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Route Selection and Environmental Strategies in Subsea Pipeline Engineering

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Environmental Considerations in Subsea Clean Water Pipeline Installation from Manado to Bunaken Island to Support Resort Sustainability

Abstract

Clean water availability is one of the main factors in supporting the sustainability of small island tourism areas, especially in regions with limited freshwater resources. Pulau Bunaken, as a marine tourism destination, has an increasing demand for clean water due to the growth of resorts, homestays, and tourism activities. One potential solution is the construction of a subsea clean water pipeline from Manado to Bunaken Island. However, the planning of such a system must consider coastal and marine environmental sensitivity, particularly coral reefs, seagrass beds, and marine habitats. This article aims to analyze the importance of environmental aspects in subsea pipeline route selection through a literature review and conceptual analysis approach. The discussion indicates that the shortest route is not always the best route if it passes through ecologically sensitive areas. Route avoidance, spatial mapping, and the integration of environmental data should be applied from the early planning stage. Therefore, clean water infrastructure development can proceed in parallel with marine environmental conservation.

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1. Introduction

Clean water supply is a fundamental requirement for sustaining tourism activities on small islands such as Pulau Bunaken. However, the development of subsea pipeline infrastructure must consider environmental impacts on marine ecosystems. Subsea pipelines are known to cause various environmental disturbances, including seabed disruption, habitat alteration, and impacts on marine biodiversity [1]. These impacts highlight the importance of integrating environmental considerations into the early stages of pipeline planning.

In addition, subsea infrastructure can influence marine life distribution (Bond et al., 2018). demonstrated that the presence of subsea pipelines affects fish assemblages and commercially important species, depending on water depth and environmental conditions. This indicates that pipeline placement is not only a technical decision but also an ecological consideration. From an engineering perspective, explained that thermal processes and burial conditions in subsea pipelines are closely related to seabed characteristics. Therefore, environmental and geotechnical factors must be integrated in route planning [2].

In environmentally sensitive marine areas such as Bunaken, route selection represents one

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of the most critical stages of subsea pipeline planning. The chosen route determines the extent to which construction and operational activities may interact with valuable marine ecosystems. A route that crosses coral reef formations, seagrass meadows, or important fish habitats can result in unnecessary ecological disturbance, even if the route offers advantages in terms of shorter distance or lower installation costs. Therefore, environmental sensitivity mapping should be conducted before route selection to identify areas that require protection and to minimize potential impacts on marine biodiversity [3].

The waters surrounding Bunaken are internationally recognized for their rich biodiversity and unique marine ecosystems. As part of a marine protected area and a major tourism destination, Bunaken contains extensive coral reef communities that support numerous species of fish and other marine organisms. Any infrastructure development within or near these ecosystems must be carefully planned to avoid direct physical damage and long-term ecological degradation. Consequently, environmental considerations should be treated as a primary design criterion rather than as a secondary assessment conducted after route determination [4].

Furthermore, the concept of sustainable infrastructure development emphasizes the need to balance engineering objectives with environmental conservation goals. In the case of subsea clean water pipelines, environmentally responsible route planning can help reduce habitat fragmentation, minimize seabed disturbance, and preserve the ecological value of marine protected areas. By integrating environmental data, marine spatial planning information, and engineering feasibility assessments, project developers can identify route alternatives that support both reliable water distribution and long-term ecosystem protection. Such an approach is particularly important in Bunaken, where the sustainability of tourism activities depends heavily on the health and attractiveness of coastal and underwater ecosystems [5].

2. Materials and Methods

The method used in this article is a literature review combined with a descriptive-analytical approach. References were obtained from subsea pipeline engineering books, marine engineering journals, and publications related to coastal zone management. The analysis stages include: Identification of clean water demand in the Bunaken tourism area. Review of subsea pipeline systems as a water distribution solution. Evaluation of environmental sensitivity factors such as coral reefs, seagrass beds, and marine tourism zones. Analysis of the importance of environmentally based route selection. Development of sustainable planning recommendations.

