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Research Article

Impact of Post-mining Transformations on Slope Stability and Sustainability Processes in the Base Titanium Mining Area, Kenya

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ABSTRACT

The gradual transformations of the open-pit titanium mining legacy in the south coast of Kwale, County in Kenya, has led to the formed gently rolling terrains into steep, unstable slopes that have endangered both the environmental and community safety. This study delves to (1) measure changes of landforms caused by post mining modifications at base titanium geosites, (2) assess how these changes impact slope stability, and (3) identify opportunities designing more sustainable post mining landforms and practices. Using drone (UAV) photogrammetry and satellite images, the research generated high-resolution digital surface and terrain models which were applied to compare pre- and post-mining topography within a transected area of 2 km x 2 km. Slope angles derived from the normalized digital surface model were categorized into stable (<30°) and high-risk (>30°) groups. Changes in vegetation cover were analyzed with the normalized difference vegetation index (NDVI) and field measurements were used to verify remote sensing data on slopes and land cover. Results show that unclaimed mine pits have an average slope of 35°, which is above the stability threshold. Areas that have been actively reclaimed through topsoil replacement and strategic revegetation have slopes below 25° and dense plant cover. High-risk zones match closely with bare-soil tailings dumps and eroded pit walls where poor drainage has increased the risk of mass wasting; however, reclaimed embankments with engineered drainage and early-stage vegetation are resistant to rainfall-induced erosion. These results prove that integrated planning for slopes, drainage systems, and ecological restoration is important in securing post-mining landscapes. In conclusion, sustainable landforms after mining can be actualized when the reclamation focus is on (a) optimization of steep slope angles to below 30°, (b) installation of cut-offs and controlling water flows using toe drains, and (c) quick establishment of native plants for soil stabilization and reduction of surface runoffs. Lastly, adopting these mitigation practices would enhance geo-hazards adaptation and resilience. In addition, this will also enhance promotion of ecological succession and enabling future sustainable resource nexus land use approaches such as water storage, water recharge, agroforestry and ecotourism, thus resulting in transformations of former mining area into stable multifunctional and sustainable landscapes.

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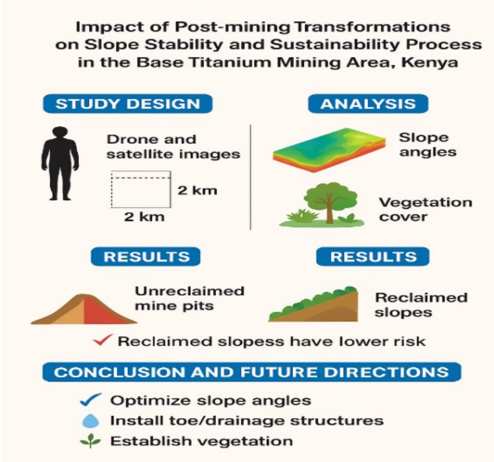

Fig. 1. Graphical abstract, adopted and modified [3]

1. Highlights of the publication

- UAV photogrammetry and satellite imagery were used to map the pre- and post-mining topography at Base Titanium's 2 km² study site.
- Unreclaimed mine pits show average slopes of 35°, exceeding the 30° stability limit.
- Actively reclaimed areas have slopes less than 25° and support thick vegetation.
- High-risk areas correspond to bare-soil tailings dumps and eroded pit walls that lack drainage control.
- Sustainable reclamation involves slope regrading, engineered drainage solutions, and swift native vegetation establishment.

2. INTRODUCTION

Globally, the quality of life for residents is threatened because open-pit mineral mines are becoming obsolete, and nearby water bodies and their ecosystems face the risk of disappearing [1-5]. The transformation of this mining area after closure has implications for slope stability that require solutions. Mining activities have contributed to pollution, climate change concerns, and environmental degradation in the region. Post-mining development efforts help restore the environment and maintain its quality. Since the early 1990s, the minerals industry has expanded to meet global demand for non-fuel minerals, leading to increased exploration and development. Mining can disturb the physical and biological components of many ecosystems, pose risks to health and safety, affect different land uses, have various social impacts, and affect catch-and-release and low-water-level storage infrastructure. Economist Herbert Simon suggested that "the basic problems of the sciences are three: (i) What is the world like? (ii) How does it work? (iii) What should we do?" [11,15]. These questions relate both to the pre-planning or discovery phase evaluation and the assessment of the soundness of operations, which can be considered a primary or secondary school set of fundamental science questions.

In May 2004, Base Titanium Ltd. commenced mining operations on the Kwale mineral sands project in Kenya's southeastern coastal region, 50 km south of Mombasa. The area has been mined for minerals such as limonite, rutile, and zircon in the past. Currently, mining takes place in cut-and-fill blocks within Pliocene Diani formation. This type of mineral extraction will have economic impacts like creating jobs and improving infrastructure but may also pose very high risks to slope stability that needs to be assessed for soundness under a wider sustainability framework. Photography and rainfall data were used to assess the performance as well as operation of the bottom drain system. It was observed that, despite minimal rainfall effects, the sides of the Base Titanium pits began to flake into the pits, and these failures should be carefully considered when assessing the short- or long-term future of operations and practices within the prospected Kwale district [5-20].

Mining activities can significantly alter landforms. Open-pit mining greatly impacts the environment. During mining, the environment is disturbed, and pits are excavated. This disturbance changes the relationship among environmental variables as a new landform is created. Such changes can raise concerns about the stability of wet and dry slopes. If the geology prevented instability or if drainage kept slopes dry, stability would not be an issue. However, in many regions, mining makes the terrain highly vulnerable to instability. Understanding a new landform before mining is possible using aerial photographs, digital elevation data, topographic maps, and remote sensing data [23-30]. After mining, various methods are used to predict the appearance of newly formed surfaces [12-17].

Traditionally, slopes are excavated in stages with a progressive vertical advance. However, this excavation method can cause hydrologic instability issues because it cannot be adequately designed to monitor precipitation and slope movements. For diamond mines operating in erodible materials, both wet and dry slope stability are primary concerns [11-31]. Current practices do not adequately address slope stability on surfaces formed by a mine pit grade, nor do they provide adequate warning of potential slope movements or concerns. Therefore, it is necessary to address an uncertain problem: using computer models to predict the new landforms that could result from various mining plans and to analyze the wetting conditions of these digital landforms statistically. Failure modes for slope cracking, based on the hydrologic filter and regional planes, will also be examined [13-18].

A significant amount of published work exists in the field of geomechanics. It is acknowledged that this is a vast field actively pursued by many experts. There have been considerable advances in methods of analysis and numerical modelling of slope stability. These advanced methods employ finite difference and finite element analysis better to incorporate rock-mechanical and hydraulic concepts in modelling stability. However, many of the problems are complex, and there is a limit to how accurately the problem can be formulated and the input data agreed upon. In addition, the empirical methods identified in prior sections have been demonstrated to provide a helpful alternative. In the present work, both approaches are developed; however, a study on how changes in landform alter slope stability conditions using an empirical method for open-pit slopes is presented first [19-22].

Post-mining land uses involve activities aimed not at continuing mine operations but at ensuring that the land can be effectively adapted for various purposes. Restoring a post-mining landscape to a functional state generally involves site preparation, rehabilitation, and redevelopment. An overall framework for post-mining land uses includes six distinct stages: post-mining assessment, initial preparation, secondary preparation and companion restoration, rehabilitation, after-use, and ongoing management. After the site is closed, it is the responsibility of the state or relevant authority to continue post-mining management activities before redeveloping the land for other uses. Redevelopment of post-mining land for alternative purposes depends on the successful adaptation of the post-mining landscape for a desired land use [7-25].

Mining companies are increasingly using social network platforms to discuss issues such as post-mining practices, community relations, and sustainable practices, among others, after the intensive mining phase of a site is completed. These networks provide not only opportunities for debate but also for discussions among mining companies, interested parties, and the companies themselves. Among many pieces of shared information and experiences, there are numerous posts documenting failures in post-mining practices that other mining companies could learn from. There are also significant motivations stemming from responsibilities, debates, federations, and even governments. However, at least in Kwale County, mining companies do not provide a mining operating map that individuals can use to avoid mining company boundaries [26-31] safely.

A comparative study of changes around a mine near a lake and in areas close to land restoration was designed using advanced paired and empirical techniques. Applying these techniques allows for predicting both relative and absolute change trends, facilitating comparisons of 'success’ in post-restoration scenarios that were previously impossible. Besides the methodological innovation, the empirical findings provide insights into post-land-use practices. Traces of mining activities have persisted for over 40 years, and measures based on newly formed lakes are rapidly evolving, requiring ongoing monitoring.

The subsequent sections present the findings and provide recommendations for future extension and replication of the approaches taken. Kwale County, located in the south-eastern part of Kenya, is endowed with large mineral deposits, predominantly titanium. Several mining companies have established operations here including Ilmin, Base Titanium, and Tiomin Kenya. Biodiversity loss and land degradation due to mining activities in Kwale County, are detrimental to the local residents' economic dynamics and the livelihoods. However, they can also present opportunities for sustainability in the post-mining transition phases [2].

Base Titanium commenced mining activities in Kwale County back in 2004. Surface mining has converted flat terrain into large mounds of disturbed earth; this conversion has not yet been studied concerning its effect on slope stability in the area. The use of drone images, satellite data, and field observations about changes in land surface before and after mining provides insights into impacts regarding slope stability, drainage systems, and land use which can help promote more sustainable practices. This project thus aims to (1) assess how landforms at Base Titanium have changed from flat terrain to steep slopes; (2) analyze how post-mining topography influences slope stability as well as informing designs for more sustainable landforms; and (3) examine potential pathways through which sustainable mining practices may occur on post-mining landforms towards better drainage systems and improved land uses [11-37].

