Brumadinho Dam Disaster: Effect of Massive Iron-ore Tailings Release on Land Cover

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1 Introduction

The mining industry plays a crucial role in producing heavy metals used globally and constitutes a significant part of the world economy. The metal extraction process generates waste materials, known as mine tailings, which are typically stored in dams, ponds, or riverine systems [9]. These storage facilities require regular maintenance and monitoring to ensure environmental safety. Ojuri, Adavi, and Oluwatuyi estimates that 5 to 7 billion tonnes of tailings are produced annually. Such large production highlights how proper storage of these tailings is vital to prevent contamination and leaching into the environment. Unfortunately, environmental protection is not always prioritized, leading to many catastrophic events throughout the history of the industry, with little evidence of improvement [7] [1].

Garcia et al. note that despite Brazil accounting for only 4 percent of global incidents, it has the most articles published about tailing spills between 1990 and 2021. This increased attention is attributed to two large-scale disasters in Minas Gerais: the Fundão Dam collapse in 2015 and the Brumadinho Dam collapse in 2019. The latter event led to Brazilian legislation banning the upstream construction method for tailings dams [2].

On January 25th, 2019, a dam connected to a mining operation near Brumadinho, Brazil, failed catastrophically. This disaster resulted in the loss of over 270 lives and caused significant ecological damage, releasing almost 10 million metric cubes of tailings into the environment [5][12]. Understanding the spatial and temporal impacts of this event is essential for evaluating recovery efforts and guiding future disaster response strategies. The findings aim to highlight the severe consequences of tailing dam failures and advocate for the dismantling of upstream tailing dams globally to prevent future disasters. Using spectral classification and spatial analysis, this project aims to analyze land cover changes following the disaster to address three key research questions:

> First, how did the disaster immediately impact land cover? Second, how much of the affected area showed signs of recovery or remediation within eight months? Finally, which classified land cover type experienced the highest rate of recovery or remediation?

2 Data Collection

To analyze the effects of the Brumadinho dam failure, we will examine three different scenes acquired by the Planet.com [1] satellite system. This satellite imagery is atmospherically corrected, has a pixel resolution of 3 meters per pixel and was recorded using the Dove classic ps2 which gathers red, green, blue, and near-infrared bands. The scenes we gathered are:

- January 24th 2019
- February 2nd, 2019
- October 17th, 2019

These scenes were chosen to display a full narrative of the disaster from its immediate devastation to the more long-term effects which were felt even 8 months after in October. The tropical climate of Brazil means that vegetation cover stays fairly constant throughout the year and therefore, data collection at different times

[1] Data source from `https://www.planet.com/`. We also made an interactive visualizer to aid our decision in choosing data points. See `https://asahahaha.github.io/geospatial-brumadinho/`.

