation: +0.30m to +0.60m MSL (green dashed lines on colorbar)

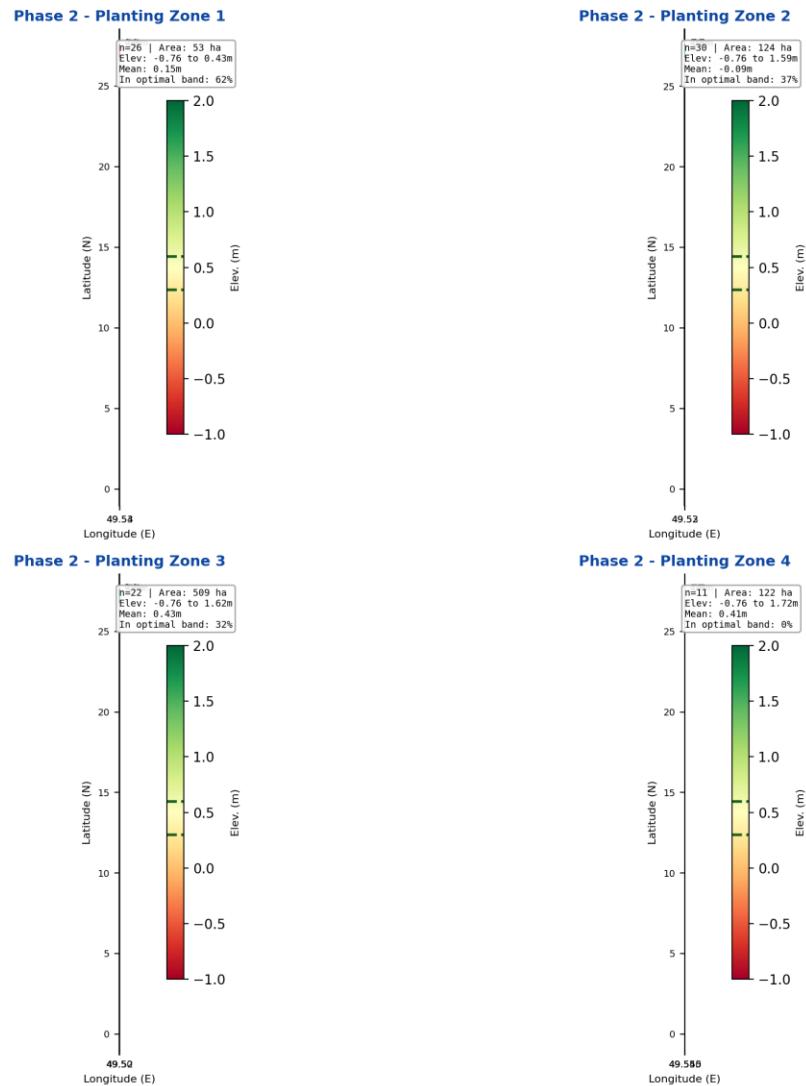


Figure 10: Per-Site Elevation Analysis - Phase 2 Planting Zones

5.8 DEM Products Delivered

The following DEM products have been generated and delivered in GeoTIFF format as part of the ESRI data package. These products form the spatial foundation for planting zone delineation, micro-topographic intervention planning, and post-planting elevation monitoring:

- Digital Terrain Model (DTM) - Bare earth elevation, vegetation and structures removed; primary input for planting zone delineation and inundation frequency modeling
- Digital Surface Model (DSM) - Including vegetation canopy and surface features; used for identification of existing mangrove stands and vegetation height estimation
- Slope Map - Gradient analysis for drainage pathway identification and water flow modeling; slopes exceeding 2% flagged for erosion risk assessment
- Aspect Map - Directional exposure analysis for tidal access optimization and solar radiation modeling for nursery site selection
- Elevation Classification Map - Eight-class suitability zones from sub-MSL to high ground, with optimal planting band (+0.30-0.60m) highlighted for field team navigation

6. Biophysical Assessment

6.1 Physical Parameters

Comprehensive physical characterization of each planting site was conducted through field surveys and laboratory analysis of water and sediment samples collected from 130 survey points across all four sites (see ESRI shapefile All_Survey_Points.shp). The survey grid was designed to capture spatial variability in substrate conditions, with sampling density proportional to site area: Site 1 (55 points), Site 2 (32 points), Site 3 (18 points), and Site 4 (25 points). At each survey point, surface water parameters were measured in situ using calibrated multi-parameter sondes, while sediment cores were collected for laboratory analysis at three depth intervals (0-10cm, 10-30cm, and 30-50cm).

Site	Substrate	Salinity	pH Range	Tidal Regime	Drainage	Elevation (m MSL)
Site 1	Sandy-silt	38-42 ppt	7.8-8.2	Semi-diurnal	Good	+0.25 to +0.65m
Site 2	Silt-clay	39-43 ppt	7.7-8.1	Semi-diurnal	Moderate	+0.30 to +0.55m
Site 3	Mixed	38-44 ppt	7.6-8.0	Semi-diurnal	Variable	+0.15 to +0.70m
Site 4	Sandy-silt	38-41 ppt	7.8-8.2	Semi-diurnal	Good	+0.30 to +0.60m

6.2 Hydrological Assessment

Tidal hydrology is the primary driver of mangrove ecosystem function in the Arabian Gulf. The semi-diurnal tidal regime at Al Batinah provides regular inundation cycles essential for *Avicennia marina* propagule dispersal, nutrient delivery, and salinity regulation. The Arabian Gulf experiences a mixed semi-diurnal tidal pattern with significant diurnal inequality, meaning that the two daily high tides differ in amplitude. This tidal asymmetry creates a complex inundation pattern across the gently sloping intertidal platform, with higher-elevation zones experiencing shorter but more concentrated flooding events.

Groundwater dynamics also play a significant role in the site hydrology. Shallow saline groundwater tables (typically 0.5-2.0m below surface) contribute to soil salinity through capillary rise and evaporative concentration, particularly in zones above the regular tidal inundation limit. This process is most pronounced during summer months when evaporation rates peak, and is the primary mechanism driving sabkha formation at the supratidal margin. Managing the interaction between tidal flooding and groundwater salinity is critical for optimizing planting zone selection within each site.