This study investigates whether post-mining changes to exhausted mines in Kwale County promote sustainability and slope stability using remote sensing and unstable-slope analysis. It presents data on mining operations, pollution, environmental conditions, and geospatial characteristics of mined areas collected from secondary sources supplemented with satellite imagery [6-14]. These features are analyzed using geospatial software tools for understanding impacts due to mining practices as well as post-mining changes.

Important activities for geospatial, topographic, and slope stability closure have been implemented. Lastly, possible mechanisms that trigger slope instability in abandoned mining sites are discussed, and geologically recorded conditions before failure are chosen. Using satellite data, potential pre-failure indicators for slope stability are created. The findings show that the combination of derivatives from areas that have been mined and reclaimed works as a post-mining transformation for effective slope stability. Reclamation in areas with dense vegetation is successful, while mined-out lands with little recovery are still prone to slope instability. Extracting natural resources through mining activities provides raw materials, utilities, and services. The mining face at the beginning of mineral extraction changes open-pit sites into large holes, resulting in significant volume variations and influencing adjacent infrastructure. Mining can also greatly affect nearby ecosystems by causing permanent changes in land cover, land use, and ground conditions [2-19]. It is difficult to predict accurately the impacts of mining and land reclamation due to snowfall, vegetation cover, and seasonal water levels that affect slope stability. In addition, as an open-pit mineral deposit is extracted, the quality and quantity of geotechnical data often increase [20-27]. This has the potential to improve reliability and reduce uncertainty in input parameters. Environmental aspects play a major role in mining projects; ecological impacts from a project define how big the scope of an Environmental Impact Assessment (EIA) will be. Mine closure requires future development planning for the titanium mining area located within Kwale County [1-10].

3. MATERIALS AND METHODS

The location of the study is in the south coast parts of Kwale County in Kenya (Figure 2). It lies between the latitudes 4° 02' 07" and 4° 04' 45" South, and longitudes 39° 32' 09" and 39° 34' 51" East, covering an area of twenty thousand hectares. The study area is accessible via extensive network of paved roads as well as through an international airport which lies to the northern parts in Mombasa City with 14 kilometers from the study site. A larger portion of this land has been utilized for commercial mining activities (ilmenite, rutile, and zircon extraction). This study mainly examined the post-mining phase-outs such as inactive mined out zones, abandoned open pits, tailings storage facilities, landfills and returned topsoil.

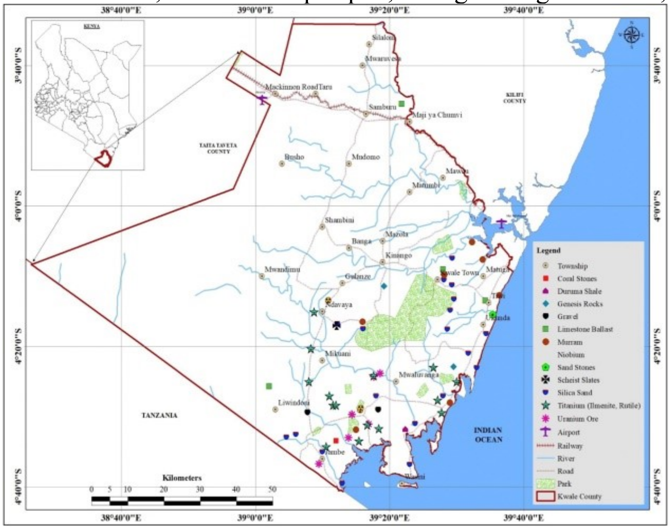

Fig. 2. Study area Map showing distribution of mineral resources in Kwale County, Mwakumanya and Mwachupa [64]

Data acquisition is an important part of research. This study has used primary and secondary data. The primary data were collected through different means, such as a camera attached to a drone for aerial landscape imaging, survey levels, GPS, Auto-Level, and cameras for measuring tree stems. An Unmanned Aerial Vehicle (UAV) took the drone images/videos over the mining site. The photogrammetry processing results in 3D digital surface models and orthomosaics of the area. A Normalised Digital Surface Model (nDSM) was derived from the Digital Terrain Model (DTM) by subtracting it from the Digital Surface Model (DSM) to analyze changes in landforms. The drone and satellite images supplement each other by providing information at both local and landscape levels about post-mining change as well as slope stability [38-40]. Secondary data comprised topographic, satellite, geological, and soil maps. These data were very useful for analyzing and modeling impacts related to post-mining transformation on slope stability toward sustainability in the study area [23-34].

The post-mining investigations were carried out within a 2 km by 2 km section of the study area. Six maps were created using software, including the original pre-mining map showing the area's initial features before mining activities, secondary features such as the Tailings Storage Facility, mined-out areas which are open pits where excavation created land depressions, returned topsoils that were dumped after mineral separation, and the new road networks. Slope stability was assessed based on the angle of the transformed slope relative to standard slope stability criteria. The slope angle map was generated using the Slide 2 software for analyzing Digital Elevation Model data. The slope angles were categorized into low- and high-slope regions, representing gentle and steep slopes, respectively. Low-slope regions with angles less than 30° indicate stable slopes, which is the standard threshold for slope stability.

The size and location of these slope categories were determined through shape analysis. The slope angle data served as essential evidence for analyzing and modeling slope stability. Land use and land cover, along with vegetation cover density, were estimated and classified using the Normalized Difference Vegetation Index and supervised classification techniques. The impact of mining on vegetation cover density was assessed by comparing vegetation cover before mining and 10 years afterward. The vegetation coverage and density maps were also used to evaluate the feasibility of re-vegetation and area rehabilitation.

4. RESULTS

Transformations caused by the shutdown of mining operations change slope characteristics, and many quarries, tailing dams, or mined areas worldwide that are no longer active require their former stability conditions and hazards to be analyzed. Two primary mine tailing dams were breached in the USA, one for taconite and the other for copper/molybdenum operations. Most slopes within the multi-year-operated dark-grey dolomite quarry's mined areas are steep and consist of broken rock. Artificially cut slopes and extremely deep open pits in the most frequently mined rocks are further excavated, becoming progressively deeper and situated close to the excavation walls. Quarries with soil-slope facades built for the potash industry experienced significant lateral earth pressure, leading to failures near mining sites. Safety assessment of slopes usually involves the limiting equilibrium method to calculate the safety factor, which is the ratio of resistance to sliding forces. One method in mining is to determine stability safety factors, assuming the ground supports the excavation and that ground parameters, including rock permeability and porosity, remain constant. An overview of methods used to assess slope stability and safety has been provided for the quarry [42-45].

The safety assessment methodology for slope stability in iron ore quarry pits involved developing multi-criteria lumped-parameter models for the formation, growth, and condition of cut slopes, as well as identifying hazards based on past topple and wedge failures. Construction activities and vehicle traffic on the low-height slopes are negatively impacting their stability. Vehicle accidents could trigger slides, which can be catastrophic for hotels located at the toe of the pit slope. The safety analysis of the upper embankment slope of the metasedimentary mining road was performed using geotechnical software, and slope stability can be improved by managing groundwater. Building high earthfill embankment dams in mining areas requires careful consideration, as these structures can affect the stability of surrounding slopes. Factors contributing to slope failure are discussed within the context of open-cast mining operations involving thick sandstone. The geotechnical effects of open-cast mining on a thick coal seam near abandoned tranches are assessed, revealing ground rupture and a retrogressive failure extending into an un-mined area [46-51], as illustrated in (Figure 3).

Fig. 3. Depiction of an open-pit quarry with an excavator, detailed rock faces, and water accumulation, adopted from the et al. [12]

The mining area morphology in the tropical regions, keeps changing from deep mining pits to low or flat sloped surfaces during/and or after rehabilitation processes. After the determination of the excavation limits at the end of mining, the rearrangement of the affected zone, construction of the landfills and the levelling of the surfaces are designed and done according to a specific rehabilitation plan and frameworks. The abandoned mining sites on the earth's surface have high pit walls that raise slope stability questions.

Globally, the main focus of engineering is on stability of rock slopes in various mine surfaces to provide solutions to solve problems based on different perspectives. Natural conditions and/or anthropogenic activities trigger and accelerate the occurrence of pit wall causing loss of lives and as well as economic losses. The high pit wall slope stability of the titanium mine was evaluated as part of identifying a future reservoir site, using a hierarchical assessment system. The average annual probability of a landslide was estimated at 0.02. Following this, planning intervals, critical slopes for management, and rainfall thresholds for warning systems were established. Slope failure occurred in 6% of scenarios, resulting in estimated losses of USD 3.9 billion [41].

To ensure the safety, sustainable construction and operations of mining activities and civil engineering projects, the assessment of slope stability of the rocks is imperative. Rock slope failure risks human safety and disruption regional infrastructure. In this study, the 1D spatial velocity and turbidity fields were combined nonlinearly to examine rock slope stability. A comparison of various slope stability assessment methods based on different modeling principles was provided [2-33]. The results showed that when different failure mechanisms occur, the critical root of the oblivion function characterizing slope stability varies. Meanwhile, the ratio-to-ratio volumetric motion remains quite similar. The application to the Baihetan dam slope demonstrated that during critical rainfall events, the slope safety factor can be dynamically evaluated using real-time monitoring data. The approach developed can be applied to various scenarios.

4.1 Post-mining Sustainable Transformations

One of the post-mining transformations in the Base titanium mine area, including the Kenyan Mining Business License (KUP), was the construction of ponds and dredging onshore pits and areas previously deemed part of the post-mining environment to serve public facilities. The reduction in construction costs is also very significant, about 40%, or around IDR 450 million. Whether it's a pond or one formed through mining, the process of water filtration must be taken into account. Water filtration, for example, not only detects oil or potentially toxic chemicals but also identifies algae, which can affect water color and overall aesthetics. To some extent, modifying the design of dredging pits is not very difficult, even on a large scale. The submerged dredging ponds, for instance, have a slope of about 1:5 and cover approximately 8,000 square meters, indicating that landslides can occur whenever it rains. This means investing in a machine capable of rebuilding the banks of these large ponds is necessary before converting them into water filtering areas [56-60] (Figure 4).

