From Trenching to Micro-tunnelling: Adaptive Optioneering to Achieve Compliance Amid Design Uncertainty

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1. Introduction

Red Sea Global (RSG) is developing regenerative tourism infrastructure along Saudi Arabia's Red Sea coast. At AMAALA destination, this includes a reverse osmosis (RO) desalination plant delivered through a 25-year Public–Private Partnership (PPP) to provide potable water for the destination. The project consortium comprises EDF, Masdar, Korea East-West Power, and SUEZ. The Environment and Social Impact Assessment (ESIA) was prepared by 5Capitals and AMAD.

Coastal infrastructure in sensitive marine settings often requires investment decisions before designs are fully resolved, while environmental approvals depend on credible predictions of impact and mitigation (PIANC, 2011; European Commission, 2017; World Bank, 2017). This paper shows how baseline data and modelling informed early optioneering for the RO intake and outfall pipelines construction by comparing open trenching with micro-tunnelling. It outlines the project setting, RSG's adaptive compliance framework, the post-ESIA verification, monitoring, and enforceable construction requirements.

2. Site selection

The RO plant, with a design capacity of 94,471 m3/day, is located on the Red Sea coast in Tabuk Province between Al Wajh and Duba. Site selection followed master planning and multi-criteria assessment that considered environmental constraints and operational needs. Five candidate sites as shown in Figure 1 were screened using the following land categorization:

- Developable – land with no significant constraints (e.g., hydrology, habitats, slope, heritage, protected landscapes, or infrastructure corridors).
- Developable with restrictions – land with constraints (e.g., heritage, bird flyways, protected landscapes) requiring conditions on use, height, density, and design; and
- Undevelopable – land where development should not/cannot occur (e.g., coastal zones, wadi channels, steep slopes) or is otherwise unavailable.

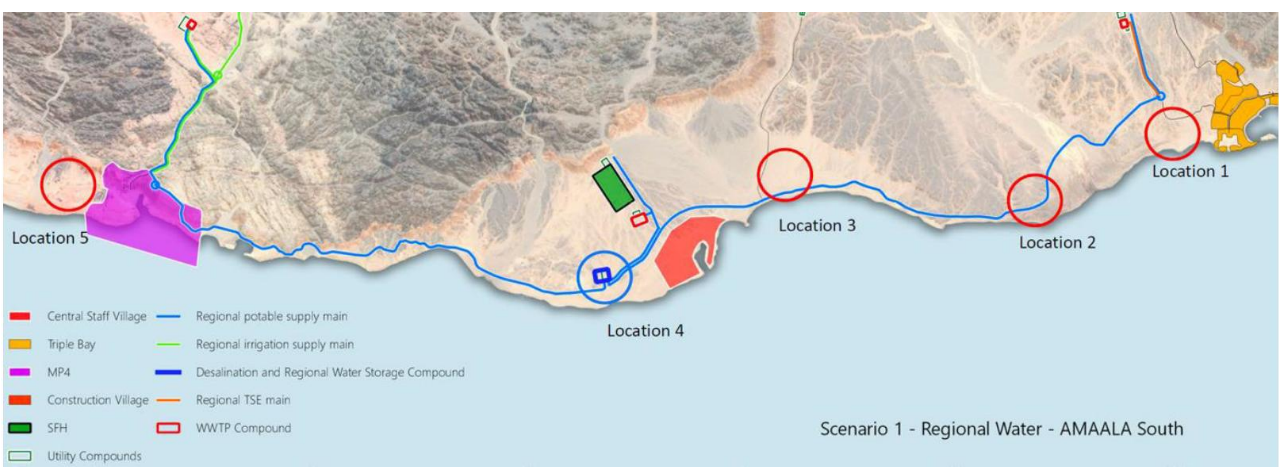

Figure 1 Site screening showing locations considered for the RO plant [ASCE, 2024]

Subsequently, the following four-step screening matrix was used to assess the suitability of potential sites (Figure 1) based on feasibility, environmental constraints, brine dispersion, and marine baseline survey findings (Buro, 2021; ASCE, 2024):