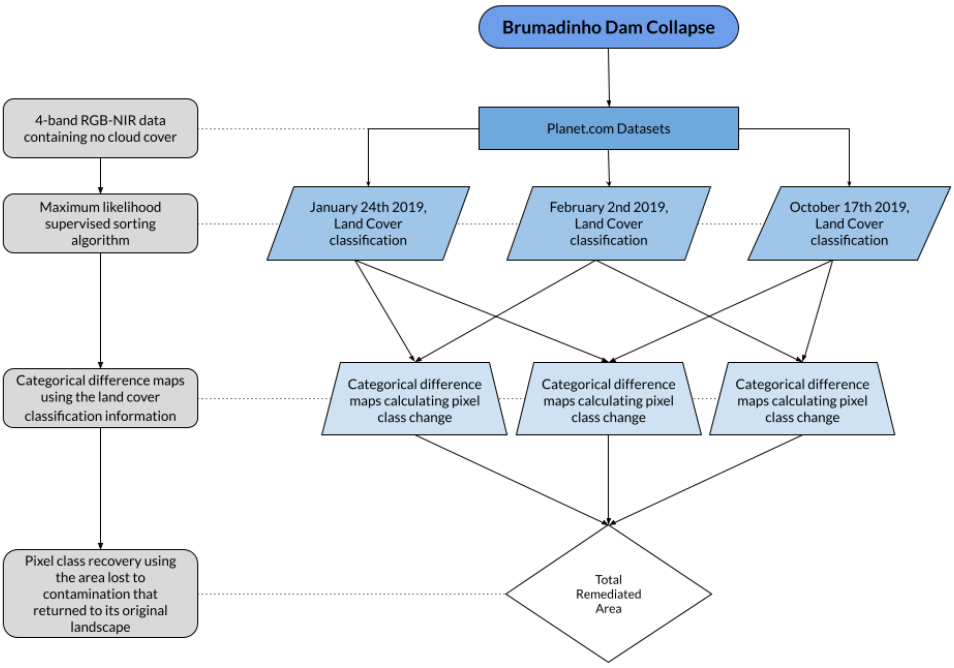

Figure 1: Flowchart that explains our methodology in pre-, during & post-classification efforts, to analyze the land cover change of the Brumadinho dam disaster.

of the year would not heavily affect the overall land cover of each scene. The general extent of the scenes which we chose was larger than the true extent of the disaster itself. This was done intentionally to observe any significant land use changes as a result of the disaster no matter how far away from the actual epicenter they were.

3 Methodology

Once this satellite imagery was collected, the next step was to create land cover classifications for all three scenes. Our flowchart is shown in Figure 1.

The classifications we created in ENVI 6.0 were supervised and based on training data defined by us. One of our areas of focus related to the disaster involved looking into the ecological devastation caused by the Brumadinho dam disaster. Therefore, all scenes included a class for water and forest, two types of land cover intrinsically linked to wider ecological health. Another focus for our analysis surrounded the flood's effect on human settlement and community. For this reason, we included classes encompassing Non-forest agriculture, built-up (human construction), and mine (operations). Finally, all scenes included a contamination classification, which centred on the tailings spilled by the mining disaster. Furthermore, our October scene included an auxiliary mud classification meant to encompass the remaining devastation left behind in the wake of the flooding and contamination caused by the mining disaster. After this was decided and the training data was created, the maximum likelihood algorithm was used to generate land classification across all three scenes (see Figure 2).

Once this was completed, we were left with three raster datasets, which were georeferenced from Planet.com with the projected coordinate system WGS 84 / UTM zone 23s. This meant it was possible to accurately look at the pixel or classification coverage difference across these three scenes, in ArcGIS Pro. The data was first cropped to remove extraneous classification unaffected by the flooding disaster. After this, we looked at three separate pixel changes between the scenes in hopes of answering our three central research questions.

As shown in Figure 3, first, we analyzed what classes changed into contamination From Jan-