Fig. 4. Comparative Diptych of Natural Vegetation and Post-Extraction Quarry Landscape, Amirshenava and Osanloo [24]

Increasing the semi-permanent structure becomes even more challenging because it must cover the sedimentation pond, which was designed to last around two to four years in a circular model. Using this design is only practical, and when it is applied to filter raw water in a demolition pond designed to hold a 20-year-deposited slurry from water marshes and sediments, it should be noted that a cover structure should also be built. Stabilizing it, it should also be indicated whether pond 3 is adjacent to pond 2 to adjust both the existing design and the height of the water filtration mechanism. The most significant challenge is designing both education facilities for dune sand mining and wetland ecosystem restoration, which is relatively complicated since it involves many stakeholders from individual scope institutions to the government level and requires advocating for organizational and group efforts, which could take years after the approval of the studies and designs. They all depend heavily on funding, responsible organizations, and related governance [61].

This section will evaluate the effects of post-mining changes on slope stability. Mining is a dynamic activity that involves many interconnected actions. Coordination of mining operations argument short term productivity. But the processes of mining and post mining impacts are long lasting, and their consideration after decommissioning is imperative. The artisanal activities of mining cause significant environmental impacts that require spatial planning to manage setbacks on mining lands. These measures are taken in response to changes in the mining area. The transformation process must comply with the applicable rules and regulations to ensure that all parties benefit. During the initial permitting phase, the applicant must prepare a comprehensive set of plans describing how several aspects of mining will be managed; this includes Environmental Impact Assessment (EIA), Feasibility Study (FS), Mine Closure and Reclamation Plan (MCRP), among other plans.

All of these documents address impacts, including post-mining impacts, although to varying extents. The EIA is a legal requirement in most countries, as mandated by mining statutes. Environmental Impact Assessments (EIAs) provide prospective analyses of environmental impacts and are designed to inform decision-making related to proposed actions. Since it must be completed before operations begin, the prospectus must suggest practical solutions to mitigate the impacts identified and quantified throughout the mine's life. The MCRP describes the condition technology and other tools that may be put in place after closure to minimize visual impacts on the surrounding area; this document is primarily oriented towards compliance, but must also address closure costs. The FS relates to the site-specific assessment of the risks involved in mining without a systematic approach, from which closing conditions and fees may be derived, and takes the most fantastic time [55-63].

When evaluated at the same stage, the results of these documents can be compared. The compliance audit, being a very important retrospective record, describes the assessment of compliance efforts concerning closure of the operation against regulatory and policy requirements, as well as against obligations in the plans. One factor has been increasingly recognized as being valuable in mining. Knowledge and expertise transfer have been largely neglected in the mining sector, which is a critical consequence of this abundance. On the other hand, the usefulness of this excess information can be easily overstated. Even with very substantial knowledge, an acceptable solution is rarely proposed because transferred methods or information do not fit properly to the problem at hand or are not understandable for local stakeholders.

4.2 Sustainable Processes and Practices

A great deal of work remains to be done to optimize sustainable practices through the strengthening of legal and regulatory frameworks, improvement in methods for predicting downside risk, and capacity for implementation. Recommendations from the study include creating compensation mechanisms for communities most impacted by mining and fostering integrated planning between mining waste, settlement patterns, and infrastructure. It is further recommended that communities come together to embrace a more comprehensive landscape approach to post-mining planning that would dovetail with ongoing initiatives aimed at improving the mining industry. A more cohesive approach to policymaking that considers cumulative impacts would also be advantageous.

The existing literature on mining does not offer funding mechanisms for implementing eco-friendly land restoration methods in the region. The government must create a fund or similar venture capital mechanism to support financial execution of potential eco-restoration projects or enhance existing funding sources. Investments in eco-friendly restoration should be taken with caution. Risk assessment, land use suitability evaluation, and expected outcome analysis should adopt probabilistic methods. The emphasis should not only be on land restoration activities; rather, officials should strive to include vegetation design options that provide higher economic and social benefits. Because there are considerable uncertainties regarding natural recovery of mined landscapes, priority should be given to intervention measures for vegetated mined lands where undisturbed vegetation is relatively accessible post-mining. Mid-potential mining companies should form consortia to pool resources for larger interventions, with an emphasis on financial prudence prioritizing cost-effective, efficiency-enhancing measures over symbolic or superficial actions using a cost-potential evaluation and zoning scheme to prevent inadequate management and intervention.

Finally, to extend this study’s findings beyond the case of Base Titanium, communities in various outsourcing nations and sectors should participate in meaningful stakeholder engagement on the post-industrial use of commercial plots and spaces for sustainable vein recovery, providing both direct and indirect benefits [43,63].

To promote sustainability and ecotourism in post-mining land use, revegetation activities must be implemented appropriately and constructed. Other necessary activities include mine closure and reclamation from the mining sector, blasting, fertilizer use, and storage of materials in line with the EIA plan, to provide recommendations for independent committees and to inspect the newly built structures. Post-mining activities can also include ecotourism, aquaculture, agriculture, and post-mining construction, including buildings and recreational facilities. Areas within the border that could be developed for eco-tourism include hills, exotic trees, locations resembling safari destinations, and hiking and ziplining trails. Eco-tourism, which often offers a return on investment, is typically marketed at high rates and in local environmental settings [39].

Waste utilization must consider environmental impacts at the new source site and the planned activities there to prevent waste. Clear communication and proactive steps should be taken to review policies thoroughly and involve the community for insights. Waste land use or the use of waste for road construction and tourism development must follow proper procedures. When funding is needed, research on site utilization and budgeting that maximizes returns should be done while protecting ecological or wetland conditions [63]. Naturally valuable areas should be reported and published regularly to keep the global community informed of developments. In addition to action plans, the government should put in place legal frameworks for waste land use, including eco-tourism and tourism land use in general, to give effect to the recommendations.

Mining industry is the major driver of growth and contributes significantly to Zambia's and Kenya's GDPs. Consequently, the extension of the mines' life is imperative, since they are essential for supporting economic growth and achievement of national development goals. This enhances reviews of the past and current approaches applied on waste management in the sector of minerals. This necessitates, the correction of past mistakes and safeguard future practices. Globally, the mineral industries are facing intensive scrutiny on the design of waste or tailings storage facilities, waste management practices, and environmental stewardship due to increased regulation and community involvement inspired by past mining activities.

4.3 Slope Stability Analysis

Surveying and modeling the larger processes and future landforms that will result from the operation allow landform stability analysis to commence early in the project development cycle. Focusing on too much detail at the feasibility stage may be unproductive if a project does not proceed; however, having an overall picture of likely outcomes is important for obtaining approvals for mining projects. Similarly, deferring geotechnical input until final engineering design stages of new pits may preclude identifying an acceptable solution before the old pit closes and production is lost. Simple slope models of the final landform, based on existing data, can indicate possible stability hazards, critical haulage paths for land rehabilitation, and interactions between haul routes and interference pits even in advance of detailed geotechnical knowledge of the orebody [2-23] (Figure 5).

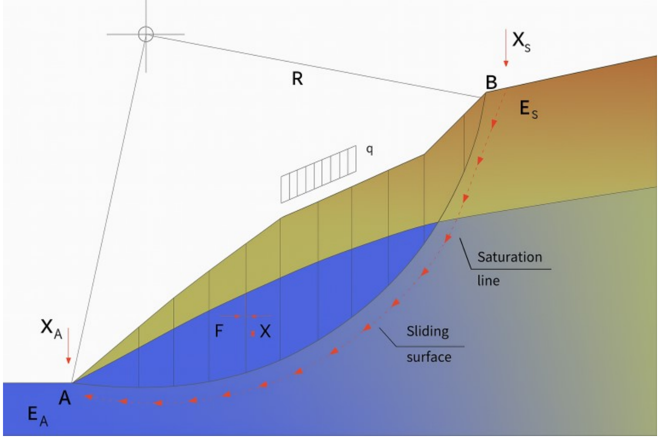

Fig. 5. Slope stability diagram illustrating the failure surface, saturation line, and force vectors in a 2D soil cross-section, Maulana et al. [3]

These are usually integrated into comprehensive models that assess slope and catchment stability, analyze debris flow risks and velocities, and evaluate treatment options and funding needs. Models should include sensitivity tests to account for inevitable variations in rainfall duration, frequency, and intensity throughout the mine's life. Measurement campaigns should start as soon as the first areas are disturbed to support model calibration, with continuous monitoring providing early alerts for slope stability issues or new active processes [41]. Additionally, capabilities for both forward predictive modeling to anticipate future behavior and risks, and backward modeling to identify trends and define process boundaries, are essential. The length of time a slope remains undisturbed after mining influences its final landforms and settling processes. Sensitivity analysis helps evaluate how changes in rainfall intensity, duration, volume, frequency, distribution, and storm conditions impact stability. Post-mining landforms, typically characterized by gentle, continuous slopes, usually have a lower failure risk. The potential for slope failure after mining depends on past performance and on how well-chosen treatment options stabilize slopes over the medium- to long-term. Triggering mechanisms standard in operational failure analysis, such as toe support stripping, storm events, and mining disturbances, do not apply here. Hence, the approach to stability analysis must differ significantly and be based on an understanding of the processes that affect post-mining stability.

