BRIDGING CITIES, FOSTERING MOBILITY, SAFEGUARDING NATURE: THE ROLE OF ENVIRONMENTAL MONITORING IN INFRASTRUCTURE PROJECTS

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1. Introduction

Infrastructure projects are pivotal in enhancing connectivity between cities and people, thereby driving economic growth but also fostering social development and improving urban mobility systems [1, 2, 3]. However, these infrastructure projects can also pose significant environmental risks [4]. This is where the role of Environmental Impact Assessment (EIA) becomes crucial, with environmental monitoring serving as a cornerstone of this process [5]. In the context of modern infrastructure development, environmental monitoring has become a critical tool for ensuring sustainable growth [6]. Environmental monitoring, articulated in, pre-operam, in-operam and post-operam, plays a crucial role in the sustainable management of infrastructure projects ensuring that environmental impacts are not only continuously monitored but also mitigated with implementing actions throughout the entire lifecycle of the project [7].

This research delves into the role of environmental monitoring in infrastructure projects by analyzing three case studies from the SEW-Line Project, an inter-university research initiative involving research units from the Universities of Padua, Bergamo and Rome. In alignment with European directives, the project aims to develop a model that adopts a holistic approach, which is replicable and applicable on various scales, to propose the adaptation, as well as a more suitable planning, of infrastructures [8].

The principal issue addressed in this research is the challenge of balancing infrastructure development with environmental sustainability and urban mobility [9]. Infrastructure projects, especially large-scale ones, inherently lead to environmental changes even if they implement mobility system [4]. However, through rigorous environmental monitoring, it is possible to minimize negative impacts and ensure that projects contribute positively to regional development [7, 10]. The aim is to explore how environmental monitoring has been implemented in the infrastructure projects, evaluate its effectiveness, and find elements for improvement and innovation.

The methodology involves a thorough review of the existing literature, the consultation of project reports, environmental assessment documents and national regulations. These data were used for developing a comparative analysis to evaluate the effectiveness of the monitoring process. The focus has been on identifying recommendations to emphasize a continuous evolution of monitoring technologies and methodologies to further enhance the sustainability of large infrastructure projects.

2. Discussion and methods

The challenge of balancing infrastructure system and sustainability goals has been analyzed with a comparative analysis of three case studies in urban mobility, highlighting both similarities and differences in the topic of environmental monitoring. These cases were selected based on specific characteristics, such as the project size, the purpose of the project and the different stage of development, to better define an analysis that could compare a wide range of infrastructure projects. Each case has been briefly analyzed, focusing on crucial aspects of the monitoring phase of the during and post-operam phase, like monitoring actions, tools used, environmental parameters measured, results obtained, but it also sought to highlight some strengths, weaknesses, and potential innovations. The data from the pre-operam phase were not considered because they provided the state of the environment and estimated some possible qualitative effects of the project. This study has provided an initial overview of environmental monitoring practices, offering valuable insights to enhance the sustainability of infrastructure projects.

2.1. Case Study 1: BreBeMi A35 Highway

The A35, an alternative route to the A4 Highway, was opened to traffic in 2014 to connect the cities of Brescia, Bergamo, and Milan, from which the name "BreBeMi" originates. It represents a significant infrastructure project aimed at improving regional connectivity [11]. Despite these benefits, the construction and operation of the expressway introduced several environmental challenges, particularly in terms of air quality, noise pollution, and potential soil contamination [12]. To address these concerns, the environmental monitoring plan was implemented and was conducted under the supervision of ARPA Lombardia with the Environmental Observatory, focusing on various environmental factors such as air quality, noise levels, soil and water contamination, fauna, and flora. In Table 1 are reported the overall considerations emerged by this initial analysis.

ASPECTS	**DETAILS**
Monitoring Actions	Continuous monitoring of air quality, noise pollution and impacts on local ecosystems.
Tools Used	Real-time sensors for detecting NO_X, CO, PM10, and acoustic sensors for noise.
Parameters Measured	Air quality, noise levels, soil and water contamination, fauna, and flora.
Strengths	Real-time data collection, allowing prompt responses to emerging environmental issues.
Weaknesses	Limited biodiversity monitoring; potential underestimation of long-term ecosystem impacts.
Potential Innovations	Development of a more extensive biodiversity monitoring system; integration of new technologies for ecosystem management.

Table 1. Aspects analysed from the BreBeMi environmental monitoring

An interesting aspect was the attention to historical and archaeological pre-existing elements, along with the preliminary risk assessment. It has conducted a preventive investigation to verify these pre-existing elements, then retrieved during the construction process and now preserved in the M.A.G.O museum of Pagazzano, located in the province of Bergamo [13].

The monitoring stations were deployed along the route to continuously collect and register data. The results, as stated from the report [14], indicated that while the highway facilitated faster travel times and reduced congestion on the A4, air quality remained within acceptable limits, noise levels near residential areas occasionally exceeded the threshold. The overall results of the monitoring will be available when the post-operam monitoring will be completed, and so it will be possible to make more valuable considerations.

2.2. Case Study 2: Mestre A4 Highway Bypass

The Mestre Bypass, opened to traffic in 2009, is one of Veneto's key infrastructures, designed to reduce congestion on the Mestre ring road and separate local traffic from through traffic. [15]

The environmental monitoring plan was conducted by ARPA Veneto coordinated by the Soil and Remediation Observatory Service, focusing on various environmental factors.