- Step 1 – Feasibility: Assessed alignment with the RSG master plan and engineering requirements, including ground conditions, land take, access, utilities, flood risk, redundancy, and maintenance.
- Step 2 – High-level environmental screening: Considered proximity to turtle nesting areas, sensitive habitats, deep water, and offshore megafauna sightings. Locations 1 and 5 ranked lowest, so Locations 2, 3, and 4 were carried forward.
- Step 3 – Brine dispersion: Plume modelling confirmed compliance with national ambient seawater quality standards, with Location 4 performing best.
- Step 4 – Marine baseline survey: Locations 2 and 4 showed similar coral conditions, but Location 2 had higher seagrass cover. Overall, Location 4 was selected as the preferred site.

3. Project and environmental setting

The desalination plant consists of three concrete pipelines: one outfall pipeline 815m long, 1.6m in diameter, and a seabed depth of 25m; two intake pipelines each 600m long, 1.6m wide at seabed depth of 16m. The corridor shown in Figure 2, crosses heterogeneous substrates and ecologically valuable habitats including live coral, back reef, seagrass, macroalgae, and rocky shoreline, with records of turtles and whale sharks. These habitats are important because they are sensitive, support biodiversity, and are difficult to avoid due to their nearshore location. Baseline surveys identified 151 hard coral species representing 52 genera, confirming a healthy reef system and a high-sensitivity receiving environment.

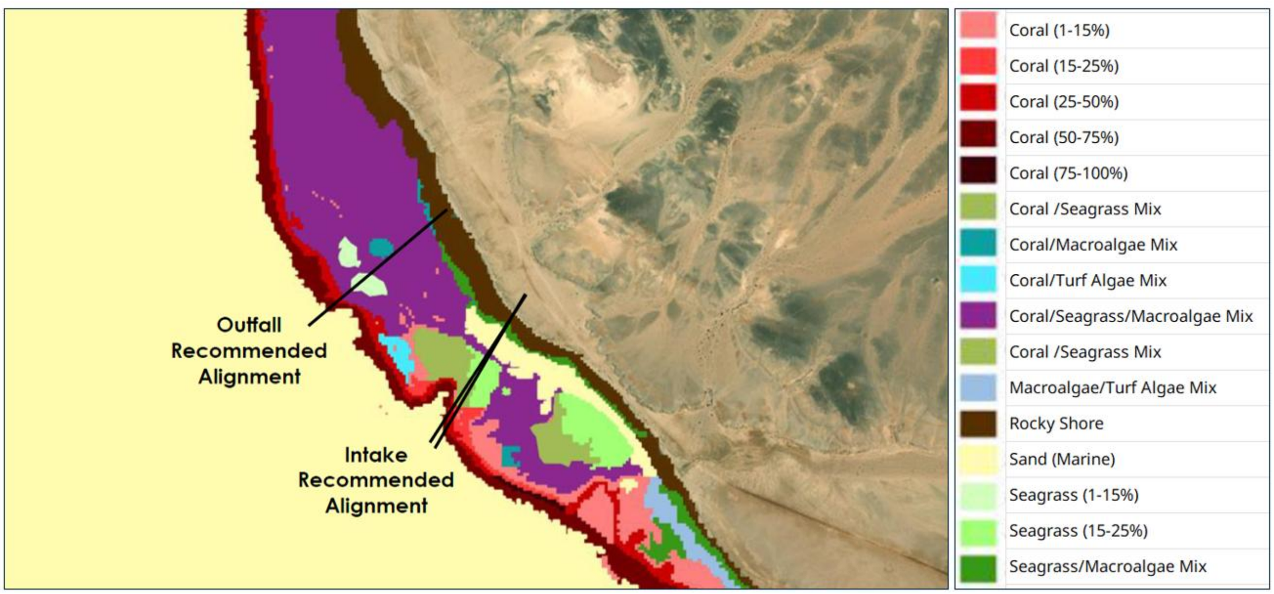

Figure 2 Habitat map of the project area [ASCE, 2024]

4. Optioneering Methods

At ESIA stage, optioneering drew on four linked inputs: baseline environmental data, construction options and comparative metrics, regulatory compliance requirements, and a framework for managing design uncertainty.