The determination of slope stability is crucial in any mining operations since it affects the productivity duration and safety in the mining sloppy area. The direct significant factors influencing slope stability (height and steepness), include the gradient of a slope and the height of a step. The increase in the height of a guidance slope, affects it stability due to the magnitude of complex forces from raised geological inhomogeneity levels, the gradient of mass, and the saturation levels which weakens cohesive and adhesive bonds. Evaluating slope stability, particularly during aerial surveys, is a primary focus of mine control research [22-33]. To address this, five types of rock mass slope stability evaluation methods are introduced. A four-level evaluation index system is developed, with each index's weight assigned through a fuzzy analytic hierarchy process. Additionally, a back-propagation neural network model is used to assess slope stability and generate results, including the slope stability index (SSH), influence range (ER), and recommended measures. Application results show that this approach is practical and reliable [34,41]. For existing projects, feasibility verification enhances understanding and provides a basis for engineering measures. In practical applications, developing an expert system and establishing a geo-information system platform with remote sensing and multi-source data fusion technology are key to automating slope stability assessments. Earthquakes, rainfall, and construction activities can induce tremors and unstable slopes, which can be mitigated by precautions such as implementing a safety warning index, semi-dynamic analysis comparing baseline values, monitoring the slice stability index, warning ratios, and using computerized control systems [34-62].

4.4 Hydrotechnical Modelling Techniques

Modern geotechnical modeling tools help mining engineers in slope design by lowering the risk of slope failure. High productivity and reduced operating costs are needed for engineered slopes. Therefore, understanding the characteristics along with domain-specific input parameters for numerical modeling is crucial to support short- to long-term stability assessments [60].

Geotechnical conditions are vital for the success of open-pit mines. Slope failures can lead to significant costs, including loss of life, equipment damage, and revenue loss [22-44]. Mining engineers have increasingly relied on computational geotechnical tools to evaluate slope stability. These tools can model and assess existing slopes, examining their stability in relation to local recession mechanisms (Figure 6).

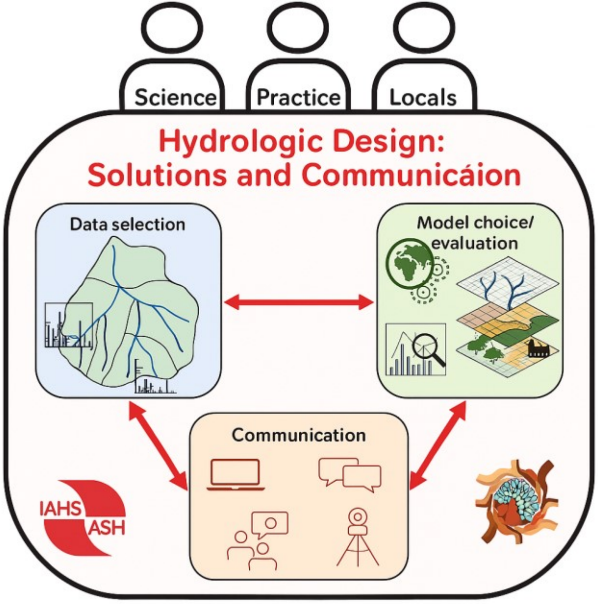

Fig. 6. Hydrologic Design: Solutions and Communication Framework, Louloudis, et al. [17]

Slope stability analysis was conducted in a wide variety of geotechnical engineering applications, including assessing the overall stability of notched walls on slopes or over potentially unstable soils, and of homes situated on slopes or over potentially unstable soils, among others. Mining procedures entail significant risk at each working stage, and slope stability is an integral part of inadequacy pits or opencast mines, as the entire working process depends on it. Strip mining is a surface mining process used to extract mineral layers when they lie at shallow depths. This methodology involves removing large amounts of earth and minerals by stripping hundreds of hectares of surface area, with the soil-to-earth ratio ranging from 1:1 to 5:1, depending on the type of country and the mineral-bearing material being stripped. The shelving provided for the slides to prevent setbacks, the exposure of high walls to erosion and natural weathering, the exposure of the mined topsoil to rain and wind erosion, the degradation of the quarried surface and disturbed area caused by erosion, and the management of runoff water are considered complex topics. They are also identified as critical factors affecting the surface operations of mining areas in feasibility studies [55,63].

The conditions of mining involve significant risks at each manipulation stages, slope stability system of the overall pit or open-cast mines safety is a crucial part. This entire process depends on the maintainable stable slope's modifications. Shallowly underlying layers are extracted using strip mining technique. This method involves the usage of machineries across extensive surface areas to remove soil and minerals in large quantities, with a typical ratio range of soil-to-mineral from 1:1 to 5:1, depending on the terrain and mineral deposits being excavated. The operational aspects of open-pit mining projects are influenced by slope stability and angle. Steep-slope systems with a factor of safety of 1.3 or less are potentially unsafe. An effort was made to evaluate the overall slope stability of the Base titanium and limestone deposit in Kwale County, including the development of a numerical stability matrix to guide further evaluation. The limited equilibrium method, which considers a sequence of slope conditions, was initially used to determine the stable geological and mining conditions of the slope [23-33].

4.5 Soil and Groundwater Dynamics

In coal-mining regions, soil permeability decreases due to overburden dumps and muck piles. Due to excavation, the soil surface becomes rough with rocks and vegetation dieback. Day-to-day, mining activity is carried out using giant machines, such as loaders, dumpers, and dozers, which can affect the environment. The dumping and re-handling of mar and mined-out overburden causes high energy dissipation. Backfilling partially mined areas with M-sand in the entry area is a green revolution [50]. The soil mining process, carried out by heavy machinery, disrupts soil structure, resulting in variations in the soil density column (3.1, 4.2, 5.5, and 5.9 from top to bottom) of the soil type. Other soil properties required for soil health are difficult to restore in mined areas. Restoration of plant species diversity in coal mining regions depends on the availability of soil nutrients. A steady increase in SDI and CSSD values indicates an improvement in vegetation cover and, subsequently, in soil nutrient restoration within 6 years of reclamation.

After mining activities stop for a period, slopes of all sizes become vulnerable to erosion, plastic deformation, and mass movement due to prolonged exposure to rainfall and stresses from temperature fluctuations. This weathering process initially overcomes isolation and detachment mechanisms, leading to slope failure. Trafficability and stability cannot be fully predicted or universally addressed solely based on the physicochemical or geological properties of the materials. New metrics are needed to evaluate the fabric of both weathered and non-weathered slopes. This study introduces a new geometric metric to assess the trafficability and, ultimately, the stability of weathered slopes at scales ranging from 100 nm to 100 m. The metric measures how much the slope materials deviate from the ideal of complete vegetation cover. Therefore, trafficability, represented as a Gaussian distribution in the 2D principal plane, is seen as a probability density function of the profile angle. The model is used to examine how ex-pit fining, along with post-mining ecological reconstruction, affects the stability of a newly excavated, improved slope [1-23]. It shows that there is a size-specific stable weathering timescale threshold, below which weathering processes dominate over other mechanisms, not only improving slope stability but also creating porous media suitable for afforestation, landscaping, and surface water storage.

The study of how slope transformations and dimensions influence slope stability is still in its early stages in the mining context [1-19]. Although facades, excavations, and transformations mainly consist of similar materials, research has shown that even slight differences in grain size can cause significant variations in soil forces. Earlier studies of sudden flood regions examined newly exposed hollows or slopes, while this study further emphasizes, investigates, and extends previous findings. Using accurate, thrift-transformed 3D terrain data, additional analyses of mirroring, exhuming, and channeling are performed, alongside a comparison of various observation, transformation, and construction cases. New and improved methods for collecting and analyzing large-scale 3D point cloud data significantly enhance understanding of slope and transformation processes, as well as the detection and analysis of small initiation seams. Larger operational machinery will inevitably require larger-scale assessment methods: aerial terrain data, early slope initiation stages, and 3D self-programmed numerical runoff calculations are addressed in a follow-up paper. Each mined pit or excavation can develop a transformed mineralized or sedimentary façade nearby. Due to the eroded surface and newly exposed material, these façades may also serve as significant sources for reintroducing defects or affected particles into the hydrological cycle [76]. Hydrological research shows that material from this fresh ground almost always moves in and out of the soil system and travels independently within it. As a result, less stable earth slopes will return to their original states, similar to those before mining activities. During runoff, high or oversaturated stocks will wash away loose material, and increased levels of transparent water will carry dirt into basins, making it easier to detect and verify for further analysis [37-45].

4.6 Geohazards in Mining Areas

Geohazards are mainly linked to post-mining environments and occur because social and environmental processes haven't yet reached stability, as the crushed or exposed geological material which was once in equilibrium now experiences significant, and sometimes irreversible, changes. Most geohazards become visible after a specific period, and although a situation might stay stable for centuries, the original pre-mining state is usually not restored, or at least it no longer functions in the same way. In environmental assessments of mining activities, geohazards focus on understanding, evaluating, and managing post-mining ecological stability, and should be integrated within the broader field of geographical information systems [3]

Protecting the environment and planning urban settlements in post-mining areas is therefore a crucial issue, as not all geohazards are caused by mining-related developments. Most, if not all, mining activities ultimately impact the surrounding environment. As mineral resources grow scarcer, developing countries are increasingly targeted by mining companies from developed nations. Geohazards are not limited to mining; they also occur during road and dam construction and through natural geological processes. Therefore, settlement planning and related research should include geohazard studies to promote sustainability [23].

This article presents geohazards related to post-mining environments and discusses landforms and land-use planning in a post-mining area of a developing country, South Africa. The paper also demonstrates how the mining sector can be cornered by both authorities and the public, thus leading to harmful actions motivated by reckless cost-cutting. Globally, mining industry is imperative in many regions; but it significantly affects the environment and communities. The environmental effects of mining activities are noticeable only after a long time since the surrounding areas of mined sides are influenced by geohazards [11]. The processes of extraction produce some undesirable by-products that are evident when most valuable components have been extracted from the resource. Waste mines emit dusts that deteriorate the quality of air in the adjacent urban areas. Acid mine and drainage into groundwater sources is pollution problem in mining areas with leads in most gold mines. This endangers the entire populations' access to potable water quality. Until recently, very few countries had laws regarding mining and reclamation activities; currently, there are believed to be more than 1 million abandoned mines across the globe ranging from good to bad conditions [2, 6, 7].