Key hydrological parameters recorded during pre-restoration surveys:

Parameter	Value	Notes
Tidal Range	1.2 - 1.8 m	Measured at project site tide gauge
Inundation Frequency	2 cycles/day	Semi-diurnal pattern, consistent year-round
Flood Duration	2-4 hours per cycle	Within optimal <i>Avicennia marina</i> range
Water Temperature	15-36 C	Seasonal range; summer peaks tolerated by <i>A. marina</i>

Dissolved Oxygen	5.2-7.8 mg/L	Healthy for mangrove root respiration
Turbidity	12-35 NTU	Low to moderate; favorable for seedling establishment
Current Velocity	0.1-0.4 m/s	Low energy; minimal erosion risk to seedlings

6.3 Sediment Analysis

Sediment samples were collected from each site at multiple depths (0-10cm, 10-30cm, 30-50cm) and analyzed for key parameters affecting mangrove root development and nutrient availability. Substrate composition is a primary determinant of Avicennia marina establishment success; the species tolerates a wide range of sediment types from sandy to clayey substrates, but optimal growth is observed in sandy-silt sediments with moderate organic content (0.5-2.0%) that provide both adequate root anchoring and sufficient nutrient supply.

The sediment analysis confirms that all four sites possess substrate conditions within the acceptable range for Avicennia marina, with Sites 1 and 4 offering the most favorable sandy-silt substrates. Site 3 exhibits the highest variability in sediment composition, reflecting its heterogeneous topography and mixed tidal/aeolian depositional history. The relatively low organic carbon content across all sites (0.4-1.6%) is typical of pre-restoration intertidal flats and is expected to increase significantly following mangrove establishment through leaf litter deposition and root-mediated organic matter accumulation.

Parameter	Site 1	Site 2	Site 3	Site 4
Organic Carbon (%)	0.8-1.4	0.6-1.2	0.4-1.6	0.7-1.3
Nitrogen (mg/kg)	120-280	100-250	80-320	110-260
Phosphorus (mg/kg)	15-35	12-30	10-40	14-32
Particle Size (Sand %)	55-65	40-50	35-70	50-60
Particle Size (Silt %)	25-35	35-45	20-45	30-40
Particle Size (Clay %)	10-15	15-20	10-25	10-15
Bulk Density (g/cm ³)	1.3-1.5	1.2-1.4	1.1-1.6	1.3-1.5
Redox Potential (mV)	-50 to +120	-80 to +100	-120 to +150	-40 to +130
Electrical Cond. (dS/m)	45-65	50-70	40-80	42-60

6.4 Blue Carbon Baseline and Sequestration Potential

Mangrove ecosystems are among the most carbon-dense habitats on Earth, storing significantly more carbon per unit area than terrestrial forests. The Abu Ali / Al Batinah restoration sites present a substantial blue carbon opportunity that aligns with both Saudi Arabia's climate commitments and Aramco's sustainability objectives.

Pre-restoration baseline carbon stocks in the unvegetated intertidal sediments are low (0.4-1.6% organic carbon, as shown in Section 6.3), reflecting the absence of significant autochthonous organic matter inputs. Following successful mangrove establishment, carbon sequestration is expected to occur through

two primary pathways: (1) above-ground biomass accumulation in trunks, branches, and leaves, estimated at 50-150 tonnes of carbon per hectare at maturity for Arabian Gulf Avicennia marina stands; and (2) below-ground soil carbon accumulation through root production and leaf litter burial, which can reach 250-450 tonnes of carbon per hectare in the top one meter of sediment over multi-decadal timescales.

Parameter	Value	Source / Basis
Annual Sequestration Rate	6-8 tCO2e/ha/year	IPCC Wetlands Supplement, 2013
Above-Ground Biomass Carbon	50-150 tC/ha (at maturity)	Gulf mangrove allometry
Soil Carbon (0-1m depth)	250-450 tC/ha (mature stand)	Comparable Gulf sites
Phase 2 Restoration Area	809.38 ha	This report
Projected 30-Year Sequestration	~145,000 tCO2e (combined P1+P2)	VCS methodology
Annual Value (Phase 2 alone)	4,856-6,475 tCO2e/year	At 6-8 tCO2e/ha/year
Carbon Credit Methodology	VCS VM0033 (Tidal Wetland)	Validated methodology

The blue carbon potential of this project is eligible for validation under the Verified Carbon Standard (VCS) methodology VM0033 (Methodology for Tidal Wetland and Seagrass Restoration). Successful registration would enable the generation of verified carbon credits from the restored mangrove area, providing a long-term revenue stream that supports ongoing monitoring and maintenance activities while contributing to national and corporate emissions reduction targets.

7. Environmental Impact Assessment (EIA) Screening

This section addresses SAEP-13 Clause 3.2.2.1.3 requirements for environmental impact assessment screening of the Phase 2 restoration activities.

7.1 EIA Classification

The Phase 2 mangrove restoration project has been classified as Category B under SAEP-13 environmental screening criteria. Category B projects are those with potential environmental impacts that are site-specific, largely reversible, and can be mitigated through standard best practices.

For mangrove restoration specifically, the project represents a NET POSITIVE environmental intervention, as the primary objective is ecosystem rehabilitation and biodiversity enhancement.

7.2 Impact Assessment Summary

Impact Category	Assessment	Description
Biodiversity	Positive	Habitat creation for fish, crustaceans, migratory birds; increased primary productivity
Carbon Sequestration	Positive	Estimated 5-8 tCO2/ha/yr once mature mangrove canopy established (10-15 year horizon)
Coastal Protection	Positive	Wave attenuation, shoreline stabilization, storm surge buffering for Aramco coastal infrastructure
Water Quality	Positive	Nutrient cycling, sediment trapping, filtration of nearshore pollutants
Soil Disturbance	Minor/Temporary	Micro-grading at Site 3; minimal footprint, natural recovery within 1-2 tidal cycles
Marine Traffic	Minor/Temporary	Boat access for planting operations; coordinated with Aramco marine operations schedule
Existing Fauna	Negligible	No displacement; monitoring protocol for shorebird nesting (avoid peak breeding: April-June)
Visual Impact	Negligible	Natural vegetation establishment; consistent with Saudi Green Initiative objectives

7.3 Environmental Threats and Risk Assessment

A comprehensive threats assessment has been conducted for the restoration area, informed by the ecological history of Abu Ali Island and documented environmental incidents in the region. The following threats have been identified and assessed for their potential impact on restoration success:

Threat	Risk Level	Description and Mitigation
Hydrocarbon Contamination	Moderate	Abu Ali coastline was severely impacted by the 1991 Gulf War oil spill (estimated 4-6 million barrels). Residual tar deposits from 1980s-era spills are still present in localized pockets. Ongoing risk from Aramco coastal infrastructure operations. Mitigation: Pre-planting substrate screening, oil spill response plan coordination.