4.1 Baseline environmental data and habitat mapping

Marine ecology surveys combined rapid assessments, side-scan sonar, and detailed benthic mapping to define the existing conditions along the intake and outfall corridors (ASCE, 2024). These datasets were used to quantify sensitive habitats, identify coral risk, and establish conservative impact envelopes where detailed drawings were still evolving.

The Strategic Environmental Assessment (SEA) data was also used to provide data on historic sightings of marine fauna including dugong, reef fish, whale sharks and turtles. Where design details were uncertain, conservative buffers and realistic construction footprints were applied so that predicted impacts would remain valid under plausible alignment refinements. Baseline data inputs typically included a combination of habitat transects and spot-check observations, georeferenced photographs and/or video records, side-scan sonar track lines, drop down videos and shoreline/intertidal walkovers. Semi-quantitative data regarding substrates and habitats, was recorded using hand-held tables whilst the habitat map was prepared using the QGIS software. These observations were consolidated into a habitat map and sensitivity layer suitable for optioneering, with polygons representing the best available delineation of coral, seagrass, macroalgae, back reef, and rocky shoreline habitats in the nearshore zone. Where detailed construction drawings were not yet finalised, impact envelopes were defined using conservative footprints representing plausible working corridors, temporary access needs, and construction tolerances. This "design-aware" (Ng and Chuah, 2016) conservative approach was intended to avoid underestimation while still providing decision makers with a means of distinguishing between options. The same baseline and envelope assumptions were applied consistently to both trenching and micro-tunnelling so that differences reflected method effects rather than mapping artefacts.

4.2 Construction options and comparative metrics

Construction method selection was treated as a primary mitigation decision rather than downstream optimisation because it largely determines the scale and reversibility of disturbance. Two methods were compared: open trenching and micro-tunnelling. They were assessed against disturbed habitat area, likely coral interaction, and qualitative cost and constructability considerations. A typical example of a micro-tunnel is presented in Figure 3, whilst a photograph of a typical open trench for a pipeline is presented in Figure 4.