Geohazards are mainly associated with post-mining environments, where expert knowledge from various geological fields is crucial for investigating and assessing risks. Since mining activities inevitably damage ecosystems, restoring the environment and planning urban development in post-mining areas have become essential yet underexplored research topics. Unfortunately, information on the geo-environmental impacts of post-mining areas including runoff and erosion, leachate management, economic geo-environmental assessment, groundwater contamination, and air pollution is limited and often hard to access within a reasonable timeframe [45-63].

A geohazard occurs if and when and where the following two characteristics are fulfilled: (a) a natural or reconstructed, present or former, artificial environment fulfills the necessary and sufficient conditions for an observable geoprocess, which (b) has negative consequences in terms of economic value, social status, health, or safety. Examples of geohazards with mostly adverse impacts on urban development's following mining are evident in the Witbank coalfield of South Africa. Data are provided on mining practices that have raised concerns in the urban environment regarding dust and subsidence.

4.7 Geoenvironmental Characterization

Mine Geo-environmental Characterization is a component of Environmental Assessments conducted within the framework of NEMA. It relates to the soil, water, and air components characterized by geochemistry, biota, and geophysical methods. The mine geo-environment is continuously integrated into EAs through mining companies, regulators, and stakeholders. This approach will be compared with that of a South African global mining company operating a mine for 30 years to assess its effectiveness. A comprehensive framework for mine Geo-environmental Characterization is presented, covering elements such as Local Level and Problem Context, Impact Pathways, Indicators of Impact, Indicators of Stress, Modelling Framework, Reliability Assessment, Data Management, and Policy Development. Retrospective analysis reveals that sustainability at local mines existed until an unexpected event caused socio-political unrest. Stakeholder management and engagement in governance planning and monitoring are among the benefits and key findings deduced from this knowledge which has been applied to other sectors, industries as well as developing countries [17]. Blasting at MRC's Kwale site is done with ANFO explosives. Sulphide minerals like pyrite and arsenopyrite can generate acidic drainage while ilmenite-rutile-zircon-monazite-titanite are relatively inert; therefore, heap leaching will not be applicable due to their hydrophobic nature in Kwale. Fe oxides may weather and precipitate at mine sites and monitoring sites. Mining impacts on site characterization are assessed using the Monazite geochemistry method. Dyke within rutile, ilmenite, and zircon will affect the recovery of these minerals as well as 2% of the monazite resource which must be off-site processed. Different mineral associations plus thermophysical properties per deposit type require different mineral processing methods.

4.8 Assessing Surface and Groundwater Quality in the Catchment Area of River Mtowana Kwale County Kenya

The catchment area of River Mkurumudzi located in Kwale County Kenya has severe water quality problems attributed to artisanal mining activities. Gold panning together with illegal quarrying activities within this river highly influences its turbidity temperature pH conductivity total dissolved solids among others hence necessitating qualitative as well as quantitative assessment on an urgent basis for sustainability measures toward protection of water quality within the catchment. Documentation on current conditions of the river all contributing factors plus a clear connection between processed minerals and affected rivers is however required [12].

Water quality was sampled from surface and groundwater sources in the Mtowana catchment over a period of 3 months. The laboratory tests and field assessments were carried out using a UV-visible spectrophotometer. Turbidity at the sampling points varied between 1.305 NTU for groundwater to 204.3 NTU for river water, indicative of pollution from panning activities. Groundwater temperature ranged between 24 and 39.5°C, while river water temperature ranged from 24 to 31.5°C. pH ranged between 6.56 and 12.41, with river water having pH values at 9.56–12.41 which indicates basic water source quality. Conductivity varied between 170 µS/cm and 54,907 µS/cm indicating increasing salt levels; total dissolved solids varied from 0 mg/L to 41.122 mg/L with river water at348 mg/L exceeding safety limits; statistical analysis indicated strong relationships among parameters as expected for water analysis [2, 7, 8].

The significant environmental and ecological challenges posed by Artisanal mining include contaminations of water, degradation of land, disruption of ecosystems, biodiversity loss, and long-term geo health impacts. The artisanal mining activities also have the following major impediments; enforcement challenges, health and safety risks, and financial instability of small informal businesses that make up this sector. These problems are critical public concerns calling for an immediate assessment of surface water quality in artisanal panning activities.

4.9 Rehabilitation Strategies

Land rehabilitation is required for quarry sites after mining and the recovery of minerals from them. Mine reclamation covers a broad area involving restoring productivity, minimizing erosion as well as other environmental issues. It could involve re-establishing the soil or even replanting trees, shrubs or other forms of vegetation or redistributing natural soil materials before replanting takes place. The idea is to bring back the vegetation to its original state prior to mining [7,9]. Besides that, dam construction is also required in such places where there are chances of landslips post-mining activity; hence post-quarry mining interventions vary by degree towards addressing erosion and related matters amongst others effectively. Dam construction not only aids in vegetation restoration but also serves other functions such as being a water reservoir for crops and livestock within proximity. The lowest point on the area is about 20 meters below its original level due to high extraction mining from a ridge which stood at a height of about 210 meters above sea level."

Before 2016, post-mining land rehabilitation by mining companies in the case study area included planting trees, redistributing topsoil from previously cleared land, and dozing exposed quarry benches on sandy ground. After the formation of the BMHG, rehabilitation also involved the construction of dams. These dams were made from waste sand on the lower quarry bench and used to store water for crop irrigation, livestock watering, and other daily human needs. Methods of post-mining rehabilitation varied across companies, quarry sites, and mining stages. Currently, re-vegetation of these post-mining lands is progressing reasonably well. All quarry sites can support either tree stands or bush cover across the entire area.

Regarding landscape stability, the results confirmed that post-mining interventions help reduce erosion by covering the most vulnerable areas beforehand. Unsurprisingly, the conditions without intervention showed the most significant change in landscape stability. The plants established through post-mining interventions significantly improved landscape stability. However, at old quarry sites outside the new BMHG jurisdiction, whether by burying all breaches or simply leaving them, a sizable part of the area remains more unstable, even nearly 10 years after mining and interventions ended. The work of the BMHG significantly changed the terrain and increased landscape stability at both the dam site and its surroundings, where previously only bare sand or quicksand existed.

The growing environmental impacts of mining activities, combined with other human-driven factors, have increased societal concerns about the need for sustainable practices [7,9]. Africa's mining sector is being encouraged by civil society, regulatory agencies, and social networks to adopt sustainability principles that include adequate environmental and socio-economic mitigation measures. Various post-mining land uses or transformations are carried out in both developed and developing countries, such as creating wildlife reserves to lessen adverse ecological and socio-economic effects. Unfortunately, information on the long-term impact of these transformations on slope stability and environmental and socio-economic sustainability remains limited. Effective management of natural resources is essential for economic growth in African nations; however, concerns about the sustainability of mining development persist.

Kenya is one of Africa's developing nations with abundant mineral resources. Turbidite-hosted mineral sands along the coast of Kwale County were mapped under exclusive prospecting licenses in the mid-1990s. Mineral Sands Resources Ltd applied for the mine and later granted it to Tiomin Resources, which eventually became Iluka Resources through corporate consolidation. An Environmental and Social Impact Assessment (ESIA) was carried out, and a mining license was issued in 2005, establishing Kenya's first large-scale commercial mining (LSM) project. A complaint by Kwale residents and environmental activists about sand tailings spilling into the Indian Ocean prompted the International Finance Corporation to review the concerns and the involved parties. The area of interest underwent ESIA studies before, during, and after mining activities. Efforts to conduct semi-structured interviews with retired mine employees and regulators received few responses, and older personnel who could have provided valuable insights were not engaged. Estimates of sediment budget stabilization, based on exponential modeling of observed erosion rates whose linear component was observed after mining ceased were proposed as an alternative primary focus of study.

4.10 Impact Assessment

Concerning landform stability in the Kwale area, soil development is advanced due to the weathered basement rocks below. This results in a thick mature soil mantle at some places. The weathering residue gives rise to a surface characterized by widespread gravels and a well-developed lateritic profile in the highland areas and deep red clay formations in flat low-lying areas. Trenching and boring operations for base titanium mineral have revealed that mining is possible since this mineral occurs below the weathering zone. Extensive reworking of the soil profile has taken place, leaving thin remnants behind. The ban on sand mining along major river systems and beaches results from its negative impacts on coastal life which includes plant, fish, and animal life. In Kwale County surface mining, motivated by either economic considerations or company interests, is currently being carried out for base titanium mineral [11-17], leading to increased unemployment among artisanal gem miners who now have no place to dig their stones.

The artisanal mining activities in Kwale County have degraded land [13] through soil erosion, river sedimentation, and ecosystems destruction. Fresh water resources are impacted by artisanal mining activities. This affects aquifer recharge, agriculture, fisheries as well as biodiversity. Dust pollution from ephemeral sand floodplains of rivers brings about health problems in the form of respiratory diseases. Displacement of artisanal small-scale miners drives others into illegal gem mining which may endanger the lives of residents. Environmental degradation threatens rare or endangered species. Complaints against surface mining companies regarding post-mining reclamation and restoration obligations with respect to reshaping, re-vegetation, surface drainage, waste disposal noise, and air pollution should be directed at the government's environmental watchdog.

The mainland tourism sector is viewed as a major contributor to future economic growth but there are fears that the visual landscape will be impaired by mining activities particularly quarry earthworks on the escarpment slopes above the tourism area. An assessment of impacts of rock extraction on efficiency, safety, and visual aspects led to a comparison between design principles for Olivera Quarry and those applied previously in design and management practices for Kalulushi Red Quarry operated by Geo-Research Corporation. That quarry yielded less material but functioned more safely with fewer adverse impacts on its neighborhood's visual environment [11]. It would also probably have been less expensive than today's bigger more recently opened quarry.