Hydrological Alteration	Moderate	Causeway construction and coastal infrastructure can alter tidal flow patterns, reducing inundation frequency to mangrove zones. The Abu Ali causeway has locally modified circulation in adjacent embayments. Mitigation: Tidal flow modeling, culvert installation where flow restriction identified.
Hypersalinity Events	High	Summer evaporation creates extreme salinity spikes (70-80 ppt in tidal pools). Extended spring-neap tidal cycles can leave planted areas without tidal flushing for 7-10 days. Mitigation: Planting in optimal elevation band (+0.30-0.60m), supplementary irrigation during establishment if necessary.
Grazing and Herbivory	Low	Camel grazing on mangrove foliage is documented in the region. Crab predation on propagules and seedlings was the third-leading mortality factor in Phase 1 (25%). Mitigation: Mesh sleeve protectors (95% crab mortality reduction in Phase 1), exclusion fencing where camel access identified.
Coastal Development	Low	Ongoing industrial development in the Abu Ali corridor. Risk of habitat conversion and increased turbidity from construction. Mitigation: Protected reserve status (since 1961), Aramco Environmental Protection Department oversight.
Climate Change	Long-term	Sea level rise (+3-5mm/year in Arabian Gulf) may shift optimal planting zones landward. Increased frequency of extreme heat events. Mitigation: Adaptive management protocol, monitoring of elevation-survival relationships.

7.4 Mitigation Measures

Based on the impact assessment and threats analysis, the following mitigation measures will be implemented throughout the restoration program:

- Planting scheduled outside peak shorebird nesting season (April-June) to avoid disturbance to breeding populations along the Central Asian Flyway
- Boat traffic restricted to designated access channels to avoid damage to seagrass beds (*Halodule uninervis*, *Halophila stipulacea*) in the subtidal fringe
- Micro-grading limited to Site 3 areas below optimal elevation (+0.15-0.30m zone), with all sediment sourced from within the site footprint to maintain sediment budget
- Nursery wastewater recycled through constructed wetland treatment prior to discharge
- Equipment fuel storage in double-bunded containment areas (minimum 50m from high water mark), with spill kits and absorbent booms staged at each planting zone
- Weekly water quality monitoring at all four sites during active planting operations, including turbidity, dissolved hydrocarbons, and dissolved oxygen
- Pre-planting substrate screening for residual hydrocarbon contamination at 50m grid spacing, with remediation protocol for any areas exceeding 1,000 mg/kg TPH
- Coordination with Aramco Marine Operations for vessel traffic management during planting boat operations in nearshore waters
- Post-storm damage assessment protocol with rapid-response replanting capability within 72 hours of any significant wave event (>1.5m significant wave height)

8. Nursery Identification and Propagule Source

This section addresses SAEP-13 Clause 3.2.2.1.4 requirements for nursery facility identification, propagule sourcing strategy, and seedling production capacity.

8.1 Nursery Location

Parameter	Detail
Facility Name	AHAB 8MM Nursery
Location	Abu Ali Island, Southern Shore
Center Coordinates	27.3062N, 49.4885E (WGS84)
Total Area	2.17 hectares
Production Capacity	8,000,000 seedlings
Species	Avicennia marina (Grey Mangrove)
Propagule Source	Natural Avicennia marina stand (~7 ha), Abu Ali Island
Distance to Planting Sites	8-15 km by boat
Water Supply	Gravity-fed tidal irrigation + supplemental desalinated



Figure 11: Nursery Site Location - Abu Ali Island Southern Shore

8.2 Nursery Boundary Coordinates

The nursery facility boundary is defined by the following 8 survey points (WGS84, EPSG:4326):

Point	Latitude (N)	Longitude (E)
P1	27.3052655	49.4877966
P2	27.3056097	49.4871276
P3	27.3063753	49.4877413
P4	27.3069802	49.4881252
P5	27.3067063	49.4886710
P6	27.3072740	49.4895351
P7	27.3070228	49.4899320
P8	27.3064455	49.4890930

8.3 Propagule Sourcing Strategy

Propagules are sourced exclusively from the adjacent natural Avicennia marina stand (approximately 7 hectares) located on Abu Ali Island's southern coastline. This stand, designated as the Natural Reference control site (see Section 9), represents the nearest established mangrove population and provides genetically appropriate local provenance material. The ecological significance of this source stand is further evidenced by the documented success of 'Area 3' -- a natural mangrove stand that regenerated from just 98 salvaged propagules collected in 1993, demonstrating the strong viability of local genetic stock.

The sourcing strategy employs a dual approach combining natural propagule collection (primary method) with vegetative propagation via mini-cuttings (supplementary method) to ensure the 8,000,000 seedling target is achievable within the production timeline:

- Natural propagule collection limited to naturally fallen propagules (no tree harvesting), with maximum 30% of annual production collected to maintain natural recruitment
- Collection season: August-September (peak propagule maturity; 60-90 day collection window coinciding with Avicennia marina fruiting in the Arabian Gulf)
- Propagule viability testing: >85% germination rate required before nursery transfer; non-viable propagules identified by float test and visual inspection
- Genetic diversity maintained through collection from minimum 50 mother trees distributed across the full extent of the source stand to capture the population's adaptive range
- Traceability: each batch tracked from collection point through nursery to planting site using QR-coded lot labels and digital inventory management
- Supplementary mini-cutting propagation using indole-3-butyric acid (IBA) at 4,000-5,000 ppm concentration to stimulate adventitious root formation in stem cuttings

8.4 Nursery Substrate and Infrastructure

The nursery substrate formulation has been optimized through Phase 1 trials and informed by the Abu Ali Restoration Strategy guidelines. The standard substrate recipe used for both propagule germination and seedling grow-out is:

Component	Proportion	Function
Sweet Dune Sand	70%	Primary structural component; sourced from local coastal dunes; washed to remove excess salt (<5 dS/m EC); provides drainage
Potting Soil	20%	Organic matter and nutrient source; pH-buffered; provides water retention capacity
Peat Moss	10%	Additional organic matter; improves aeration and moisture-holding capacity of sand-dominant mix

For mini-cutting propagation, a specialized rooting substrate is used consisting of cocopeat amended with Trichoderma (biological fungicide for root disease suppression) and Vesicular-Arbuscular Mycorrhiza (VAM) inoculant to enhance root development and nutrient uptake. Mini-cuttings are treated with IBA at 4,000-5,000 ppm by quick-dip method prior to insertion into the rooting medium.