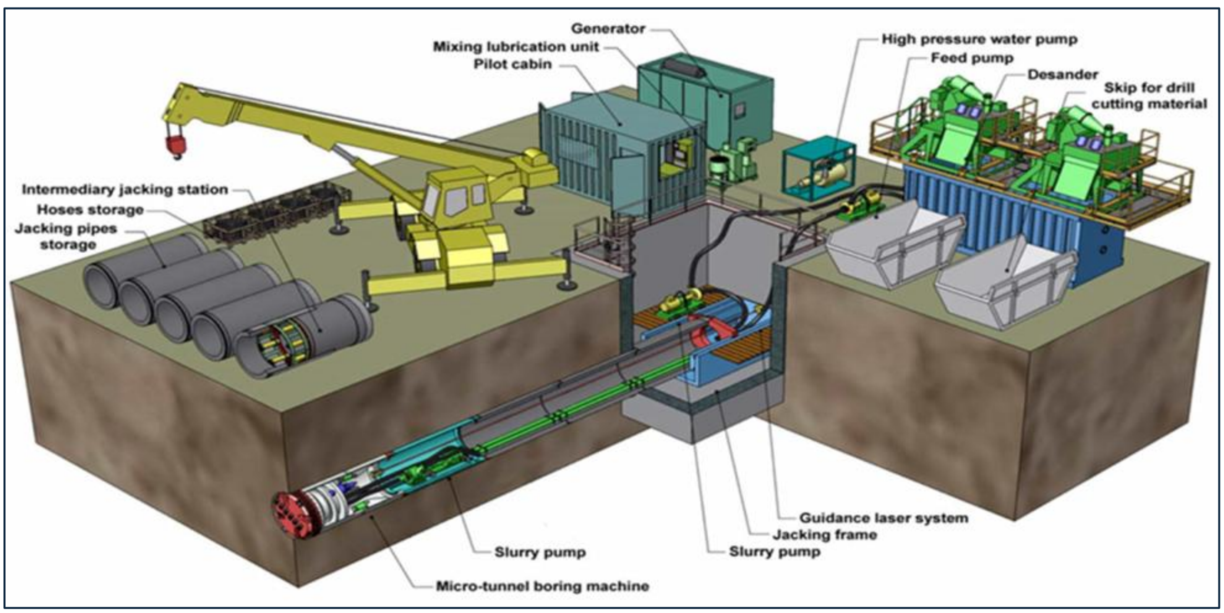

Figure 3 Typical microtunnel model [ASCE, 2025]

In Saudi Arabia, open trenching is the conventional methodology for installing marine intakes and outfalls. This method is generally cheaper (Sandale Utility Products, 2025; Tabesh, Najafi and Korky, 2016), but requires seabed excavation, pipe lay, and backfilling, which results in direct benthic disturbance and turbidity. Preliminary drawings were used to estimate a conservative trenching footprint based on burial depth, a trapezoidal trench profile, wet excavation using floating plant, barge removal and reuse of excavated material, and the expectation of greater sedimentation, noise, vibration, and construction duration when compared with micro-tunnelling (ASCE, 2024)

Micro-tunnelling is generally more expensive (DVUC, 2024) due to the requirement for specialised equipment, advanced technology, skilled labour and operational expenses compared to open-cut methods (Sandale Utility Products, 2025; Tabesh, Najafi and Korky, 2016). Micro-tunnelling advances below the seabed, limiting direct interaction mainly to launch and reception areas and short tie-ins. Micro-tunnelling was the preferred option because it minimises surface and seabed disturbance, sediment release, and direct interaction with corals. To provide further context of the potential footprint and impact of the trenching option, the outfall pipeline construction footprint was overlaid on the coastal habitat map to show the impact on corals as presented in Figure 5.