Among the different factors, the water quality monitoring was notable for its use of bioindicators to assess the impact on nearby water bodies. In Table 2 are reported the overall considerations emerged by this initial analysis.

ASPECTS	**DETAILS**
Monitoring Actions	Monitoring of air, water, soil quality, noise levels and biodiversity along the route.
Tools Used	Fixed and mobile monitoring units; use of bioindicators for water quality.
Parameters Measured	Air pollution (NOx, PM), water quality (bioindicators), soil contamination, noise levels.
Strengths	Holistic approach to environmental monitoring; broad coverage of environmental parameters.
Weaknesses	Complex management of soil contamination; need for more effective soil protection strategies.
Potential Innovations	Implementation of integrated soil protection strategies; development of advanced technologies for contaminant monitoring.

Table 2. Aspects analysed from the Mestre Bypass environmental monitoring.

The project was one of the first cases of wildlife monitoring application for the control of large- scale infrastructure construction. It focused on vertebrate species in ecologically valuable areas to assess biodiversity and ensure compliance with European and national environmental laws. During construction, monitoring controlled target populations, while post-construction, it evaluated the effectiveness of mitigation measures [16].

The general results, as stated from the report [17], demonstrated a broad improvement in traffic flow and a reduction in vehicle emissions in the urban area, although some localized increases in soil contamination were observed due to construction activities.

2.3. Case Study 3: Verona-Padova High-Speed/High-Capacity Railway section

The Verona-Padova railway section (1st subsection completed, 2nd ongoing, and 3rd in design phase) is part of the Turin-Milan-Venice railway line, a component of the Mediterranean corridor of the trans-European transport network (TEN-T core network) that will link Spain and Ukraine. The project aims in 2026 to quadruple the railway line, while also relocating the old line where the two tracks come close to each other [18].

The environmental monitoring for this project focused heavily on noise and vibration impacts due to the proximity of the railway to urban centers [19, 20]. Advanced monitoring technologies, including remote sensing and GIS-based tools, were employed to assess these impacts along the railway corridor. In Table 3 are reported the overall considerations emerged.

ASPECTS	DETAILS
Monitoring Actions	Monitoring of water, soil quality, vibrations and noise levels, and biodiversity along the route.
Tools Used	GIS tools, remote sensors, advanced vibration monitoring technologies.
Parameters Measured	Noise and vibration levels, impacts on urban centers and nearby green areas.
Strengths	Use of innovative monitoring technologies; detailed spatial analysis of environmental impacts.
Weaknesses	Limited monitoring of wildlife impacts; potential underestimation of long-term effects.
Potential Innovations	Introduction of more extensive biodiversity and wildlife monitoring; development of new techniques for vibration management.

Table 3. Aspects analysed from the Verona-Padova Railway section environmental monitoring.

The monitoring for the pre-operam phase, estimated, among other factors, the reduced travel times and improved logistic efficiency. Although, there were reported challenges in managing noise levels, particularly in densely populated areas, but there will be a clearer scenario when the 3rd subsection will be finished, and the monitoring completed.

3. Results and Conclusions

The comparative analysis of these three case studies underscores the pivotal role of environmental monitoring in infrastructure projects. Although each project has made significant strides in mitigating environmental impacts, the analysis reveals areas where improvements and innovations are needed. By addressing these deficiencies and integrating advanced monitoring tools and

RECOMMENDATIONS	DETAILS
Invest in advanced monitoring technologies	Infrastructure projects should invest in the latest monitoring technologies, such as real-time sensors and predictive models, to ensure accurate and timely data collection. (e.g. use of drones and IoT sensors for a more detailed and efficient monitoring)
Implement adaptive management strategies	Projects should adopt adaptive management strategies that allow for adjustments in monitoring and mitigation measures based on real-time data. (e.g. implementation of AI systems on the monitoring program)
Engage local communities	Transparent communication and active engagement with local communities are essential for building trust and ensuring the success of environmental monitoring efforts. (e.g. use of apps for reporting environmental anomalies)
Promote continuous learning	Encourage continuous learning and improvement in monitoring methodologies by staying updated with the latest scientific research and technological advancements. (e.g. public workshop for citizens to explain updates on the monitoring program of a project)

Table 4. Recommendations for environmental monitoring in infrastructure projects.

methodologies, future infrastructure projects could achieve a more balanced development approach, ensuring both environmental sustainability and advancements in urban mobility.

This analysis establishes an initial framework for enhancing environmental monitoring practices. The subsequent step involves planning additional case studies to further advance the goal of sustainable infrastructure development. The findings presented in Table 4 suggest that future infrastructure projects would benefit from adopting more comprehensive monitoring practices, which should include a broader range of environmental parameters such as biodiversity and long-term ecosystem health. Furthermore, the potential for innovation in monitoring technologies – such as the development of sophisticated systems for managing vibrations and soil contaminants – offers a promising avenue for improving the effectiveness of environmental assessments.

In conclusion, while the analyzed projects have effectively enhanced connectivity and fostered socio-economic growth, they also reveal areas where environmental monitoring could be strengthened. By leveraging insights from these case studies, future infrastructure development can achieve a more sustainable balance between economic advancement and environmental conservation, ultimately contributing to a more resilient mobility system.

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