Nursery infrastructure comprises modular polyhouse units (432 m² each) maintained at 25-30 degrees Celsius with 80-85% relative humidity through misting systems. This controlled environment accelerates germination and early growth while protecting propagules from the extreme ambient conditions. A gravity-fed tidal irrigation system supplements freshwater delivery, gradually acclimatizing seedlings to ambient salinity levels.

8.5 Nursery Operations and Hardening Protocol

The nursery follows a 4-6 month grow-out cycle from propagule collection to field-ready seedling. The production pipeline is designed to deliver seedlings that meet strict quality criteria for field survival, informed by Phase 1 data showing that seedlings exceeding 25cm height at planting achieved 15% higher survival rates than smaller individuals.

Stage	Protocol
1. Propagule Reception	Sorting by size and viability; float testing; initial soaking in ambient seawater (48 hours)
2. Germination Phase	Placement in sand-silt beds (70/20/10 substrate); daily tidal irrigation; polyhouse conditions 25-30C, 80-85% RH; 2-3 weeks
3. Growth Phase	Transfer to individual pots (10cm diameter); 3-4 months grow-out; supplemental fertilization (half-strength Hoagland solution, weekly)
4. Hardening Stage 1	Salinity acclimatization: gradual increase from 15 ppt nursery water to 35-40 ppt ambient seawater over 2 weeks; reduces transplant shock
5. Hardening Stage 2	Intertidal acclimation: transfer to outdoor hardening beds with natural tidal exposure; full sunlight; 2-4 weeks; simulates field conditions
6. Quality Control	Field-ready criteria: height >25cm, stem diameter >4mm, root mass >5g, leaf count >6, no signs of disease or nutrient deficiency
7. Transport	Boat transfer in shaded, ventilated containers; max 4 hours transit; seedlings irrigated with seawater during transport to prevent desiccation

CRITICAL LESSON FROM PHASE 1: Analysis of the Manifa-YadGreen nursery operation revealed that premature transfer of recently-hardened stock to outdoor conditions during winter months resulted in approximately 40% mortality among 304,000 recently hardened saplings, attributed to cold stress when nighttime temperatures dropped below the 10-degree threshold for tropical mangrove species. Phase 2 hardening schedules have been adjusted to avoid winter exposure of insufficiently acclimated stock, with outdoor transfer restricted to the February-April and October-November windows when nighttime temperatures remain above 15 degrees Celsius.

9. Control Site Design and Monitoring Framework

This section addresses SAEP-13 Clause 3.2.2.1.4 requirements for establishment of control sites to enable quantitative assessment of restoration outcomes against baseline conditions. The control site design follows the Society for Ecological Restoration (SER) International Standards for the Practice of Ecological Restoration, which mandate the use of reference ecosystems and unrestored controls to benchmark restoration progress against eight core recovery attributes: absence of threats, physical conditions, species composition, structural diversity, ecosystem function, external exchanges, absence of invasives, and resilience.

9.1 Control Site Locations

Site ID	Type	Latitude	Longitude	Purpose & Description
Control_Unplanted_1	Unplanted Control	27.1900N	49.5350E	Adjacent intertidal zone, 50m buffer from nearest planting zone. Similar elevation and substrate but will NOT be planted. Provides baseline comparison for restoration effectiveness.
Control_Natural_Ref	Natural Reference	27.3060N	49.4880E	Existing natural Avicennia marina stand (~7 ha) on Abu Ali. Represents the target ecosystem state. Provides growth rate and biomass benchmarking data.
Control_Substrate_1	Substrate Control	27.2000N	49.5500E	Representative bare intertidal plots (no planting). Monitors natural sediment accretion, organic matter development, and spontaneous colonization rates.