Three human and technical networks are considered: the quarry earthwork scheme, quarry slope management and operations, and handling of quarrying materials and equipment. These networks will use a socioeconomic decision tree plus some economic criteria to get the desired outcome. This tree structure requires assessing safety over the entire performance life of civil and engineering works and optimizing dirt movement costs for the entire cycle within the quarry including operating life costs. The criteria seem mathematically well defined for tourism development on the escarpments around Kalulushi tourist strip [1-12]. A checklist for aesthetic screening of future quarry designs would make this presentation more useful.

Two main human/water systems are considered: the town's water supply system and the water-holding capacity of the slopes forming its escarpment. On these slopes, water falling affects supply, demand, and quality in town. Future impacts from these factors are assessed plus a review of measures to restore mound integrity since 1990. More development on the groundwater model would help improve accuracy and usefulness.

4.11 Monitoring and Evaluation

The mines and quarries monitoring program will be used by the Ministry of Mining and the Mining and Quarrying Regulatory Authority in assessing how well this sector is performing to ensure that it meets environmental standards as well as safety requirements. Ecological monitoring of background levels in soil and water resources around the site will be part, as well as ambient air quality monitoring.

This approach to developing a monitoring program will be consultative so that it can better understand what those expectations are from The Ministry of Mining, The Regulatory Authority, industry, and stakeholders; existing resources/capacity will also be reviewed including data availability for conditions set out in an initial minerals sector assessment report. This information is then used to produce a preliminary outline of a monitoring program which is discussed at a workshop with relevant stakeholders. The overall objectives will be broken down into specific indicators which could then translate into data/information/analysis needs as well as addressing capacity considerations for implementation. The final design based on this consultative process shall take place together with detailed implementation planning whereby some initial assessments can already start using existing monitoring capacities before completion of detailed design study regarding the monitoring program.

The capacity for public monitoring within knowledge management units in semi-public contexts will be enhanced as a priority. Monitoring and communication tools will be supported as responses to governance democratization, social acceptance, and political accountability through public scrutiny of secondary information, peer-reviewed expert analyses, and stakeholder dialogues. The final assessment is part of the capacity building and knowledge development for this function. These assessments will use the same criteria as the monitoring.

Local authorities, such as the Kwale County government and NEMA, must actively participate in developing Monitoring and Evaluation programs before issuing beach mining permits. This need has arisen due to advances in knowledge, methods, technology, threats, and human organization. The challenge of preventing major disasters in Kenyan mining areas by 2020 requires an anticipatory approach, similar to the precautionary one, to tackle environmental deterioration caused by bush encroachment and ongoing soil loss through gully formation, stream bank erosion, and other forms of erosion [8]. Descriptions of the required methods with ongoing adjustments, backup of analyses with data and information retrieval, comparison with standards, making results transparent, accessible, and communicable, and indicating responsibility are prerequisites for success. These success prerequisites are conceptualized in monitoring, in its integrated forms of assessment and follow-up, in the recommended and expected ways for one's ongoing human activity. Evaluation questions regarding the design of both monitoring and evaluation, in these discussions' terms, are assessable: primarily about how well the Monitoring and Evaluation systems are functioning and performing, answering questions about the systems themselves.

The potential disastrous consequences of mining activities and the more significant, but possibly less immediate, future problems compared to the larger disturbances caused by mining must be considered, mainly because of their indirect, less visible, and time-delayed nature. An inherent uncertainty hinders definitive decision-making. Both distant and local stakeholders choose to keep uncertainties somewhat in the background, depending on their stakes, attitudes toward risk, approaches to prevention and remediation, and knowledge of disturbances and events, as well as their involvement and influence.

5. DISCUSSION

It is estimated that 50% of Kenyans rely on agriculture for their livelihood. This sector contributes over 30% of the national GDP and employs more than 80% of the rural population. The Ministry of Agriculture has therefore taken steps to address ongoing environmental degradation. A sub-sector policy document has been developed to help mitigate the adverse effects of agricultural production. Agriculture and the environment can complement each other. Without a healthy environment and resource base, agriculture cannot thrive. To improve food security, agricultural output must increase. However, increasing agricultural production without accounting for potential environmental degradation from farming practices can lead to national insecurity. The ecological impacts of farming activities can be grouped into four main themes: land degradation, water resource degradation, atmospheric degradation, and effects on biota, including biodiversity loss.

Generally, crop farming and livestock keeping practices continue to impact the environment. Deforestation, soil degradation, air and water pollution, loss of biodiversity, solid waste pollution, and other issues are common environmental threats caused by crop and livestock activities. The ecological effects of irrigation-based farming systems have been documented in previous studies, including waterlogged and salinized farmland, river diversion and downstream usage, soil salinization, environmental alteration, silted lakes, and poorly managed farm drainage. However, a comprehensive assessment of the ecological impacts of agricultural practices in rural Kenya has rarely been addressed. Therefore, information on ongoing environmental changes is essential for developing effective measures to mitigate or reverse these negative impacts.

Disasters of slope instability in developing countries are a result of both natural and anthropogenic factors. Most studies focus on the anthropogenic wastes that contribute to slope instability. These can be easily ignored or entwined with local wisdom and global knowledge, such as land clearing for agriculture, slash-and-burn, informal settlement in marginal lands, unregulated quarrying and mining, and agriculture methods that create gullying. Or they may be directly related to some financial issues like uncontrolled urban planning and extraction of resources. Local wisdom is important for conservation in countries with food insecurity. Economic and policy issues related to disasters of slope are important for public policy reform and international funding. The effect of new or disturbed slopes on households living in rural mountainous areas is a significant factor in development because this area has disaster due to slope instability [2].

Post-mining rehabilitation refers to transforming mined land into sustainable systems by reinstating the range of sustainable practices that existed prior to mining. The stability of slopes may change from stable to questionable during mining operations. According to the data collected, large slopes after mining are rehabilitated at an energy-efficient angle of 4°. With the establishment of shrub vegetation, this angle decreases further down to 3° or less which is considered temporarily stable (arma=2° limit). Mining has generally changed the way in which vegetation grows and how it is established. Previously involved practices included making tailings dams as dykes or dumps over 10 m high. The current practice involves making and operating a tailings dam directly at heights between 3-5 m with more sustainable catchment management support. Existing practices that were successfully restored include waste removal, slope stabilization, and sustainable vegetation growth. Results showed several extremes in slope stability resulting from post-mining attempts to restore sustainable practices [2, 12]. These results help provide information on the condition of slope stability, changes in slope stability due to mining, and the restoration of sustainable practice afterward. Adaptive management research methods that combine spatial measurements of slope configurations especially at extremes with weather erosion monitoring and vegetation assessment are recommended further study on computational calculations of slope stability based on extreme configurations and established sustainable practices [11-34].

5.1 Comparative Analysis with Other Mining Regions

Post-mining transformation has been reported at various locations worldwide as incorporating social, cultural, institutional, and technical aspects in different sectors, with particular attention to the communities impacted or influenced by mining activities [63]. Visible changes due to mining are a major component of post-mining transformation and may be differentiated from other intangible changes. At Awaya and Muthiru sites within Meru Central District, the post-mining landscape has shifted from a hilly terrain characterized by sinkholes to gently sloping grounds while views of dams have been converted into agricultural fields after aggregate mining. Several purposely kept barren post-mining pit sites-with or without vegetation-at Lorian Falls & Quarry, Kenyasi serve as potential replanting sites. Similarly, post-mining transformation and degradation at the base of titanium mines in Kwale Colony, Kenya include the lowering of topographical peaks.

Apart from these, less destructive methods of mining like those practiced in earthen sand mines have been reported to create little or no noticeable post-mining changes that directly contribute to downstream swampy lowlands. Also, the transformation of quarry holes found in road-on-slope quarry mines was regarded as an impact of land degradation. Other quarry mines located within Meru Central District created pit sinkholes after mining which were later repurposed for agricultural use. Some transformed quarry pit sites were simultaneously mined and reclaimed. The quarry pit sites that had some patches of vegetation were minimally affected by the post-mining transformation process.

Post-mining transformations increase, such as accelerating slope instability and other anthropogenic alterations of the mining landscape. A significant portion of the area is characterized by earth-worked-out pits where backfilling and rehabilitation works are either incomplete or in progress. Possibly the most critical post-mining transformation is the absence of natural environmental rehabilitation practices or at least efforts to protect natural infrastructure such as slopes and rivers. This ongoing earth movement is exacerbated and intensified by increased rainfall and wet conditions that offset dry weather preceding the onset of a more humid climate. These areas become destabilized, continuously affecting overall slope stability as well as mining sites. The area at Km 4 is severely impacted; however, effects are also seen outside the mining area with increasing severity over time, just like what is happening now. This study was mainly based on field surveys that included GPS and drone surveys combined with remote sensing to produce accurate elevation data and assess post-mining changes in the area. Changes in flash floods, stability problems on slopes, and carried sediment loads were analyzed. All information indicates an urgent need for further reconstruction measures; post-mining areas (KM4) need additional stabilization and rehabilitation to ensure overall slope stability as well as sustainability for mining activities. Drastic action is required to ensure long-term sustainability in this area. Further stabilization of mudflows, maintaining vegetation on slopes, planting vegetation, building walls at the toe of slopes, tilting slopes so that erosive energy will be reduced - these are some proposed solutions. Such earthworks should go hand-in-hand with a strong program for vegetation establishment aimed at encouraging natural stability of all slopes involved plus retaining or absorbing sediment energy before it gets to receiving areas. Close cooperation and perspective modeling from both the mining area side plus local Natural Resource management are needed to realize these solutions. Further research covering all aspects about condition of slope should include monitoring cover by vegetation which must be part of long-term research plan [23-47, 62].