The literature reviewed in this study consists of scientific journal articles, conference papers, technical standards, and engineering reference books related to subsea pipelines, marine environmental management, and sustainable infrastructure development. Particular attention was given to studies discussing environmental impacts of subsea installations, route selection methodologies, seabed interactions, and marine conservation practices. Relevant publications were selected based on their applicability to coastal and island environments with characteristics similar to those of Bunaken and the surrounding waters.

The analytical process focuses on identifying the relationship between engineering requirements and environmental protection objectives. Information gathered from the literature was compared and synthesized to evaluate how environmental sensitivity influences route planning decisions. Factors such as coral reef distribution, seagrass coverage, marine protected areas, navigation activities, and seabed characteristics were reviewed to determine their significance in subsea pipeline planning. This approach enables the identification of key environmental constraints that should be considered during project development.

In addition, a conceptual framework was developed to illustrate the integration of environmental considerations into route selection processes. Rather than emphasizing detailed engineering calculations, the study focuses on decision-making principles that support sustainable infrastructure development. The framework highlights the importance of balancing technical feasibility, economic considerations, and environmental protection to achieve reliable clean water distribution while minimizing impacts on marine ecosystems.

3. Results

This section may be divided into subheadings. It should provide a concise and precise description of the experimental results, their interpretation, and the experimental conclusions that can be drawn.

3.1 Potential of Subsea Pipeline Installation

A subsea pipeline system from Manado to Pulau Bunaken has the potential to become a long-term solution for supplying clean water to resorts and local communities. Compared with water transportation by vessel, pipelines offer better continuity of supply and are less affected by weather-related disruptions. This advantage is particularly important for tourism facilities that require a stable and reliable water supply to support daily operations. Resorts, hotels, restaurants, and other tourism-related businesses depend on adequate clean water availability to maintain service quality and visitor satisfaction. Therefore, the installation of a subsea pipeline can contribute not only to improving water security but also to supporting the sustainable development of tourism activities on Bunaken Island [6].

3.2 Environmental Factors to be Considered

Several major environmental aspects should be considered in the planning and installation of a subsea clean water pipeline, including coral reefs, seagrass beds, diving and snorkeling tourism routes, and marine conservation zones. Coral reefs are among the most sensitive ecosystems because they provide habitat for a wide variety of marine species and support the tourism attractiveness of Bunaken. Seagrass beds also play an important ecological role by functioning as feeding and nursery grounds for fish and other marine organisms. In addition, the selected pipeline route should avoid areas that are frequently used for tourism activities and zones designated for marine conservation. Careful consideration of these environmental factors can help minimize ecological disturbance and reduce potential conflicts between infrastructure development and environmental protection objectives [7].

3.3 Route Avoidance Principle

According to Bai and Bai, the route avoidance approach is an important strategy in modern pipeline design, meaning high-risk areas should be avoided during the planning stage. In the Bunaken context, a slightly longer route may be preferable if it can reduce environmental disturbance and protect sensitive marine habitats. This principle is consistent with the concept of preventive environmental management, which emphasizes avoiding impacts before they occur rather than relying solely on mitigation measures after construction. By selecting routes that bypass coral reefs, seagrass areas, and conservation zones, project developers can significantly reduce environmental risks while maintaining the technical feasibility and operational effectiveness of the pipeline system [8].

3.4 Environmental Interaction with Seabed

Subsea pipelines interact directly with seabed materials and environmental conditions. Soil properties and thermal behavior play a significant role in pipeline performance, especially for buried pipelines. Previous studies have shown that heat transfer within seabed soils influences pipeline behavior and stability [9]. Although this study focuses on gas pipelines, similar principles apply to subsea clean water pipelines. In addition, variations in sediment composition, seabed morphology, and hydrodynamic conditions can affect pipeline support conditions and long-term stability. Understanding these environmental characteristics is therefore important not only for engineering design and operational reliability but also for minimizing environmental impacts during pipeline installation and operation [10].