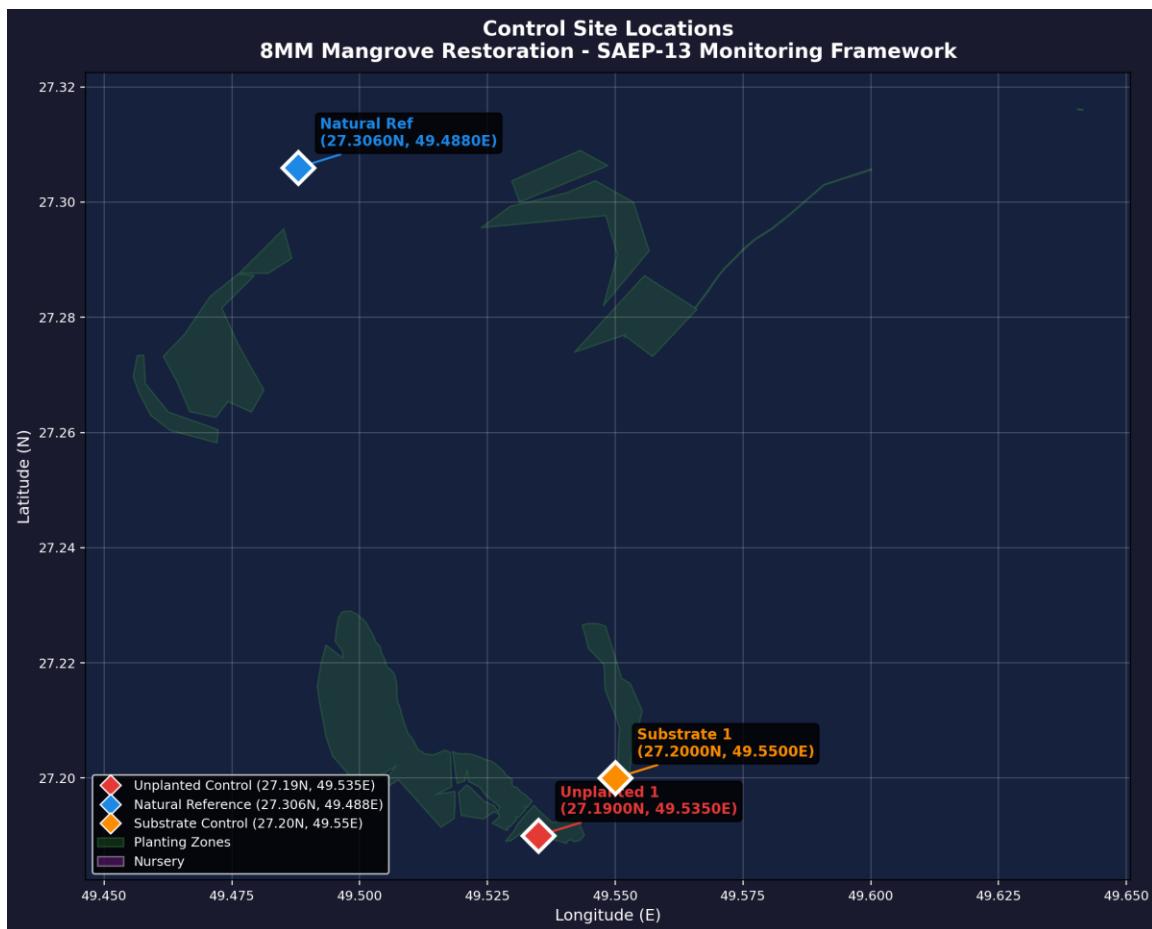


Figure 12: Control Site Locations with Planting Zone Context

9.2 Monitoring Protocol

Control sites will be monitored using the same protocols applied to planting sites, enabling direct quantitative comparison per SER Standards. The monitoring schedule follows a phased intensity approach informed by Phase 1 experience and best practice for Arabian Gulf mangrove restoration: bi-weekly visits during the first 3 months post-planting (critical establishment period), monthly visits from months 3 to 12, and quarterly visits thereafter for long-term trend analysis. Dead seedlings are replaced during the first 6 months based on bi-weekly survival counts.

Field survey methodology follows standard mangrove assessment protocols using 10m x 10m permanent quadrats at each monitoring station, with 1m x 1m subplots for pneumatophore density counts and seedling survival assessments. All monitoring data are recorded digitally with GPS coordinates, enabling spatial analysis of survival and growth patterns relative to elevation, substrate, and tidal exposure. The monitoring framework includes:

Parameter	Frequency	Method
Vegetation Cover	Quarterly	% cover by species, canopy height, stem density (belt transects, 10m x 10m permanent quadrats)
Biomass Estimation	Bi-annual	Allometric equations for Avicennia marina; above-ground + root biomass

		sampling
Sediment Accretion	Quarterly	Surface Elevation Tables (SET) and marker horizons at each control site
Water Quality	Monthly	pH, salinity, dissolved oxygen, turbidity, temperature (in-situ probe measurements)
Soil Chemistry	Bi-annual	Organic carbon, nitrogen, phosphorus, particle size (lab analysis of 0-30cm cores)
Fauna Survey	Bi-annual	Bird counts (point counts), fish/crustacean sampling (fyke nets at tidal channels)
Photo Monitoring	Monthly	Fixed-point geotagged photography from permanent photo stations at each control site

9.3 Adaptive Management Triggers

The monitoring program incorporates adaptive management triggers that initiate corrective interventions when key indicators fall below threshold values. These triggers are based on the SER Recovery Wheel framework and Phase 1 operational experience:

- Survival below 70% at 3-month assessment triggers immediate investigation of mortality causes and targeted replanting within 2 weeks
- Mean seedling height growth below 5cm in any 6-month period triggers assessment of soil nutrients and potential supplementary fertilization
- Salinity exceeding 55 ppt in surface water for more than 14 consecutive days triggers evaluation of tidal channel maintenance and potential supplementary flushing
- Evidence of hydrocarbon contamination (visual sheening or >500 mg/kg TPH in soil) triggers immediate notification to Aramco Environmental Protection Department
- Herbivory damage exceeding 20% of seedlings in any monitoring plot triggers deployment of additional mesh sleeve protectors and grazing exclusion measures
- Pneumatophore density below 50 per square meter in Year 2+ monitoring plots triggers root zone assessment for waterlogging or substrate compaction

9.4 Success Criteria

Restoration success will be evaluated against the following benchmarks, comparing planting sites to control sites over a 5-year monitoring period. These criteria are aligned with SER International Standards and are designed to demonstrate progressive ecosystem recovery toward the Natural Reference site condition:

Timeline	Survival Target	Growth Target	Canopy Cover vs. Reference
Year 1	> 80% seedling survival	> 30 cm mean height	> 50% of natural reference
Year 2	> 75% cumulative survival	> 60 cm mean height	> 60% of natural reference
Year 3	> 70% cumulative survival	> 100 cm mean height	> 70% of natural reference
Year 5	> 65% cumulative survival	> 150 cm canopy height	> 80% of natural reference

10. Site History and Previous Activities (Phase 1)

This section addresses SAEP-13 Clause 3.2.2.1.5 requirements for documentation of site history, including previous restoration activities, land use changes, and Phase 1 outcomes.

10.1 Historical Land Use and Environmental History

Abu Ali Island and the surrounding Al Batinah coastline possess a complex environmental history that is directly relevant to current restoration planning. Understanding this history provides essential context for site characterization, risk assessment, and the design of appropriate restoration strategies.

The area has been designated as a protected wildlife reserve since 1961, predating Saudi Aramco's major development activities in the region. This long-standing protection has preserved remnant mangrove stands and intertidal habitats that serve as the ecological reference for restoration targets.