Figure 4 Typical pipeline open trench excavation

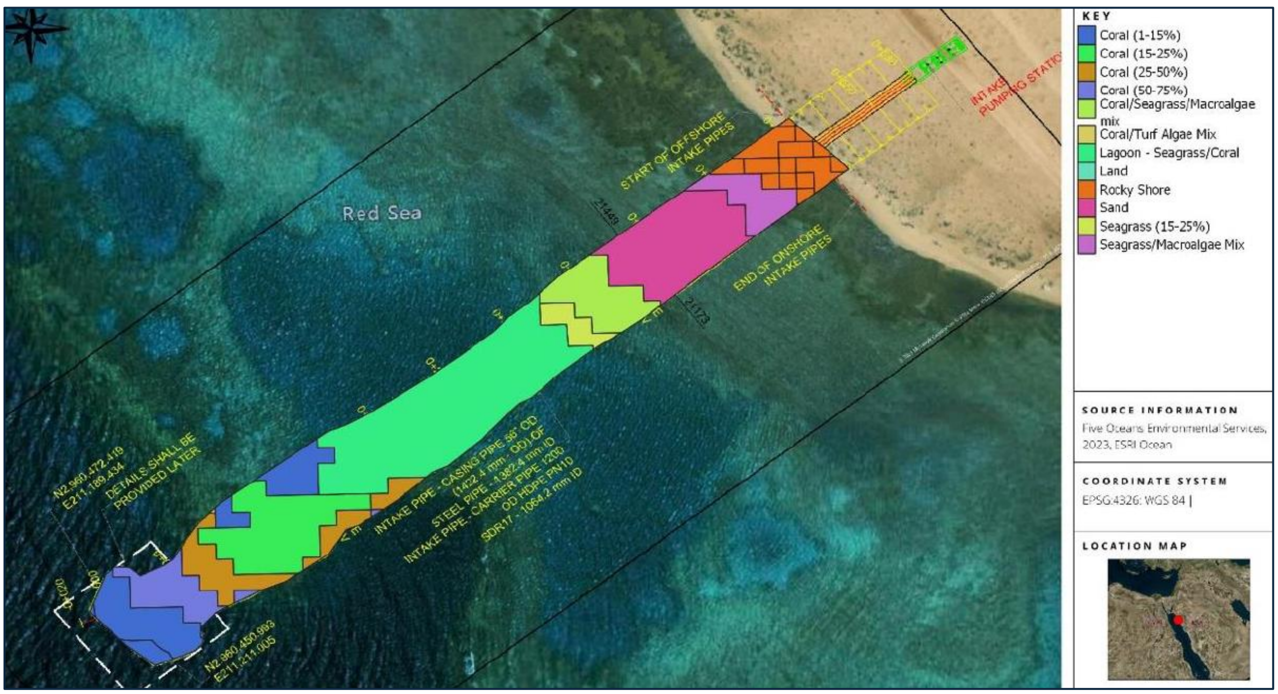

Figure 5 Outfall pipeline showing trenched option with coastal habitats [ASCE, 2024]

4.3 Regulatory Compliance commitments and decision governance

Given the ecological sensitivity and complexity of the site, the project team engaged the following regulators early and regularly; National Center for Environmental Compliance (NCEC); Ministry of Environment Water & Agriculture (MEWA); National Center for Vegetation Cover Development & Combating Desertification (NCVC); General Organization for Conservation of Coral Reefs and Turtles in the Red Sea (SHAMS); and Prince Mohammad bin Salman Royal Reserve (PMBSRR). A governance structure aligned environmental specialists, engineers, and investment stakeholders around a shared evidence base and decision gates, to reduce the risk of late design changes and approvals.

Optioneering was embedded in the ESIA through method-linked commitments that could be verified during detailed design and construction. These included disturbance limits around launch and reception areas, pre-construction verification surveys, adaptive responses if previously unmapped sensitive habitats were identified, and construction monitoring requirements such as turbidity, coral health, and benthic surveys.

In addition to the ESIA commitments, the respective regulatory bodies imposed certain pre-construction, construction and operational phase conditions on the project. Some of the notable construction phase requirements include the installation of silt curtain (Type III); coral relocation and health monitoring (survival rate, coral bleaching, coral cover); benthic surveys, water quality monitoring (turbidity plume, sedimentation, salinity, dissolved solids, dissolved oxygen, hydrocarbon, pH); validation of sediment dispersion modelling results, marine mammal observers onboard offshore vessels, reef stability studies, unrestricted site access for regulatory visits and submission of detailed progress reports.

4.4 Managing design uncertainty through adaptive optioneering

Integrating findings into ESIA decision-making remains challenging, especially when comparing options and stakeholder priorities (UNEP, 2018). Regulators were engaged early throughout the process, from SEA phase, site selection, surveys, design reviews, construction methodology, and ESIA submission.

To support ESIA approval amid evolving design, the project adopted an adaptive compliance approach (Taylor, 2026): decisions were anchored in baseline conditions and impact pathways that would be robust to reasonable design changes. In practice, this meant prioritising methods with inherently lower interaction with sensitive receptors and defining conservative impact envelopes. It also meant that commitments could be verified during detailed design and construction (e.g., constraints on nearshore disturbance footprints and habitat avoidance principles). This framework increased regulatory confidence by demonstrating that the preferred option reduced residual risk and narrowed the range of potential outcomes under uncertainty.

5. Optioneering Outcome

The baseline-informed comparison showed a substantial reduction in direct habitat disturbance when micro-tunnelling replaced open trenching. Under the assessed footprints, open trenching would disturb about 49,425 m^2 of marine habitat, whereas micro-tunnelling would affect about 4,679 m^2, mainly at launch, reception, and tie-in areas. This equates to an approximate 90% reduction in direct disturbance. Using the same spatial baseline, trenching was predicted to result in direct interaction with all mapped coral habitat within the pipeline corridor, while micro-tunnelling reduced that potential effect by about 75% by avoiding continuous seabed excavation. The impact on corals is presented as a chart in Figure 6. Although engineering feasibility and cost were considered, the decisive factor was environmental performance, especially the reduced likelihood of coral removal and turbidity-generating disturbance.