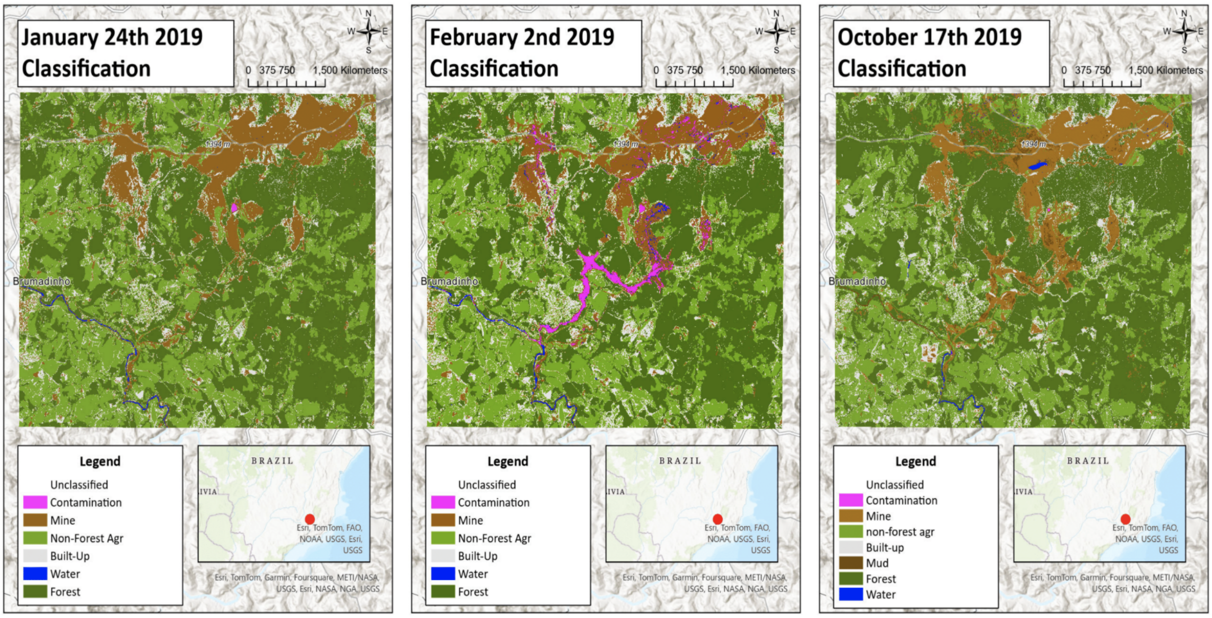

Figure 2: Pixel based classification of Brumadinho, Brazil on January 19th, 2019, February 2nd, 2029 and October 17th 2019 using 4-band RGB-NIR Imagery from Planet.com.

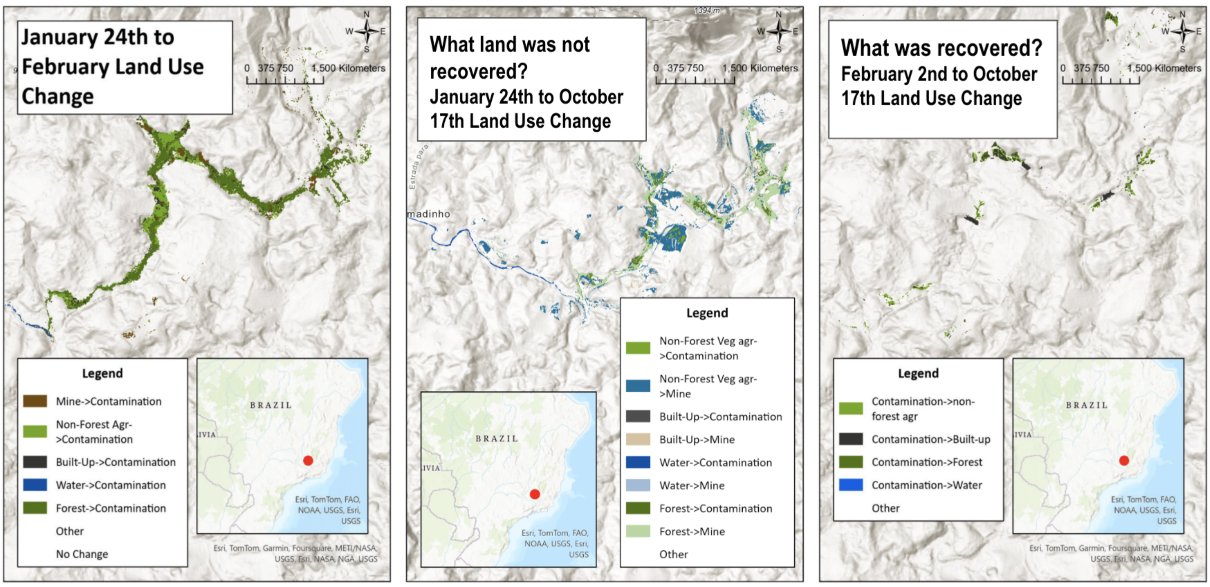

Figure 3: Pixel change using categorical difference to illustrate the landscape change in Brumadinho, Brazil following the tailings dam failing.