5.2 Challenges in Implementation

Despite legislative provisions and commitments by policymakers to effect sustainable practices in the mining sector, it has proved difficult to implement sustainability in the practical sense after mining operations [63]. Particularly in emerging economies where regulatory institutions and policies are still maturing, several loopholes continue to hinder sustainability efforts within the post-mining environment. This includes, among other things, unqualified personnel carrying out post-mining assessments due to lack of expertise; inadequate financial and technical resources for enforcement of regulations; corruption and exploitation; lack of transparency in license allocation; lobbying by big companies; lack of political will; and silence agreements [8]. Though these challenges of mining sustainability are very well known theoretically, there have been few empirical case studies on how governance as well as environmental and social practices actually play out in day-to-day operation within the sector's post-mining activities.

The impact of the biophysical legacy from recent and historic mining on shaping policy options and outcomes for sustainability management has also been largely overlooked. An appraisal of past and current post-mining policies and practices through the prism of biophysical functioning as well as mining legacies is largely missing in Kenya. Heavy mineral sand extraction for titanium started in 2004. This knowledge is critical to evidence-based advocacy and policy change toward sustainable results at both the local and global levels in this sector. To fill this gap, the study will assess post-mining governance policies, their implementation, and opportunities for adaptation during 15 years following mining activity within Base Titanium Mining area, Kwale County, Kenya.

Post-mining activities aim at reducing the adverse impacts of mining on natural resources such as land, air, and water. One challenge toward achieving sustainability in post-mining is the limited understanding by stakeholders of changes that occur during post-mining. Environmental assessments conducted on former mining sites reveal that changes brought about by mining are pervasive and may even deteriorate with time. The first mapping done for purposes of identifying areas for mining did not take into consideration peri-mining transformations. It is important to know these transformations for purposes of establishing regulations that will compel restoration of ecosystem functions as well as promote sustainable practices [4].

Mine surface and groundwater management frequently turns out to be problematic, usually involving effluent treatment and diversion measures rather than the more innovative approach of considering post-mining sustainable land use [63]. Groundwater conditions change after mining but do not necessarily revert to their pre-mining conditions. There is little modeling of post-mining transformation impacts since it has only been on surface sub-models related to future mining developments. Monitoring, modeling, and regulations should cover both surface and groundwater in an integrated way that considers both water and land aspects with agencies responsible for ensuring this as recommended by international best practices. Post-mining land uses can provide multiple benefits to communities; however, actual opportunities to develop such uses are very rarely pursued especially in difficult regions like Africa where mining companies hold a significant amount of the land in southern and eastern Africa. This is a problem for sustainable post-mining practices resulting in the loss of both financial and land opportunities. Other investments are often blocked by a lack of trust in government or dissatisfaction with mining companies' performances.

5.3 Best Practices for Sustainable Mining

This research studies how changes after mining affect slope stability and practices that support sustainability. The area being studied includes stages of life cycles, types of land use, and current socio-economic conditions. The changes that affect slope stability fall into three main categories: changes in land use, transport, and deposition of sediments as well as surface roughness changes. The effect of post-mining activities on sustainable practices like erosion control, water flow changes, and vegetation monitoring is also described here. The results are based on a conceptual framework adjusted through remote sensing and GIS techniques along with freely available datasets [61].

The geological setting gives an overview and general description of the study area. It discusses geology and land cover with changes in land cover after mining activities. Determination of land cover is based on Global Forest Change dataset. The expansion of cut-off for mining operation and that for land cover comes from SRTM as well as LANDSAT 8 data. Exposed slope residual strength plus effective internal angles are explained by a database consisting of 120 slopes; current stabilization for the slope is attained from recently aerial mapped information based on remote sensing data while status regarding structures meant for slope stabilization is reported herein. Most geology dates back to Pleistocene age whereby units belonging to limestone manifest themselves in forms of sedimentary rocks; southern location indicates beach-like topography while southwestern positioning suggests hill-like relief [63].

After mining, it is important to manage the area and stop further degradation of the environment. Usually, a mine closure plan will contain post-mining activities [6]. These activities typically include closing the pit and the tailings facility, recontouring the residual mined area, and planting native grass and trees. The company will monitor the success of post-mining transformation efforts; however, additional actions may be required by the company or the authorities. A major waste event occurred on July 17, 2014 in the downgradient area of base titanium operations. Site expert engineers reviewed the site and made recommendations including installing a top-down locking mechanism at the entrance to the pit, sealing previously opened buttress drains with high-capacity dozers, and building mounds to serve as vertical barriers at points of groundwater exit. Maintenance of cut-off drains and other drainage systems is still necessary. Even though several stabilization measures have been put in place, further collapses on the left side of the pit are possible.

Just like Bt, deeds are required for both incremental and instantaneous failures. Spillways will be built to cater for large instantaneous failures. It will also be necessary to construct deposition basins so as not to allow total failure of tailings dam structure [61]. The presently lowered tailings edge is prone to failure. The suggested method is raising the height on that end which is farthest from already existing slope. Other measures include using upland soil for parapets on current down-slope edges of tailings structures as well as constructing cut-off drains that ensure all tailings water flows horizontally across tailings before being returned back into ocean. Moving earth is capital-intensive and will probably take more time to source than most other rapid deployment measures.

5.4 Technological Innovations in Mining Rehabilitation

Mine closure and rehabilitation are integral parts of sustainable mining endeavors. This comprises an array of activities aimed at restoring land-use capacity, mitigating environmental impacts due to mining activities, and shaping landscapes that are safe and aesthetically pleasing. The success of post-mining land uses basically depends on how much pre-mining transformations were done; what type and method(s) were used in mining; as well as rehabilitation techniques adopted thereafter. Landforms, hydrology, soil, and vegetation need rehabilitation maintenance since these are elements critical for sustainable mining after reclamation but they also require long-term monitoring in areas impacted by mining activities with an assessment on environmental impacts regarding slope stability.

Remote sensing, geospatial technologies, and field observations were used to assess post-mining transformations in the Base Titanium mining area of Kwale County, Kenya. The analysis indicated increased greenness and vegetation cover as a result of mining reclamation efforts. The dynamics of post-mining transformation are influenced by landform design, rehabilitation technique, drainage system restoration, and land ownership. Results like these shall be beneficial not only to Base Titanium and other international companies in their rehabilitation efforts but also to the local community and the country at large in managing sustainable mining practices.

Technique scientific-technical progress in rehabilitation of mining and restoration of former environmental conditions post-mining landscape shall support industry planning plus legislative frameworks achieving productive sustainability. Any future project in mining will depend upon how the landscape is managed after mining plus how all stakeholders from the company owners' operator's government communities plus NGOs participate in discussions about this landscape.

Post-mining landforms using mining waste are regarded as the ultimate sustainable use of mining waste because they provide a dependable and cost-effective solution to mine closure that corresponds with the target market for recovery. However, designing these landforms and understanding their impacts on different social and environmental factors is not easy due to many variables and uncertainties in the system. The nature as well as possible impacts of post-mining landforms should be studied thoroughly so that they can be successfully implemented. This calls for multidisciplinary research possibly based on a consortium.

Open cast mining of minerals has been a widely adopted practice due to its high production rate, economic viability, and resource availability. However, it poses severe environmental impacts through landscape denudation which increases land instability rendering the land unsuitable for diverse agricultural activities; destruction and degradation of flora and fauna within and around the mining areas; soil erosion; heavy metal contamination; health hazards to adjacent communities. Slope stability analyses are imperative in open-pit mining settings for safety assurance and minimization of environmental degradation. All maintenance measures should aim at promoting sustainable environments. In most cases, post-mining rehabilitation becomes expensive and difficult due to financial constraints, issues of prioritization, engineering solutions as well as inadequate policies that align with the needs of host communities. Innovations, new processes, and designs are very important in the successful rehabilitation of mining sites. To minimize the universal effects of opencast mining, technological advancements based on biotechnological, biogeochemical, and geotechnical treatments as amendments to mine spoils have been suggested. A literature review on the management of mine spoils and rehabilitation strategies using biotechnological, chemical, and geotechnical methods was conducted. The primary aim was to come up with practical interventions applicable at disposal sites in Kwale County for restoring damaged ecosystems to improve sustainability in new ones toward supporting sustainable development in mining areas. These approaches can also be integrated into existing codes of practice together with local approaches for optimizing ecological restoration and stability of disposal sites all over the world. Furthermore, multi-factor research is recommended to evaluate success at regional levels.

5.5 Economic Aspects of Rehabilitation

The economic impacts from the mining sector are substantial; it provides foreign exchange for the country as well as funding via royalties and taxes. It also brings about conflicts, problems, and different social and agricultural issues on the issuance of mining licenses. Areas become barren and abandoned because post-mining land-use is not properly implemented resulting in landslides, environmental pollution, and challenges in reclaiming land to other uses apart from mining. Therefore, ecological improvement cultural conditions as well as an economic upliftment post-mining should be initiated at the earliest possible time. Mining is a natural resource exploitation activity that may lead to environmental problems. Mining-related problems are categorized under social and economic conflicts which include issues regarding compensation for mines ecological impacts plus cultural adversity.

Post-mining activities at the end of mining operations are summarized in a Mine Closure Plan, project closure plan, or closure plan. The activities mentioned in the Mine Closure Plan consist of installing a diversion drain, placing geotextile in the final pit, excavating and refilling sedimentation basins, lining the final pit with geomembrane, making water filling pools, planting native succulent plants and native trees as well as increasing community capacity to maintain environmental rehabilitation together with water treatment. Approximately 80% of household water supply in a mining area comes from natural springs and ponds. Protection and sustainability efforts for these sources must be realized by keeping spring and pond areas free from pollution (no-tolerance zone). The rest 20% of drinking water is supplied from the potable water treatment plant located in each expanded housing area. Catchment protection for those springs that are the main source of raw water for the Water Potability Treatment Unit is quite simple to do. In general, post-mining areas in Indonesia have hollow lands or excavated pits which can be potentially used as artificial water reservoirs (pools). These pools have enough amount of water to fulfill both industrial and domestic water treatment needs coming from various sources of supply.