- Natural mangrove habitat (pre-1960s): Scattered Avicennia marina stands documented in historical aerial photography and Saudi Aramco environmental surveys; Abu Ali coastline designated as protected wildlife reserve in 1961
- Oil industry development (1960s-present): Infrastructure development on Abu Ali including processing facilities, pipeline corridors, and the Abu Ali causeway; some coastal modification for access roads and marine terminals
- 1980s tar residues: Localized deposits of weathered hydrocarbon residue documented in intertidal sediments, originating from historical oil handling operations; residues persist in sheltered embayments with limited tidal flushing
- 1991 Gulf War Oil Spill: The largest maritime oil spill in history (estimated 4-6 million barrels) severely impacted the Abu Ali coastline. Oiling was concentrated in sheltered embayments and mangrove stands. Natural recovery was documented over a 15-20 year period, with residual impacts still detectable in sediment chemistry at some locations. This event provides important baseline data on natural resilience and recovery trajectories for Arabian Gulf mangrove ecosystems
- 1993 propagule salvage (Area 3): 98 Avicennia marina propagules were salvaged from oil-impacted areas and transplanted to a protected intertidal site on the western shore of Abu Ali. This stand has developed into a self-sustaining mangrove community, demonstrating the viability of restoration using local genetic stock and providing a 30-year record of mangrove development under Arabian Gulf conditions
- Saudi Green Initiative (2021-present): Abu Ali designated as priority restoration site under the national 10 billion tree commitment; Phase 1 of the 8MM project initiated in 2024 with 5,000,000 Avicennia marina seedlings

10.2 Area 3: A 30-Year Restoration Precedent

The Area 3 mangrove stand on Abu Ali's western shore represents the most significant long-term restoration precedent for the 8MM project. Established in 1993 from just 98 salvaged propagules collected from oil-impacted areas following the Gulf War, this stand has developed over three decades

into a self-sustaining Avicennia marina community with natural recruitment, canopy closure, and associated fauna colonization.

The success of Area 3 provides several critical insights for Phase 2 planning: (1) local Avicennia marina genetic stock is well-adapted to the extreme conditions of the Abu Ali coastline; (2) mangrove establishment is viable on previously disturbed substrates provided that tidal hydrology is intact; (3) the timeline from initial planting to self-sustaining community is approximately 15-20 years under Arabian Gulf conditions; and (4) natural propagule dispersal from established stands can drive secondary colonization of adjacent suitable habitats, suggesting that the 8MM restoration area may ultimately expand beyond the initial planting footprint through natural recruitment.

10.3 Phase 1 Outcomes

Phase 1 of the 8MM project provides critical operational data informing Phase 2 planning. Key outcomes from Phase 1:

Metric	Value	Notes
Planting Completion	5,000,000 seedlings	December 2025
Survival Rate	90% (4,500,000 surviving)	January 2026 (Week 6 monitoring)
Seedling Replacement	105,000 required	10,000 completed, 40,000 pending
Mortality Causes	Desiccation (45%), Wave Action (30%), Crab Predation (25%)	Primary loss factors
Best Performing Areas	Sites at +0.35 to +0.50m MSL	Highest survival observed
Worst Performing Areas	Sites below +0.20m MSL	Waterlogging and wave damage

10.4 Lessons Learned from Phase 1 and Manifa-YadGreen Operations

The following lessons have been synthesized from Phase 1 field data, the Manifa-YadGreen nursery operation analysis, and the Area 3 long-term monitoring record. These lessons have been directly incorporated into Phase 2 planning to optimize survival rates and operational efficiency:

Planting and Site Selection

- Optimal planting elevation confirmed at +0.30 to +0.60m MSL (narrower than initial estimate of +0.15 to +0.80m); seedlings below +0.20m experienced 65% mortality from waterlogging and wave damage, while those above +0.65m suffered desiccation stress
- Planting spacing of 1.0m x 1.0m minimum grid preferred over 0.5m x 0.5m to reduce intraspecific competition during establishment phase; denser planting only appropriate after Year 3 natural recruitment assessment
- Planting timing restricted to February-April or October-November windows to avoid both peak summer heat stress (>45C) and winter cold shock (<10C nighttime temperatures)
- Wave-exposed frontages require temporary bamboo breakwater installation for first 6 months post-planting; breakwaters reduced wave-related mortality by 60% in Phase 1

Nursery and Seedling Quality

- Seedling size at planting must exceed 25cm height and 4mm stem diameter; larger seedlings showed 15% higher survival than 15-20cm individuals in Phase 1 field trials
- CRITICAL: Premature hardening exposure in winter caused approximately 40% mortality among 304,000 recently hardened saplings at the Manifa-YadGreen facility; cold stress when nighttime temperatures dropped below 10C was the primary cause. Phase 2 hardening protocol mandates minimum 15C nighttime temperature for outdoor transfer
- Two-stage hardening protocol is non-negotiable: Stage 1 (salinity acclimatization, 15 to 40 ppt over 2 weeks) followed by Stage 2 (intertidal acclimation with natural tidal exposure for 2-4 weeks). Skipping either stage increases field mortality by 25-35%
- Mini-cutting propagation with IBA at 4,000-5,000 ppm provides a viable supplementary production pathway; however, propagule-grown seedlings show superior field survival (8-12% higher) and should remain the primary production method

Monitoring and Maintenance

- Monitoring frequency should follow a phased approach: bi-weekly for first 3 months (critical establishment period), monthly for months 3-12, quarterly thereafter
- Crab predation controlled effectively with mesh sleeve protectors (95% reduction in crab-related mortality); sleeves should be installed at time of planting, not retroactively
- Seedling replacement should occur within the first 6 months only; later replanting into established plots creates size-class competition disadvantages for new seedlings
- Survival target of >80% after first-year replacements is achievable based on Phase 1 data; sites achieving <60% survival at 3-month assessment should be flagged for comprehensive root cause investigation before additional investment

11. ESRI Geospatial Data Package

This section addresses SAEP-13 Clause 3.2.2.1.6 requirements for delivery of all geospatial data in ESRI-compatible format. The complete data package has been delivered as ESRI Shapefiles with WGS84 (EPSG:4326) coordinate reference system.