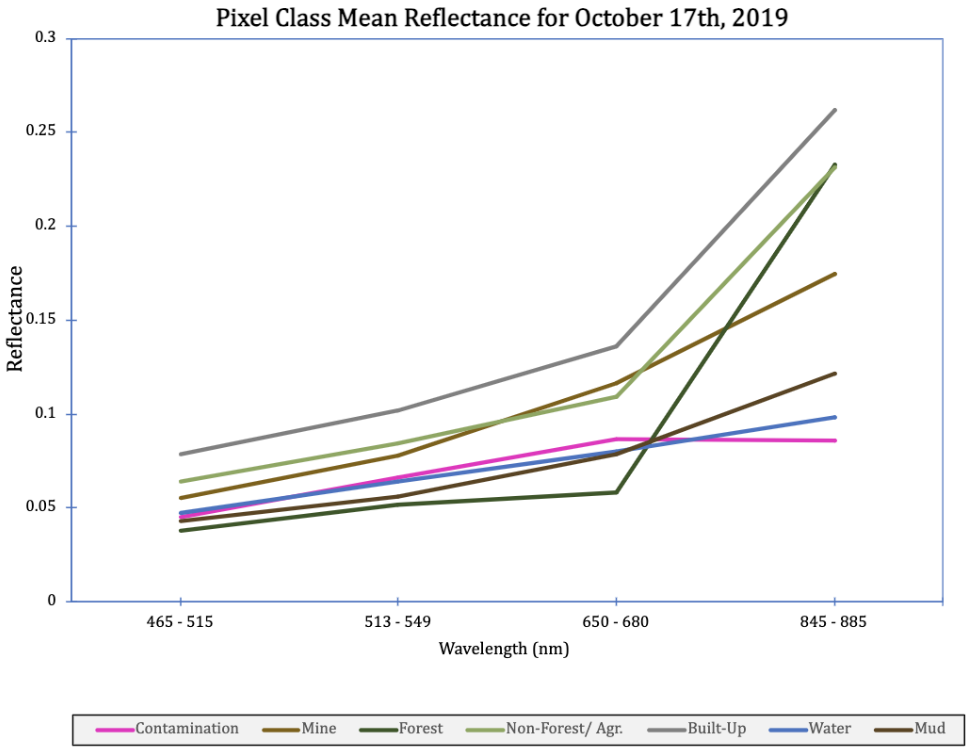

Figure 4: Spectral reflectance of different pixel classes in Brumadinho, Brazil on October 17th, 2019. *Note: The Mine, Mud, and Built-Up Classes share similar spectral shapes. It should be highlighted that this is an important factor affecting these pixel classifications' accuracy.*

uary to February to see the immediate effects of the flood. Next, we looked to see which classes had changed from contamination into another classification from February to October to understand how the landscape had recovered from the disaster. Finally, we analyzed long-term ecological changes by looking into the change of classes in January into either the mine or contamination/mud class in October.

4 Results

Our classification resulted in an overall good accuracy rating of 96.9% for January, 89.6% for February, and 88.5% for October, with the kappa coefficients being 0.96, 0.93, and 0.87, respectively. While the Kappa coefficient [10] measures agreement between the classification and true land cover, this slight decline in both accuracy and Kappa over time suggests increasing classification challenges due to the environmental changes post-disaster, especially the increase of complexity due to the addition of mud class as mentioned in Section 3.

The confusion matrices for the February 2nd classification (as an example) reveal key insights into classification accuracy. Table 1 shows that Built-Up and Contamination areas were classified accurately,while classes like Non-Forest Veg. and Water exhibited higher misclassification rates, which were consistent with our observations, where these areas showed more complex classification issues. Table 2 reveals significant errors of commission for Mine (24.73%), which corresponds with some misclassifications between Mine and surrounding areas. It also shows a notable omission error for Contamination (23.53%), reinforcing the challenge of detecting contamination areas accurately. Finally, Table 3 confirms that Built-Up and Water had high accuracy scores, supporting our results, while Mine had lower user accuracy, which we identified as a critical area for improvement in the classification process.

The complexity in October can be shown when we plot the spectral signatures for 4 bands of our classes, where the signatures are very similar amongst Mine, Mud, and Built-Up, as shown in Figure 4.

Analyzing the pixel data from ArcGIS Pro, the land cover change following the Brumad-

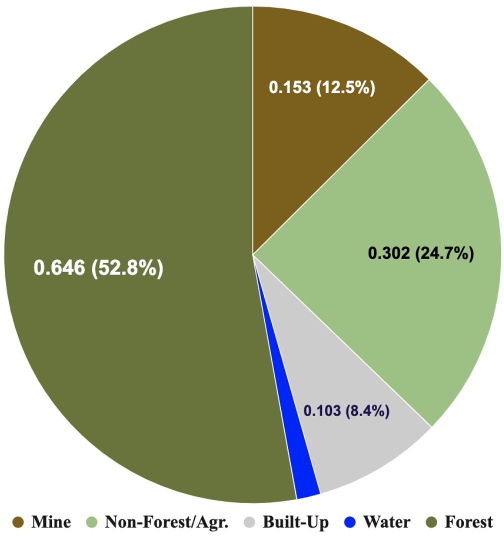

Figure 5: a) Land cover Change Into Contamination Class From January 24th , 2019 to February 2nd, 2019 (in km^2).