There are economic benefits to rehabilitating successfully mined-out land. Mining companies that carry out rehabilitation plans effectively will reduce their rehabilitation costs or receive financial incentives when wetlands and upland areas are restored. The financial gain from rehabilitated mined land could be further increased through partnerships with development organizations interested in funding restoration projects. Early priority of mined-out land for restoration could significantly increase the profitability of rehabilitation efforts. Some ongoing groundwork in restored sites can lead to large reductions in transportation costs and improve soil stability. Further economic benefits could come from promoting rehabilitated land for ecotourism and recreational use. A model showing posterior inferences about key decision points will be used to illustrate how their decisions affect what comes next and provide a system emphasizing different pathways toward skill development.

Extreme cost reduction will be brought by modeling and simulation, or the renovation and rehabilitation of existing models. Probabilistic methods to improve the robustness of initial investment models will create value-enhancing opportunities for projects. A new generation of engineers entering the workforce should be introduced to uncertainty modeling and simulation as foundational pillars that support future engineering work. A complementary review process is necessary for a radical overhaul in management philosophy along with the streamlining of technical, engineering, and production methods. Professional development in this industry should not only focus on new technical skills but also on innovative modeling opportunities that deliver competitive advantage or eliminate value-destroying risks. There is an urgent need for increased scrutiny through modeling concerning decision-making in the industry because productivity challenges are rising while traditional pathways toward extraction decline as R&D ceases to provide sustainable economic returns.

5.6 Environmental Policy Recommendations

The assessment and analysis of natural conditions, slope stability, and impacts of mining activities in the study area revealed essential findings. Environmental policy reforms among others were: 1) The Mining Act 2016. 2) National Environment Management Act and Regulations of 1999. 3) Water Act 2002. 4) Environmental Management & Coordination (amendment) Act 2015.

These policies have been developed by government officers but are not yet in place due to resistance from mining companies. For example, critical procedural measures such as environmental audits, valuations, or assessments of stability and risks are not undertaken; monitoring plans for mining activities are frequently absent; remedies for mining legacies pre- and post-impact effects on the environment, ecosystems, and slope stability are missing; local communities affected by the mines' expansion are inadequately compensated; policies to transfer mining technology and best practices to develop local industry do not exist; or perhaps more accurately stated, policies may not recognize sufficiently the spatial extent and associated liabilities with mining-induced environmental impacts. Companies often do not seem to understand what it means in terms of their operations and reputations when water resource quality deteriorates over time. These are certainly key issues for environmental policies in all producing countries! Almost 30 years after the introduction of national sovereignty over raw materials policy, no comprehensive mining law has been enacted to control such an expanding industry. In this light, proposed changes herein would aim at complementing existing frameworks for sustainability and development with procedural agreements plus corrective measures.

The study, in summary, sought to merge two previously unconnected domains: environmental impacts on slope stability within the post-mining and ongoing expansion domains, and sustainability practices within the study area. The aim was to generate findings that go beyond the company's specific interests. Having a clear understanding of the processes through which mining impacts operate provides a scientific basis for policies that seek to avoid or mitigate the risks related to slope instability, extreme rainfall, land-use changes induced by mining, and post-closure activities. However, even more important would-be technological solutions, costs of minimum practices, missed investment, and revenue from taxes or growth of local industrial capacity that can provide real benefits and cost savings for sustainability practices in mining and beyond.

Mining has generated significant amounts of waste in the form of stockpiles, tailings, and ponds. Nevertheless, it has not yet achieved a reliable means of ensuring the stable establishment of post-mining slopes capable of supporting vegetation growth after rehabilitation. A passively fed dredge pump was employed for the placement of tailings on surface slopes in this endeavor. It remained uncertain whether the pumped tailings developed sufficient surface tension and shear strength to progressively occupy voids left by coarse materials. The tailings matrix was to be determined through its effect on slope stability modeling long-term environmental impacts assessing its effect on soil quality as well as tests for vegetation establishment on this tailing's matrix. It should not only assist its rehabilitation efforts but also guide planning for expansion into that large dune just west of the mine since this area probably holds more material than required.

6. FUTURE RESEARCH DIRECTIONS

Over the past few years, the mine at Kwale has kept its output steady. Mining activities in this area are expected to continue for several more years. Due to the nature of the deposits, land-use options in the long term will be very different from previous uses of land. Key economic areas include Tsavo National Park, Mombasa Marine Park, and Malindi Marine Park; these parks are of great importance to both clans Njiru and Digo. The water bodies formed from mining pits will also carry a lot of ecological value. Baseline and post-mining monitoring of different environmental aspects has been carried out by the mining company. This monitoring describes typical post-mining land uses for the area which include horticulture, energy generation, aquaculture as well as water storage. A framework exists for assessing whether or not the post-mining environment is capable of supporting such uses. Ongoing investigations seek to better understand and quantify impacts that different excavation and closure planning scenarios have on both subaerial environments and groundwater across a range of post-mining landscapes [2]. The Kwale titanium mine has been in operation for more than 10 years now. Early on when it began operations, media reports raised concerns about possible environmental impacts [1-12]. The mines at Kwale are based on embedded ilmenite which occurs naturally forming a series of plateaus and valleys; thus, very large deep open pits have been created by this operation. It has been emphasized from the beginning that a core focus is on ensuring sustainable post-mining land use comparable to pre-mining conditions since mining began. Several investigations are ongoing in this regard. A quantitative comparison and ranking of habitat types across the quarries resulted in several high-priority areas for current and future assessment. Detailed habitat mapping for greater Kwale was done before the start of mining activities; it is critical that mapping continues as well as monitoring those particular types of habitats that develop inside post-mining pits because these two activities form part of environmental commitments to Kenya's government.

Mining has taken place on the East African coast for several years. In Kenya, mining activities have been ongoing since the early 1990s with the extraction of building materials and limestone quarrying. The coastal region of East African Community (EAC) states-Kenya, Tanzania, and Mozambique has large reserves of beach-sand mineral deposits that contain economically important titanium (Ti) minerals such as rutile ($TiO2$), ilmenite ($FeTiO3$), and zircon ($ZrSiO4$).

Heavy minerals (HMs) extraction from the beach sands in a coastal strip between Tiwi Creek north of Diani Beach up to Mombasa would necessitate the relocation of several human settlements together with related transportation infrastructure and other support services raising very important geo-environmental concerns regarding mining impacts on the geology of the area plus their impacts and those proposed mitigation measures on two major geo-environmental issues: uncontrolled surface drainage and tailings slope instability which are environmental hazards to communities relocated downslope at Diani Beach and at Tiwi.

It is estimated that the dredging method of processing beach sand from borrow pits will take about 25 years for mining operations to complete. Wetlands previously drained should be reconnected after mining, plus foreshore restoration by beach-nourishment strategy [2]. This is an initial operation of its sort in the district, thus there are no previous geo-environmental or mine-closure experiences to draw from. However, international operations have provided knowledge and expertise, as well as principles for environmental management, addenda on specific issues, and best practices developed during those operations which can serve as a guideline in identifying possible environmental hazards due to proposed mining activities and processing facilities plus carrying out relevant assessments needed to manage them.

7. CONCLUSION

The radical topographic alteration of the open-pit titanium mining in Kwale County, has left behind steep, unstable slopes which are potential sources of erosional activities and safety risks. This paper presents real time data evidence that unclaimed mines and tailings dumps, with slope angles of 35° or greater and scant vegetation cover due to biodiversity loss, are extremely susceptible to steep slope mass movement system and accelerated erosion by rainwater. In addition, mining areas with proactive on-going reclamation processes are characterized by slopes re-gradation of less than 25°, modifications of drainage systems, and dense cover of native vegetation have long-term stability and reliability. The integration of high-resolution UAV terrain models with ground truthing field measurements of slopes and NDVI analyses enhanced quantification of the extents of particular reclamation practices that mitigate geo-hazards risks and promotion of the ecological recovery. It emphasizes regrading steep embankments, cutoff and toe drains for surface and subsurface water management, and the rapid establishment of native plant communities with deep root systems. These measures can rehabilitate former mining scars into multifunctional landscapes for agroforestry, ecotourism, or water-retention practices. An emphasis on scientific post-mining landform design as well as ecological restoration will maintain environmental integrity plus community safety while yielding sustainably productive land assets that endure long after the mines have closed.

List of abbreviations

The manuscript employs several key abbreviations to streamline discussion of its methods and context: Unmanned Aerial Vehicle (UAV) for drone-based imagery acquisition; Digital Surface Model (DSM) for the 3D representation of land-surface elevations; Digital Terrain Model (DTM) for bare-earth elevation data; Normalised Digital Surface Model (nDSM), derived by subtracting the DTM from the DSM to isolate above-ground features; Normalised Difference Vegetation Index (NDVI) for assessing vegetation cover density; Global Positioning System (GPS) for precise location measurements in field surveys; Environmental and Social Impact Assessment (ESIA) for regulatory evaluation of mining projects; Large-Scale Mining (LSM) to denote primary commercial extraction operations; Heavy Minerals (HMs) when referring to the economically valuable titanium-bearing sand fractions; and East African Community (EAC) to contextualize regional mining governance frameworks.

Author Contributions

Conceptualisation, methodology, software: Kand C.P.; formal analysis, K.F. and C.P.;; Investigation, resources, data curation, writing original draft preparation, writing review and editing, visualisation, supervision: C.P. and K.F. All authors have read and agreed to the published version of the manuscript.

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