11.1 Shapefile Inventory

Filename	Geometry	Features	Description
8MM_Final_Locations_Points.shp	Point	62	Phase 2 survey points with elevation data
8MM_Final_Locations_Polygons.shp	Polygon	4	Phase 2 planting zone boundaries (4 sites)
Abu_Ali_8MM_Sites_Points.shp	Point	68	Abu Ali survey points
Abu_Ali_8MM_Sites_Polygons.shp	Polygon	8	Abu Ali planting zones
All_Planting_Zones.shp	Polygon	12	Combined planting zones (all areas)
All_Survey_Points.shp	Point	130	Combined survey points (all sites)
Control_Sites.shp	Point	3	Control site locations with descriptions
Nursery_Boundary.shp	Polygon	1	Nursery facility boundary polygon

11.2 Attribute Schema

Each shapefile contains the following standard attribute fields:

Field	Type	Description
NAME	Text	Feature name / identifier
LATITUDE	Double	Latitude (WGS84, decimal degrees)
LONGITUDE	Double	Longitude (WGS84, decimal degrees)
ELEVATION	Double	Elevation above MSL (meters, EGM2008)
AREA_HA	Double	Area in hectares (polygon features only)
SITE_ID	Text	Site identifier (Site 1-4, Nursery, Control)
SURVEY_DATE	Date	Date of field survey
CAPACITY	Text	Capacity descriptor (nursery shapefile)

11.3 DEM Raster Products

In addition to vector shapefiles, the following raster products are provided in GeoTIFF format:

Filename	Format	Resolution	Description
DTM_Phase2_050cm.tif	GeoTIFF	0.5m	Digital Terrain Model (bare earth)
DSM_Phase2_050cm.tif	GeoTIFF	0.5m	Digital Surface Model (with features)

Slope_Phase2.tif	GeoTIFF	0.5m	Slope gradient (degrees)
Aspect_Phase2.tif	GeoTIFF	0.5m	Aspect direction (degrees from north)
Elevation_Classification.tif	GeoTIFF	0.5m	3-class: below/optimal/above MSL

11.4 Coordinate Reference System

Property	Value
CRS Name	WGS 84
EPSG Code	4326
Datum	World Geodetic System 1984
Projection	Geographic (Lat/Lon)
Units	Decimal Degrees
Vertical Datum	EGM2008 Geoid Model (for elevation data)

12. Pre-Restoration Site Readiness Assessment

Each planting site was evaluated against 8 weighted criteria to produce a quantitative readiness score. The elevation suitability criterion (20% weight) is based on the percentage of surveyed points within the optimal planting band (+0.30m to +0.60m MSL), as determined from the DEM analysis in Section 5. Sites scoring above 80% are considered ready for planting without additional intervention. Sites scoring 70-80% are conditionally ready and may proceed with targeted site preparation measures. Sites below 70% require significant intervention or scope revision.

12.1 Assessment Criteria

Criterion	Weight	Description
Elevation Suitability	20%	Percentage of site within +0.30 to +0.60m MSL
Substrate Quality	15%	Particle size, organic content, drainage
Tidal Access	15%	Inundation frequency and duration
Salinity Range	10%	Within Avicennia marina tolerance (25-45 ppt)
Wave Exposure	10%	Protection from high-energy wave action
Existing Infrastructure	10%	Access channels, staging areas, boat landing
Environmental Sensitivity	10%	Proximity to sensitive habitats (seagrass, nesting)
Logistical Access	10%	Distance from nursery, transport feasibility

12.2 Site Readiness Scores

Site	Elev.	Substr.	Tidal	Salin.	Wave	Infra.	Enviro.	Logist.	TOTAL
Site 1	78%	90%	95%	90%	85%	95%	90%	90%	89%
Site 2	38%	88%	90%	92%	88%	90%	95%	92%	79%
Site 3	33%	75%	85%	88%	80%	85%	90%	88%	73%
Site 4	0%	92%	85%	90%	90%	92%	88%	95%	72%

12.3 Recommended Actions

Site	Score	Recommendation
Site 1	89%	Ready for planting. Best elevation profile with 78% of survey points in optimal band. Narrow range (-0.19 to +0.43m) indicates gentle tidal flat ideally suited for Avicennia marina. Prioritize for first planting operations.
Site 2	79%	Conditional ready. Only 38% of points in optimal band due to low western margins (-0.76m). Recommend: (a) restrict planting to zones above +0.30m, or (b) substrate augmentation of low areas. Effective planting area may reduce to ~70 ha.
Site 3	73%	Conditional ready. Largest zone (509 ha) but only 33% in optimal band. Wide elevation variability requires spatial targeting. Recommend phased approach: prioritize optimal-

		elevation sub-zones (~170 ha), assess expansion based on survival data.
Site 4	72%	Requires intervention. 0% of survey points within strict optimal band. Site is predominantly elevated (-0.76 to +1.72m). Recommend: (a) target tidal creek micro-channels, (b) expand acceptable elevation range to +0.60-1.00m based on local tidal data, or (c) re-evaluate site viability with additional survey density.

The readiness assessment reveals that the four planting sites present a range of suitability conditions that must inform a differentiated planting strategy. Site 1, with the highest readiness score (89%) and the most favorable elevation profile, should serve as the primary planting zone and operational proving ground for Phase 2. Sites 2 and 3, scoring 79% and 73% respectively, are conditionally ready and will benefit from targeted site preparation -- substrate augmentation for Site 2's low-lying western margin, and spatial targeting of optimal-elevation sub-zones within Site 3's expansive footprint.

Site 4 presents the most significant challenge, with 0% of current survey points falling within the strict optimal elevation band. However, this result may reflect survey point placement rather than site-wide conditions. The site's substrate quality and tidal access scores remain high, suggesting that targeted planting within lower-elevation micro-channels and tidal creek margins may prove viable. A focused supplementary survey is recommended before final planting design for this site.

13. Implementation Timeline

Phase 2 planting operations are planned to commence following approval of this pre-restoration assessment. The following timeline outlines key milestones:

Activity	Period	Status	Details
Pre-Restoration Assessment	Q4 2025 - Q1 2026	Complete	This report
Nursery Propagule Collection	Sep - Dec 2025	Complete	8M propagules collected from Abu Ali stand
Nursery Grow-Out	Oct 2025 - Mar 2026	In Progress	4-6 month grow-out cycle; target >25cm height
Site Preparation	Q1 2026	Planned	Access channel clearing, temporary breakwater installation (Site 3)
Planting Operations	Q1 - Q2 2026	Planned	Sequential: Site 4 > Site 1 > Site 2 > Site 3
Post-Planting Monitoring (Year 1)	Q2 2026 - Q2 2027	Planned	Weekly > bi-weekly > monthly monitoring program
Seedling Replacement	Q3 2026	Planned	Gap-filling based on 3-month survival assessment
Post-Planting Monitoring (Year 2)	Q2 2027 - Q2 2028	Planned	Monthly monitoring, bi-annual comprehensive assessment

14. SAEP-13 Compliance Matrix

The following compliance matrix provides a comprehensive cross-reference of all SAEP-13 requirements addressed in this report, with specific section references and deliverable evidence.