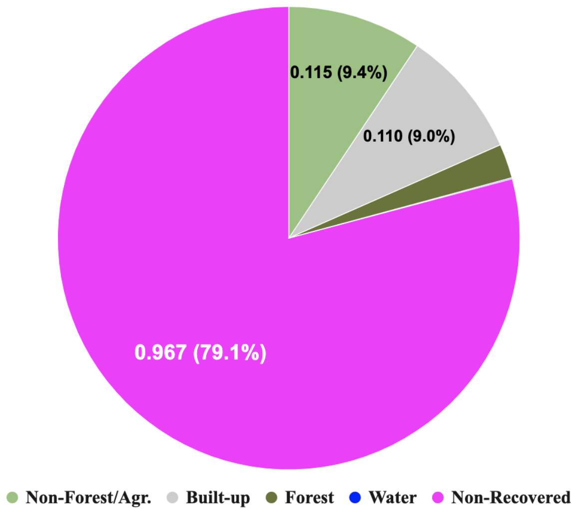

Figure 6: b) Landscape Recovery From Remediation Efforts Comparing Land Cover From February 2nd, 2019 to October 17th, 2019 (in km^2).
Note: Figures 5 and this show a visual representation of the land cover that was not able to be recovered by the remediation effort of the Brumadinho dam disaster.

inho dam disaster reveals significant impacts. The key results are summarized as follows:

4.1 Immediate Effects of Contamination (January to February)

The flood caused by the dam breach led to widespread contamination of the surrounding land. The classification analysis shows that a total of 1.22 km^2 of land was contaminated,

Table 1: ENVI generated 1st confusion matrix table depicting ground truth for the pixel-based classification of February 2nd.

	Ground Truth (Pixels)						
Class	Built-Up	Contamination	Non-Forest Veg./ Agr.	Water	Mine	Forest	Total
Built-Up	166	0	13	0	6	0	185
Contamination	0	143	0	0	7	0	150
Non-Forest Veg. / Agr.	1	0	89	0	2	0	92
Water	0	0	0	115	2	9	126
Mine	8	35	1	1	140	1	186
Forest	0	0	0	0	0	89	89
Total	175	187	103	116	157	90	828

Table 2: ENVI generated 3rd confusion matrix table depicting errors of commission and omission for the pixel-based classification of February 2nd.

Class	Commission (Percent)	Omission (Percent)	Commission (Pixels)	Omission (Pixels)
Built-Up	10.27	5.14	19/185	9/175
Contamination	4.67	23.53	7/150	44/187
Non-Forest Veg. And Agr.	3.26	13.59	3/92	14/103
Water	8.73	0.86	11/126	1/116
Mine	24.73	10.83	46/186	17/157
Forest	0	1.11	0/89	1/90

Table 3: ENVI generated 4th confusion matrix table depicting the producer and user accuracy for the pixel-based classification of February 2nd.

Class	Prod. Acc. (Percent)	User Acc. (Percent)	Prod. Acc. (Pixels)	User Acc. (Pixels)
Built-Up	94.86	89.73	166/175	166/185
Contamination	76.47	95.33	143/187	143/150
Non-Forest Veg. And Agr.	86.41	96.74	89/103	89/92
Water	99.14	91.27	115/116	115/126
Mine	89.17	75.27	140/157	140/186
Forest	98.89	100.00	89/90	89/89

with 53% of the affected area being forested land, as shown in the pir chart in Figure 5. This suggests that forested regions were significantly impacted by the tailings spill, possibly leading to long-term ecological damage.

4.2 Recovery and Remediation (February to October)

Eight months after the disaster, changes in land cover were observed, indicating some recovery, but also highlighting the slow pace of environmental remediation. Approximately 65% ± 10% of the contamination was still present in October 2019. Remember that the uncertainty is estimated from classifying the October data. This indicates that while some areas were recovering.