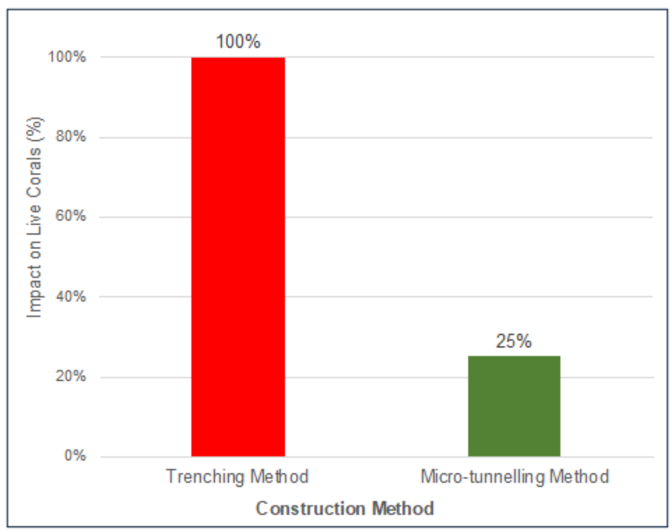

Figure 6 Comparison of installation options on corals [ASCE, 2024]

The key uncertainties included final alignment micro-siting, temporary working widths, and the extent of nearshore tie-in works. However, the conclusion remained robust because trenching requires continuous excavation along the alignment, whereas micro-tunnelling concentrates disturbance at a limited number of locations. Applying conservative envelopes to both options preserved this fundamental difference. The comparison table of the construction options are presented in Table 1.

Option	Primary interaction with seabed/habitat	Disturbed habitat (m^2)	Relative coral risk
Open trenching	Continuous excavation, pipe lay and backfill along alignment; elevated turbidity and sediment reworking	49,425	Higher (greater probability of direct coral disturbance)
Micro-tunnelling	Subsurface tunnelling beneath substrate; disturbance largely limited to launch/reception and tie-ins	4,679	Lower (avoidance of continuous nearshore seabed interaction)

Table 1 Comparison of installation options

6. Discussion

The ESIA was prepared to meet Saudi regulatory requirements, International Finance Corporation (IFC) standards, lender expectations, and international good practice. Baseline-led optioneering translated ecological information into decision-ready metrics that were meaningful to regulators, project leadership, and investors, enabling early alignment on a preferred construction approach. Although more complex and costly, micro-tunnelling reduced interaction with sensitive habitats, narrowed the range of environmental outcomes under design uncertainty, and improved confidence that commitments would remain achievable during construction. This helped avoid late redesign and supported an expedited Final Investment Decision.

The adaptive compliance value was not limited to selecting micro-tunnelling; it continued post-ESIA through verification surveys, construction controls, monitoring triggers, regulator reporting, and corrective response mechanisms. The approach also provided transparent, proportionate construction-phase controls, including habitat verification around launch and reception sites, disturbance demarcation, turbidity monitoring triggers, and adaptive responses if thresholds were exceeded or previously unmapped sensitive habitat was encountered.

7. Conclusion

This case study is transferable to other coastal projects where approvals and financing depend on timely, defensible decisions under uncertainty. The most replicable features are decision metrics derived from baseline data, conservative but consistent impact envelopes, and explicit linkage between the selected option and an adaptive compliance plan.

For the AMAALA RO pipelines, baseline environmental data and modelling were used to support early optioneering that protected sensitive marine habitats while improving schedule certainty. Micro-tunnelling reduced predicted direct marine habitat disturbance from about 49,425 m^2 to about 4,679 m^2 and provided a defensible compliance pathway that supported ESIA approval and Final Investment Decision.

Acknowledgements

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