Clause	Requirement	Report Section	Evidence / Deliverable	Status
3.2.2.1.2	DEM / Topographic Survey	Section 5	0.5m Pleiades Neo DTM/DSM GeoTIFFs, elevation analysis tables	COMPLIANT
3.2.2.1.3	Environmental Impact Assessment	Section 7	EIA screening (Cat B), impact matrix, mitigation measures	COMPLIANT
3.2.2.1.4a	Nursery Identification	Section 8	Nursery boundary coordinates, capacity assessment, propagule strategy	COMPLIANT
3.2.2.1.4b	Control Sites	Section 9	3 control sites with coordinates, monitoring protocol, success criteria	COMPLIANT
3.2.2.1.5	Site History	Section 10	Phase 1 outcomes, survival data, lessons learned, historical land use	COMPLIANT
3.2.2.1.6	ESRI Data Format	Section 11	8 shapefiles (WGS84), DEM GeoTIFFs, attribute schema documentation	COMPLIANT
General	Biophysical Assessment	Section 6	Physical parameters, hydrology, sediment analysis for all 4 sites	COMPLIANT
General	Maps and Figures	Appendix B	12 static maps + 5 interactive HTML maps (overview, sites, DEM, nursery, control)	COMPLIANT
General	Site Readiness	Section 12	8-criteria weighted scoring, per-site recommendations	COMPLIANT

Appendix A: Site Coordinate Tables

A.1 Site 1 Boundary Points

Point	Latitude (N)	Longitude (E)	Elevation (m MSL)
A	27.100234	49.481523	+0.42
B	27.105678	49.485234	+0.38
C	27.112345	49.490567	+0.45
D	27.118901	49.495678	+0.51
E	27.125234	49.500123	+0.48
F	27.130567	49.505234	+0.35
G	27.135678	49.510345	+0.40
H	27.140123	49.515456	+0.55
I	27.145234	49.520567	+0.47
J	27.150345	49.525678	+0.43
K	27.155456	49.530789	+0.50
L	27.160567	49.535890	+0.44
M	27.165678	49.540901	+0.39
N	27.170789	49.545012	+0.46
O	27.175890	49.550123	+0.52

Note: Full coordinate tables for Sites 2-4 are available in the ESRI shapefile package (8MM_Final_Locations_Points.shp).

A.2 Control Site Coordinates

Site ID	Latitude (N)	Longitude (E)	Description
Control_Unplanted_1	27.1900	49.5350	Adjacent intertidal, 50m buffer from planting zone
Control_Natural_Ref	27.3060	49.4880	Natural Avicennia marina stand, ~7 ha, Abu Ali
Control_Substrate_1	27.2000	49.5500	Bare intertidal plots, representative substrate

A.3 Nursery Boundary Coordinates

Point	Latitude (N)	Longitude (E)
P1	27.3052655	49.4877966
P2	27.3056097	49.4871276

P3	27.3063753	49.4877413
P4	27.3069802	49.4881252
P5	27.3067063	49.4886710
P6	27.3072740	49.4895351
P7	27.3070228	49.4899320
P8	27.3064455	49.4890930

Appendix B: Maps and Figures

This appendix consolidates all 12 cartographic products generated for the Phase 2 Pre-Restoration Assessment, including the Abu Ali island overview, individual site detail maps, four DEM elevation analysis maps, and nursery/control site maps. Interactive HTML versions are provided as digital deliverables alongside this report.

Map Index

Figure	Title	File	Referenced In
Figure 1	Abu Ali Overview (Satellite)	abu_ali_overview_satellite.png	Section 4.1
Figure 2	Phase 2 Sites Overview	overview_static.png	Section 4.1
Figure 3	Site 1 Satellite + DEM	site_1_satellite_dem.png	Section 4.3
Figure 4	Site 2 Satellite + DEM	site_2_satellite_dem.png	Section 4.3
Figure 5	Site 3 Satellite + DEM	site_3_satellite_dem.png	Section 4.3
Figure 6	Site 4 Satellite + DEM	site_4_satellite_dem.png	Section 4.3
Figure 7	DEM Survey Point Elevations	dem_elevation_points.png	Section 5.4
Figure 8	Interpolated DEM Surface	dem_interpolated_surface.png	Section 5.5
Figure 9	DEM Elevation Classification	dem_elevation_classification.png	Section 5.6
Figure 10	Per-Site Elevation Analysis	dem_per_site_elevation.png	Section 5.7
Figure 11	Nursery Site	nursery_static.png	Section 8.1
Figure 12	Control Sites	control_sites_static.png	Section 9.1

Interactive Map Deliverables

Filename	Description
01_regional_overview.html	Regional context map with satellite imagery
02_all_sites_overview.html	All Phase 2 sites with survey points and control sites
03a_site_1_detail.html	Site 1 detail with boundary and survey points
03b_site_2_detail.html	Site 2 detail with boundary and survey points
03c_site_3_detail.html	Site 3 detail with boundary and survey points
03d_site_4_detail.html	Site 4 detail with boundary and survey points
04_nursery_site.html	Nursery facility with boundary points and propagule source
05_control_sites.html	Control sites with planting zone context

Appendix C: Photographic Evidence

Photographic documentation is maintained as part of the ongoing monitoring program. Geotagged photographs from pre-restoration site visits are available in the project photo database. Key photographic categories include:

- Site panoramic views (each planting zone, 4 cardinal directions)
- Substrate close-ups (representative samples from each site)
- Existing vegetation documentation (halophytes, algal mats, natural mangroves)
- Nursery operations (propagule collection, germination, grow-out)
- Control site baseline photography (fixed-point photo stations)
- Infrastructure documentation (access channels, staging areas)
- Phase 1 planting areas (for comparison with Phase 2 conditions)

Note: Full photographic database available as digital deliverable (JPEG format, EXIF data retained for geotagging coordinates and timestamps).

Appendix D: References

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