4.3 Land Cover Types Most & Least Recovered

As shown in comparing the change from Figure 5 to Figure 6, among the land cover types, built-up areas showed the highest rate of recovery, with even an + 8% increase due to the growth of human settlements and construction activities. In contrast, forest cover had the lowest recovery rate, with only 4.5% of the affected forest area showing signs of recovery. These results are illustrated in Figure 4. This suggests that natural vegetation is significant more vulnerable to such environmental disasters and slower to recover compared to human-altered landscapes. These findings emphasize the impacts of tailings dam failures on the environment, particularly in tropical regions where vegetation recovery is essential for ecosystem restoration.

5 Discussion

The long-lasting contamination (65% still affected by October 2019) shows far-reaching implications for both environmental policy and future disaster response and recovery strategies [4].

5.1 Impact of the Disaster on Vegetation

Forested areas were the most affected by the contamination from the tailings spill, comprising over half of the contaminated land area. Given Brazil's tropical climate, vegetation typically remains consistent throughout the year, so any noticeable degradation in forested areas underscores the severity of the disaster's impact. The low recovery of forests (4.5%) suggests that ecosystems that depend on slow-growing vegetation are particularly vulnerable and need targeted restoration efforts, as compared to built-up which was the easiest for recovery.

5.2 Contamination of the Paraopeba River

As shown in Figure 2, where the downstream river remains as muddy contamination in October, shows that how the dam failure affected water quality and local communities for months to years. These findings showed the need for more effective monitoring and remediation strategies for water bodies too.

5.3 Relation to Previous Literatures

Our findings are consistent with the work of Garcia et al., which highlighted the long-term impacts of tailings dam failures, particularly in Brazil, where the Fundão and Brumadinho disasters have been central to the discourse on mining safety. These authors also noted the difficulty in recovering forested areas following tailings spills, mirroring our own results. The continued contamination in the region, despite remediation efforts, reflects the challenges of managing large-scale mining disasters and their aftermath.

The rapid recovery of built-up areas seen in our study aligns with trends in post-disaster recovery observed in other countries [8], where human settlements are often rebuilt more quickly than natural ecosystems. However, while rebuilding human settlements quickly after a disaster is a sign of resilience, it can overshadow the critical need to address and restore the environmental damage caused by the disaster.

5.4 Limitations

The study is subject to several methodological limitations that may affect the robustness of the analysis. The use of a **only-four-band spectral analysis** (RGB + NIR) with a 3-meter resolution, while relatively fine, but the spectral overlap between mine, mud & contamination could lead to inaccuracies in distinguishing between these classes. Secondly, we were not able to find a "good" (with no cloud coverage & full extent coverage) imagery after exactly one year of the failure, hence instead we **choose October which was 8 months after**. Although Brazil is in the tropical area so seasonal change on vegetation is minimal, but it may affect our precision of land cover assessments.

5.5 Recommendations for Future Improvements

Future studies could benefit from higher-resolution satellite imagery (e.g., 1-meter resolution) and a broader spectral range, which would allow for more accurate classification of land cover types. Furthermore, integrating data from other sources, such as field observations and additional remote sensing platforms, would help improve the overall accuracy and comprehensiveness of the analysis. It is also recommended that future research track the long-term recovery of affected ecosystems by collecting data beyond the eight-month period covered in this study. This would allow for more understanding of the temporal dynamics of recovery and provide insights into the effectiveness of remediation efforts over time.

6 Conclusion

In conclusion, this study demonstrates the severe and enduring impact of the Brumadinho dam disaster on both the natural environment and human settlements. The flood decimated buildings and agricultural fields while also destroying forested ecosystems and polluting water sources. However, our analysis made it clear that human-built infrastructure could recover much more quickly than environmental pollution created by the flood. Since these two features are intrinsically linked [3], these two findings cannot be viewed as a separate development, but rather, part of a cohesive system which should be addressed in disaster response initiatives. Because ecological devastation has a massive and lasting impact on humans [11], neither should be viewed as more or less valuable in disaster response, particularly when it comes to holding those at fault accountable. Therefore, companies like Vale [2] should be held responsible not only for the reconstruction and remediation of human infrastructure but the long-term cleanup and remediation of forested and water ecosystems until they are restored to their previous condition.