4. Discussion

Environmental considerations in subsea pipeline planning extend beyond installation impacts and include long-term ecological interactions [11] found that subsea pipelines can become

associated with benthic species and conservation features, indicating that pipelines may alter habitat structures over time. Furthermore, the influence of subsea pipelines on fish assemblages has been documented, showing that marine biodiversity distribution can be affected by the presence of such infrastructure [12]. This reinforces the importance of avoiding ecologically sensitive areas during route selection.

The importance of environmentally based route selection becomes even more significant in marine protected areas such as Bunaken, where ecological and economic interests are closely interconnected. Healthy coral reefs and diverse marine ecosystems are the primary attractions supporting tourism activities in the region. Any environmental degradation resulting from poorly planned infrastructure development may not only affect biodiversity but also reduce the tourism value of the area. Therefore, route planning should consider both ecological sensitivity and the long-term sustainability of tourism-dependent communities [13].

In addition, environmental considerations should be integrated into the decision-making process through the use of marine spatial planning and environmental sensitivity mapping. These tools allow planners to identify areas with high ecological value and evaluate alternative pipeline routes before construction begins. By combining environmental information with engineering and economic assessments, decision-makers can select routes that minimize ecological impacts while maintaining technical feasibility. Such an approach supports sustainable infrastructure development and aligns with broader environmental management objectives in coastal and marine environments [14].

Another important consideration is the role of environmental impact assessment in supporting sustainable subsea infrastructure development. Environmental impact assessments can provide valuable information regarding potential ecological risks associated with different route alternatives and construction methods. Through early identification of sensitive habitats and potential environmental conflicts, mitigation measures can be incorporated into project planning before installation activities commence. This proactive approach can reduce environmental uncertainty and improve the overall sustainability of subsea pipeline projects in marine tourism destinations such as Bunaken [15].

From an engineering standpoint, seabed conditions also influence pipeline performance. Thermal interaction and soil characteristics affect pipeline stability and operational behavior [2], [9]. Therefore, an integrated approach combining environmental and engineering considerations is essential in subsea pipeline planning. In environmentally sensitive areas such as Pulau Bunaken, route selection should prioritize ecological protection even if it results in a longer pipeline route. This approach ensures sustainable infrastructure development while preserving marine ecosystems.

5. Conclusions

The installation of a subsea clean water pipeline from Manado to Pulau Bunaken is a potential solution to support the clean water needs of resorts and local communities. However, project success strongly depends on environmental considerations from the earliest planning stage. Pipeline routes should not be determined solely by the shortest distance, but also by their ability to avoid sensitive areas such as coral reefs and important marine habitats. With proper planning, infrastructure development and environmental conservation can proceed simultaneously.

In addition, this study demonstrates that environmental considerations should be treated as a fundamental component of subsea pipeline planning rather than as a supplementary requirement. The selection of an environmentally responsible route can significantly reduce potential impacts on coral reefs, seagrass beds, marine biodiversity, and tourism activities that depend on healthy ecosystems. By integrating environmental sensitivity mapping, marine spatial planning, and engineering assessments into the route selection process, project developers can achieve a balance between infrastructure development and environmental conservation. Such an approach is essential for ensuring the long-term sustainability of clean water supply systems and the continued growth of tourism on Bunaken Island.

Furthermore, environmentally responsible pipeline development provides benefits that extend beyond ecosystem protection. The long-term sustainability of resorts and tourism businesses on Bunaken Island depends not only on the availability of clean water but also on the preservation of

the marine environment that attracts visitors. Coral reefs, seagrass ecosystems, and diverse marine species represent valuable natural assets that support local economic activities and community livelihoods. Therefore, infrastructure projects that incorporate environmental considerations from the planning stage can contribute simultaneously to water security, tourism sustainability, and regional economic development.

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