References

[1] Gideon O. Bamigboye et al. "Waste materials in highway applications: An overview on generation and utilization implications on sustainability". In: *Journal of Cleaner Production* 283 (2021), p. 124581. ISSN: 0959-6526. DOI: https://doi.org/10.1016/j.jclepro.2020.124581. URL: https://www.sciencedirect.com/science/article/pii/S0959652620346254.

[2]Vale: The largest producer of iron ore and nickel in the world. The company accountable for the 2019 tailings dam failure.

[2] Flávia Ferreira Garcia et al. "Mine tailings dams' failures: serious environmental impacts". In: *Environmental Systems Research* 53.1 (2024), pp. 1–15. DOI: 10.1007/s10668-024-04628-z. URL: https://link.springer.com/article/10.1007/s10668-024-04628-z.

[3] Christopher D Ives et al. "Human–nature connection: a multidisciplinary review". In: *Current Opinion in Environmental Sustainability* 26-27 (2017). Open issue, part II, pp. 106–113. ISSN: 1877-3435. DOI: https://doi.org/10.1016/j.cosust.2017.05.005. URL: https://www.sciencedirect.com/science/article/pii/S1877343517301264.

[4] Allen V. Kneese. "Environmental Pollution: Economics and Policy". In: *The American Economic Review* 61.2 (1971), pp. 153–166. ISSN: 00028282. URL: http://www.jstor.org/stable/1816988 (visited on 12/04/2024).

[5] Darren Lumbroso et al. "Modelling the Brumadinho tailings dam failure, the subsequent loss of life and how it could have been reduced". In: *Natural Hazards and Earth System Sciences* 20.6 (2020). Accessed: 2024-12-04, pp. 1–20. DOI: 10.5194/nhess-2020-159. URL: https://doi.org/10.5194/nhess-2020-159.

[6] O.O. Ojuri, A.A. Adavi, and O.E. Oluwatuyi. "Geotechnical and environmental evaluation of lime–cement stabilized soil–mine tailing mixtures for highway construction". In: *Transportation Geotechnics* 10 (2017), pp. 1–12. ISSN: 2214-3912. DOI: https://doi.org/10.1016/j.trgeo.2016.10.001. URL: https://www.sciencedirect.com/science/article/pii/S2214391216300897.

[7] J.R. Owen et al. "Catastrophic tailings dam failures and disaster risk disclosure". In: *International Journal of Disaster Risk Reduction* 42 (2020), p. 101361. ISSN: 2212-4209. DOI: https://doi.org/10.1016/j.ijdrr.2019.101361. URL: https://www.sciencedirect.com/science/article/pii/S2212420919306648.

[8] Feniosky Peña-Mora et al. "Building assessment during disaster response and recovery". In: *Proceedings of the Institu-*

tion of Civil Engineers-Urban Design and Planning 161.4 (2008), pp. 183–195.

[9] Nahyan M. Rana et al. "Catastrophic mass flows resulting from tailings impoundment failures". In: *Engineering Geology* 292 (2021), p. 106262. ISSN: 0013-7952. DOI: https://doi.org/10.1016/j.enggeo.2021.106262. URL: https://www.sciencedirect.com/science/article/pii/S0013795221002738.

[10] G.H. Rosenfield and K. Fitzpatrick-Lins. "A coefficient of agreement as a measure of thematic classification accuracy." In: *Photogrammetric Engineering Remote Sensing* 52.2 (1986). Cited by: 804, pp. 223–227. URL: https://www.scopus.com/inward/record.uri?eid=2-s2.0-0022927129&partnerID=40&md5=af77781e10edf38017659b7b20b501ae.

[11] Shilpa S. Shetty et al. "Environmental pollutants and their effects on human health". In: *Heliyon* 9.9 (2023), e19496. ISSN: 2405-8440. DOI: https://doi.org/10.1016/j.heliyon.2023.e19496. URL: https://www.sciencedirect.com/science/article/pii/S240584402306704X.

[12] Fangyuan Zhu, Wangcheng Zhang, and Alexander M. Puzrin. "The slip surface mechanism of delayed failure of the Brumadinho tailings dam in 2019". In: *Communications Earth & Environment* 5.33 (2024). Accessed: 2024-12-04. DOI: 10.1038/s43247-023-01086-9. URL: https://doi.org/10.1038/s43247-023-01086-9.